AN ABSTRACT OF THE THESIS OF

Mikolaj Lewicki for the Master of Science in Physical Sciences Presented on

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Title: Landsat Imagery of Estonia

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Landsat Thematic Mapper (TM) imagery was used to analyze the sediment and geomorphic features in southwestern Estonia. Landsat 4 and 5 image sets from June and July of 1986 and May of 1988 were used for the research. The objective of the research was to find the best way of processing and analyzing the Landsat images to use in the study of Quaternary sediments and geomorphic landforms. The sedimentary and geomorphologic features were interpreted from the scenes, using both unsupervised and supervised methods of classification. During the unsupervised classification Idrisi ISOCLUST and RECLASS modules were used. In supervised classification the author visually selected pixels or clusters, which represented a feature. Classified images were produced using the RECLASS module. The classified images were multiplied by the normalized difference vegetation index (NDVI) to

recognize the vegetation type, which coincided with a sedimentary or geomorphic feature.

In southwestern Estonia different types of land use coincide with the specific type of sediment or geomorphic form of terrain. Using the classified masks, different types of land use were extracted, and the attempt to link different land-use types with corresponding sediments and geomorphic features was made. During the research peat bogs appeared to be the type of sediment, which can be most easily extracted from the background and directly mapped using the Landsat TM scenes. Peat mining activity was also possible to be extracted from Tasscap moisture index scenes. Till and glaciofluvial sediments are possible to be identified and separated based on the differences of land-use types in southwestern Estonia. Areas covered by till sediment were extracted using only unsupervised methods of classification. The till sediment coincides with the specific forest-cluster, spruce, which has different spectral signatures compared to surrounding types of forests clusters, and other types of land use. Geomorphic forms including dunes, end moraines, and in many cases eskers, especially marginal eskers, gave positive results during attempts to recognize and to separate them from the background. Dunes, eskers and in some cases drumlins were possible to be extracted from the background using both supervised and unsupervised methods of classification. Drumlins, eskers and dunes are linear features, which have different types of vegetation from surrounding areas, and their spectral signatures are easy to separate from the background in many cases. End moraines are possible to be traced and located on the Landsat TM image as borders between different types of land use.

Landsat Imagery of Estonia

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Landsat System

The idea of a civilian Earth resources satellite started in the mid-1960's. The National Aeronautics and Space Administration (NASA) decided to develop and launch the first Earth monitoring satellite to meet the needs of resource managers and Earth scientists. In 1972, NASA launched the first in a series of satellites designed to provide repetitive coverage of the Earth. The first satellite - ERTS-1 (Earth Resources Technology Satellite) carried sensor systems and data relay equipment. It carried the instrument called the multispectral scanner (MSS). ERTS was renamed in 1975 to Landsat

The satellite functioned for more than 5 years after its launch date (table 1). The Landsat satellites 1 through 3 operated in a near-polar orbit at an altitude of 920 km with an 18-day repeat coverage cycle. Landsats 1 through 3 satellites carried return beam vidicon (RBV) cameras and the MSS sensor (Multispectral Scanner Landsat Data 1999). The resolution of the MSS sensor was approximately 80 m. Scenes contained radiometric coverage in four spectral bands from the visible green to the near-infrared (NIR) wavelengths. Landsat 3 had a fifth band in the thermal-infrared wavelength.

Satellite Launched	Decommissioned	Sensors
Landsat 1 July 23, 1972	January 6, 1978	MSS and RBV
Landsat 2 January 22, 1975	February 25, 1982	MSS and RBV
Landsat 3 March 5, 1978	March 31, 1983	MSS and RBV
Landsat 4 July 16, 1982	*	TM and MSS ***
Landsat 5 March 1, 1984	**	TM and MSS ***
Landsat 6 10/5/93	Failure on launch	Enhanced Thematic Mapper (ETM)
Landsat 7 April, 1999	**	Enhanced Thematic Mapper Plus (ETM+)

* in standby mode used for range and command as of December 14, 1993.

** currently operational, *** MSS data acquisition suspended in 1992

Table 1. Background information and status of Landsat satellites (Multispectral Scanner Landsat Data 1999).

The second satellite was launched January 22, 1975. It was named Landsat 2. Three additional Landsats were launched in 1978, 1982, and 1984 (Landsats 3, 4, and 5, respectively). Each successive satellite system had improved sensor and communications capabilities (Multispectral Scanner Landsat Data 1999).

Landsats 4 and 5 carried both the MSS and more advanced Thematic Mapper (TM) sensors; collection of MSS data was terminated in late 1992. The TM sensor provided data in wavelength range from the visible (blue), through the mid-infrared, into the thermal-infrared electromagnetic spectrum. The TM sensor has a spatial resolution of 30 meters for the visible, near-IR, and mid-IR wavelengths and a spatial resolution of 120 meters for the thermal-IR band.

NASA operated Landsat Satellites until 1983 when operations of the Landsat Satellite system were transferred to the National Oceanic and Atmospheric Administration (NOAA). In 1985, the Landsat system was commercialized. The EROS Data Center (EDC) remained responsible for the archive of Landsat data for the federal government. Congress passed the Land Remote Sensing Policy Act in 1992. The act established a new policy of pricing and collection of data.

The next Landsat satellite, Landsat 6, was a launch failure. In 1994, President Clinton established Landsat 7 as a joint program with NASA, NOAA (later dropped out), and the U.S. Geological Survey's EROS Data Center (EDC) (Aber 1999). The satellite was launched on April 15, 1999. NASA will operate Landsat 7 until Oct. 2000. The EROS Data Center will take control over the operations beyond Oct. 2000.

Estonia

A study of the southwestern Estonian province Pärnu was done using the Landsat TM data image sets (fig. 1). The following research was the first attempt to utilize Landsat Thematic Mapper datasets in the examination of Quaternary sediments and geomorphic landforms in Estonia. This type of research was conducted by many authors in other locations and proved to be both effective and cost efficient.

Estonia is a country located in northeastern Europe within the Baltic Sea basin. The total area of Estonia is of 45,215 km^2. Estonia has borders with Russia to the east and with Latvia to the south (fig. 2). Forest makes approximately 31 % of Estonian area, agricultural land use occupies 22 %, and other land use covers 47 % of the country (CIA World Fact Book 1996).

Estonia is a lowland country. The average elevation reaches only 50 meters above sea level (fig. 3). The highest point in Estonia is Suur Munamägi with elevation 318 m above sea level. It is located in the southeast of the country. Almost 1000 postglacial lakes cover the country. The largest Lake Peipsi, is the fifth largest lake in Europe. Its area equals 3555 km^2.

The Baltic Sea is a relatively shallow inland sea surrounded by the countries of northeastern Europe and Scandinavia. The Baltic is a semi-enclosed sea with limited water exchange with adjacent seas.

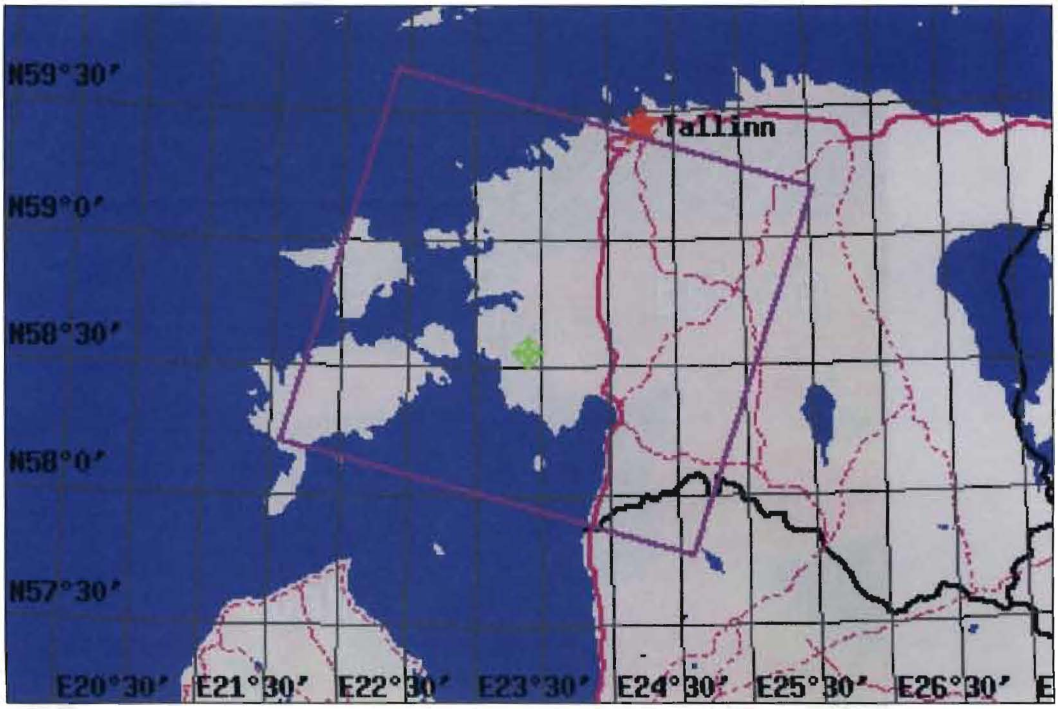

Fig. 1. Full scene covered by Landsat TM datasets. The study area encompasses western Estonia. Green star indicates Parnu province of southwestern Estonia. Taken from EROS data center.

Fig. 2. Baltic region countries. Qadir (1999).

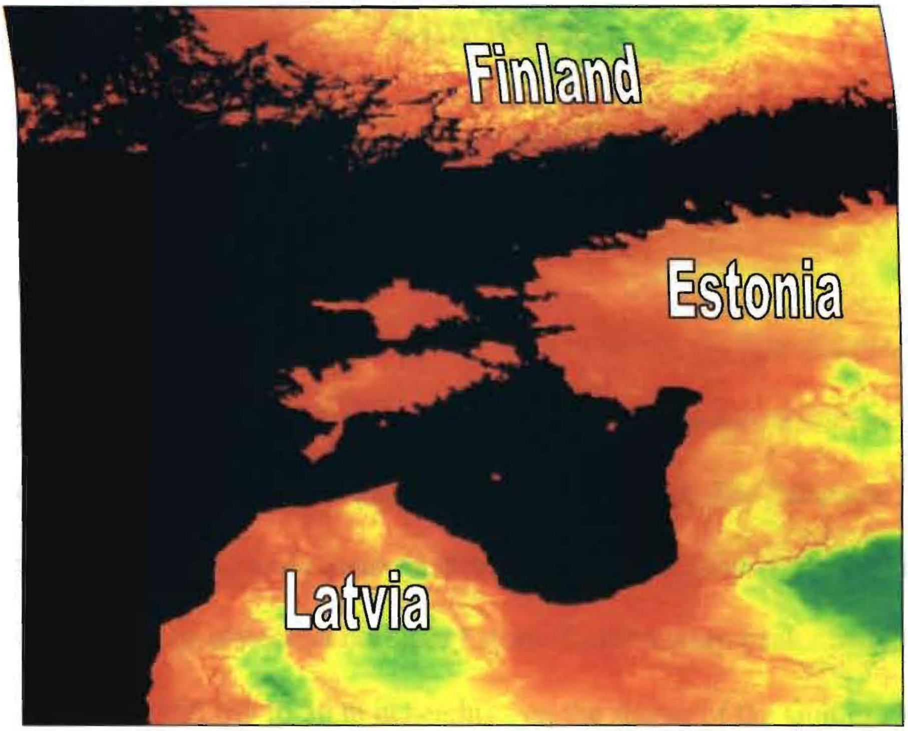

Fig. 3. Digital elevation model of Estonia. Image was processed in IDRISI 32. Orange color depicts low-elevated areas; green color depicts high-elevated areas. Hastings (1999).

The mean depth of the Baltic is 55 m, but the maximum depth reaches 459 m. The environment of the Baltic Sea is affected by the combination of the numerous factors including the shape of the sea bed, the limited water exchange, the salinity and temperature barriers between surface water and bottom water, as well as the pressure of pollution and human overexploitation. The full replenishment of water from the Baltic Sea by water from the North Sea takes 25-35 years (Küllo and Kallasmaa 1999). Almost 80 million people live within the Baltic drainage area.

Chapter 2

Estonian Geology and Land Cover

Bedrock

Estonia is situated on the level northwestern part of the East-European platform. The oldest known Estonian formations are the early Precambrian crystalline rocks covered by upper Vendian and Paleozoic sedimentary rocks. The Paleozoic sequence starts in lower Cambrian and continues through upper Devonian. The extensive Ordovician limestone plateau in northern Estonia forms a steep bank - called the Baltic (North-Estonian) cliff (up to 56 m in height) - on the shores of the Gulf of Finland (Küllo and Kallasmaa 1999). A smaller cliff composed of Silurian limestone forms the northern coastline of the large Estonian islands, Saaremaa and Muhu, which are located within the analyzed scene.

During the Pleistocene, Estonia was overridden by continental ice sheets. Glaciers covered the bedrock with layers of diverse sediment. Glacial sediment includes till, lacustrine sediments, and sediments left by glacial rivers. Another prevalent Quaternary sediment is peat. The total area covered by peat bogs is approximately 9000 km^2 with peat mass 4000 million tons. The Quaternary deposits covering the limestone layers are initially thin in the north, but become thicker towards the south (up to 200 m) - forming hilly morainic terrain on the sandstone in southern Estonia (Küllo and Kallasmaa 1999).

The main Estonian geologic resources are connected with Ordovician bedrock in northern Estonia. The main resources include oil shale and phosphorite. Other natural

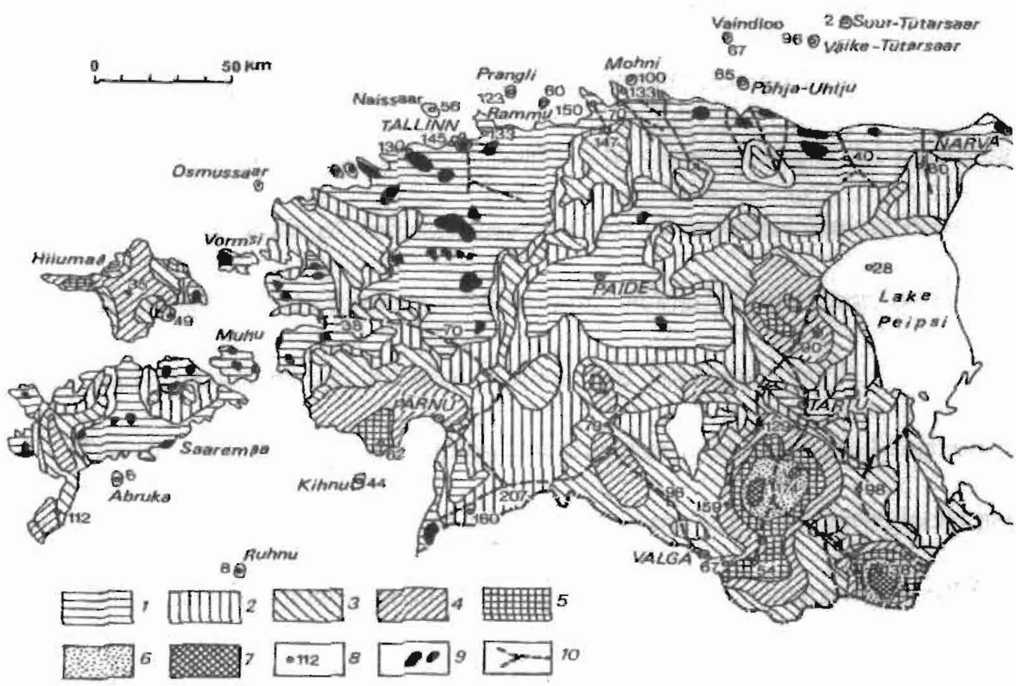

Fig. 4. Thickness of the Quaternary deposits: 1- below 5 m; 2- from 5-10 m; 3- from 10-20 m; 4- from 20-40 m; 5- from 40-60 m; 6- from 60-80 m; 7- over 80 m; 8- boreholes with thickness of the Quaternary deposits; 9- alvars; 10- buried valleys. From Raukas and Teedumae (1997).

resources include limestone, Cambrian blue clay, which outcrops on the north coast, and peat.

Quaternary Cover

Quaternary glaciations covered a vast area in eastern Europe. Estonia belongs to the zone of moderate glacial accumulation and has rather thin glacial cover (fig. 4). In northern Estonia, Quaternary cover is usually less than 5 m. The maximal thickness of the Quaternary cover occurs in southeastern Estonia and reaches 207 m. Usually several till layers compose Quaternary cover. Approximately, 48% of the Estonia surface area is covered by glacial sediments, glaciolacustrine sediments occupy 7% of the country, and glaciofluvial sediments occupy 3% of deposits. The classification of the Quaternary deposits is based on study of different genetic types of deposits. Among Pleistocene deposits six paragenetical series are predominant: eluvial, organogenic, colluvial and deluvial, aqueous, glacial and subaeral (Raukas and Teedumae 1997).

The eluvial deposits are composed of crusts of weathering, soil horizons and forms left by permafrost. Deposits of organogenous series include interglacial peat and gytia. Colluvial and deluvial deposits occur in front of escarpments where solifluction processes played an important role in the late glacial periods of time. Aqueous deposits include interstadial and interglacial lacustrine sediments. Many contemporary peat bogs are underlain by glacial lacustrine sediments. Marine interglacial deposits belong to this series as well. The biggest part of the Pleistocene cover is composed of glacial paragenetical series.

Lower Pleistocene sediments are absent in Estonia, and middle Pleistocene sequence is incomplete. Many upper Pleistocene formations are recognized (fig. 5). The center of all glaciations was Scandinavia. Estonia was covered by Baltic and Peribaltic ice-sheet streams approaching the country from varying directions during the glaciations. The main directions of ice movement came from north to south and from northwest to southeast (Raukas and Teedumae 1997). The general pattern of ice-sheet movement was affected by local topographic forms. The orientations of numerous landforms reflect these directions of ice movement (fig. 6).

General units			Local units		Palaeontological and lithological characterization	Most important sites
System	Division	Sub-division	Forma-tions	Subfor-mations		
QUATERNARY	HOLOCENE	Separate stratigraphic scheme of Holocene (Flandrian) deposits has been accepted			Variegated continental and marine deposits, 10 assem-blage zones	Continental deposits all over Estonia, marine deposits in Lower Estonia
	PLEISTOCENE	Upper Pleistocene	Järva III_{jr}	Võrtsjärve III_{vr}	Grey till in North Estonia, reddish-brown till in South Estonia, aqueoglacial deposits	All over Estonia
				Savala III_{sv}	Dry periglacial vegetation	Savala, Vääna-Jõesuu
				Valgjärve III_{vl}	Grey till in North Estonia, purplish-grey till in South Estonia, aqueoglacial deposits	Valgjärve (Kitse), Kaagjärve, Prangli
				Kelnase III_{kl}	Cryo- and hydrophilous vegetation	Prangli
			Prangli (Rõngu) III_{pr}		Forest vegetation, pollen zones P_1-P_8, marine and continental deposits	Prangli, Kihnu, Rõngu, Küti, Kitse
		Middle Pleistocene	Ugandi II_{ug}	Upper Ugandi II_{ug3}	Brown till in North Estonia, grey till in South Estonia, aqueoglacial deposits	Prangli, Rõngu, Saadjärv, Juminda, Suur-Munamägi
				Middle Ugandi II_{ug2}	Periglacial vegetation	Prangli, Keskküla, Valguta
				Lower Ugandi II_{ug1}	Brown till both in North and South Estonia, aqueoglacial deposits	Prangli, Naissaar, Keskküla, Mägiste, Lanksaare
			Karuküla II_{kr}		Forest vegetation, pollen zones K_I-K_{IV}	Karuküla, Kõrveküla
			Sangaste II_{sn}	Upper Sangaste II_{sn3}	Shaly brownish till in Central and South Estonia	Saadjärv, Keskküla

Fig. 5. Stratigraphic Scheme of Quaternary Deposits in Estonia. In the Estonian stratigraphical chart lithostratigraphical terms are used as basic units. Taken from Raukas and Kajak (1995).

Fig. 6. The map of Quaternary deposits: **g** - till, **lg** – glaciolacustrine, **m** - marine, **a** - alluvial, **l** – lacustrine, **b** - boggy, **t** - technogenous, black - Pre–Quaternary (Raukas and Teedumae 1997).

Areas of glacial accumulation were relatively stable through all Pleistocene. Such topographic forms as valleys, interlobate massifs, lee areas of elevated bedrock, and forms transverse to ice streams movement were places of glacial accumulation. Intensive erosion took place on elevated parts of bedrock, and in ice-lobe depressions.

The ice marginal depositional zones are connected with slopes of bedrock elevations and with depressions in bedrock. Drumlins are frequently located on sides of bedrock elevations distal to ice movement and in depressions where ice streams moved with different speeds. End moraines are usually located on the proximal sides of terrain elevations. Eskers are mainly connected with bedrock depressions or with ancient valleys (Raukas and Teedumae 1997). Glaciofluvial deltas, occurring mostly in northern Estonia, are characteristic for the bedrock surfaces inclined toward the ice sheet. The hilly topography of southern Estonia was determined by distribution of stagnant ice. In northern Estonia, topography is flat as a result of the presence of active ice lobes until the final melting and deglaciation.

Chains of ice marginal moraines and glaciofluvial forms well marked in the topography are places of temporary stagnations of ice sheet margins. Next to receding ice sheet margins, proglacial lakes were common features. Glaciofluvial deltas, marginal eskers, and glaciolacustrine sediments are typical in many places in the vicinity of the proglacial lakes.

Till

Approximately 47% of the country area is composed of glacial till (Raukas and Teedumae, 1997) (fig. 6). Usually till is composed from several till beds. The glacial deposits can be divided into two main groups: glacial drift, which was deposited on ground (subaerial till), and deposits underneath ice sheets (subglacial till). The subaerial group includes, ablational and marginal tills. The subglacial group includes basal till. Tills in Estonia are mainly of continental subglacial genesis. Tills have great similarity to underlying bedrock. Basal tills have the widest spread. Basal tills originated both beneath an advancing glacier and as a basal melt out tills during deglaciation. Ablational tills usually create a cover on top of the basal tills. Marginal tills are present in end moraines, push moraines and dump moraines (fig. 7).

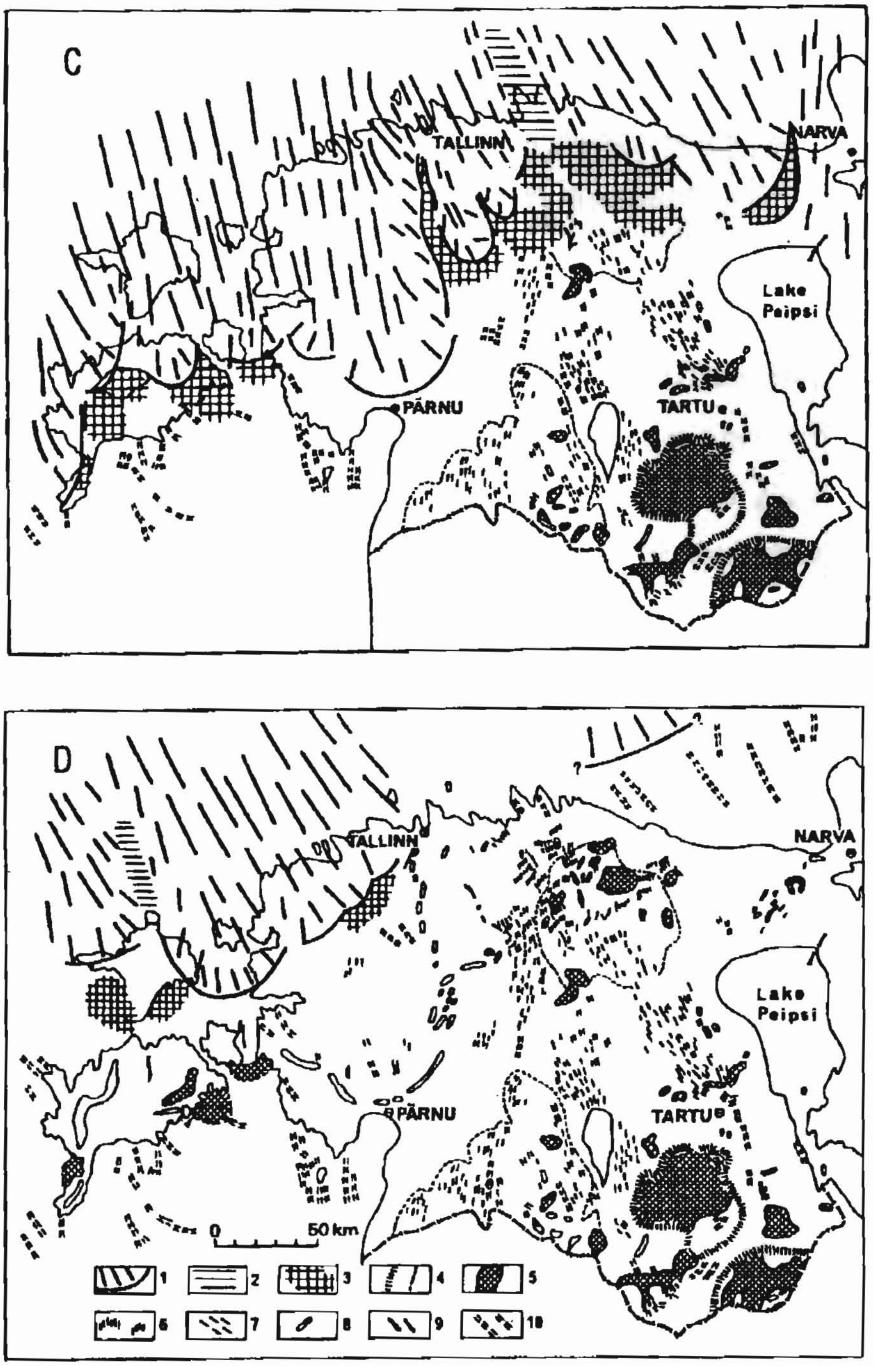

Fig. 7. Image C- Pandivere stadial of deglaciation, D- Palivere stadial of deglaciation. 1 - margin of active glacier, 2 - ice-sheed area, 3 - dead ice, 4 - foot lines of accumulative insular heights 5 - hummocky topography, 6 - marginal belts of hummocky topography, 7 - drumlins 8 -end morraines and eskers, 9 - radial eskers, 10 - orientation of elongated landforms. Adapted from Raukas and Teedumae (1997).

End Moraines and Marginal Eskers

The bedrock topography has a great impact on the distribution of ice marginal depositional zones, which are usually connected with slopes of bedrock elevations and with depressions in bedrock. End moraines are usually distributed on proximal slopes of elevations, which blocked the movement of ice sheet and caused the accumulation of till. Marginal positions of the ice sheets in the topography are marked by the chains of the end moraines. Usually end moraines are originated during the temporary stagnation of the ice margin. Large water bodies were present extensively in front of the receding ice sheet margins. Therefore glaciofluvial deltas, marginal eskers, and glaciolacustrine deposits are common features in front of the end moraines. The distribution of glacial sediments is controlled by processes connected with their origination. The end moraines and the areas behind are covered by till in contrast to zone located in front of the stagnating ice sheet which was covered by such glaciofluvial sediments as sand, silt, loam and clay. Typical sandurs are less common in Estonia (Raukas and Teedumae 1997).

Holocene Cover

Holocene continental deposits occur almost everywhere above the Pleistocene deposits. The stratigraphical scheme of Holocene deposits is based on the continental deposits and four major phases in postglacial history of the Baltic. Among the most conspicuous Holocene deposits are peat and dunes.

Peat

"Peat is a fibrous substance produced by decay of vegetation in mires and it contains high proportion of water" (Raukas and Teedumae 1997). The composition of peat depends on conditions of its formation and on location of the deposit in relation to topography. Estonia and Belarus are considered as the countries richest in peatlands in northern Europe. Formation of peat mires started immediately after the territory of

Estonia was freed from the last ice-sheet. Mires formed mostly from mineral soils or by filling the shallow water bodies.

Mires are divided into two groups: ombrotropic occupying higher elevated areas and fed by precipitation and minerotropic mires fed by ground and surface water (Raukas and Teedumae 1997). Minerotropic mires are predominant in western Estonia. The boundary between peatland genetic provinces coincides with extension of the maximal Baltic Sea transgression (fig. 8). The western, lower part of Estonia was covered by the Baltic Ice Lake and different stages of the Baltic Sea. In Estonia are mapped peat bogs thicker than 30 centimeters.

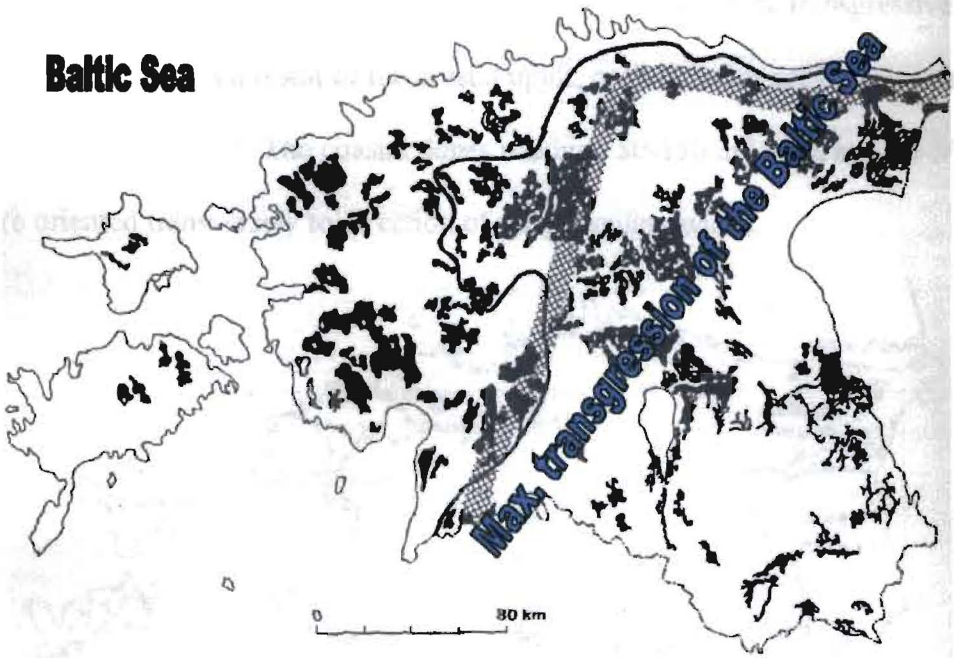

Fig 8. Distribution of peat bogs larger than 1000 ha in Estonia.

Adapted from Raukas and Teedumae (1997).

Dunes

In Estonia both coastal and inland dunes occur (fig. 9). The creation of the dunes was closely connected with such features as land uplift, wind direction, and soil moisture. Dunes are often situated on top of the old beach ridges. Coastal erosion and sedimentation have modified all lowland geomorphology. Currently there is no dune sand movement in Estonia. The parabolic and transverse shapes of dunes indicate prevalent western to northwestern paleowind directions (Zeeberg 1993). The inland dunes are usually covered by pine forest and surrounded by peat bogs. The largest coastal dunes reach heights of 20-25 meters and were formed during transgressive phase of the Baltic Ice lake. As a result of the crustal uplift, coastal dunes are located some distance from the seashore. The coastal dunes reaching 50-150 m length and 20-50 m width are oriented transversely to direction of the prevailing winds.

Fig. 9 The distribution of the largest dunes in Estonia and distribution of aeolian sand from Raukas and Teedumae (1997).

Estonian Climate

The Estonian climate is determined by its location. The Baltic Sea vicinity strongly influences the climate. The mean annual temperature varies from 6.0° C in the west to 4.2 °C in the east of the country. The mean annual precipitation is 500 mm in the coastal region to 700 mm in the uplands areas of the southeast. The heaviest precipitation occurs at the end of summer. In general, the climate in Estonia is similar to the northeastern United States (Kuresoo 1999).

Forests

Forests cover about 31% of Estonian territory (table 2). Estonian forests are nowadays less managed and exploited than those in western Europe (Kuresoo 1999). The same situation concerns forest drainage, which has been less effective. Estonian forests are usually wet and often rich in plant species.

The most common types of forests are dry pine forests and temperate spruce forests. Besides these types of forests, a wide variety of other forest types exists, like mixed spruce, dry heath pine and species-rich swampy black alder forests, as well as river bank forests and forests on bedrock (Kuresoo 1999).

Lakes

About 1500 small lakes with a surface area less than 10 km^2 are located irregularly in different landscape regions in Estonia. However in the western Estonian lowland, which is encompassed by the Landsat TM datasets, the number of lakes is small. The total number of the lakes is constantly decreasing because of infilling. In the coastal areas, the opposite process takes place, due to land uplift (up to 3 mm a year), and isolation of the new lakes from the Baltic Sea. More than half of the small lakes have glacial origin, and are filled by late glacial and Holocene deposits. Usually lake sediment records start from Older or Younger Dryas (about 10,000 to 12,000 years ago) (Kuresoo 1999).

Wetlands

Estonia is a rather wet country with peat bogs covering about one fifth of its surface. Bogs, together with the coastal and other wetland areas, occupy about one third of Estonia (Kuresoo 1999).

Land use:	% / Area
arable land:	22%
permanent crops:	0%
meadows and pastures:	11%
forest and woodland:	31%
other:	36%
Irrigated land:	110 sq km (1990)

Table 2. Land use and vegetation in Estonia. CIA dataset represents information from the beginning of 1990s appropriate to the 1980s when Landsat images acquired. Many changes in land cover have taken place since Estonia became independent; agriculture is shrinking and forest is expanding. Taken from 1996, CIA World Fact Book.

Rivers

In Estonia there are more than 400 rivers of more than 10 km in length (Kuresoo 1999). In Estonia, many rivers are still unregulated, other rivers and creeks have been regulated only to moderate extent. As a result of the unregulated rivers substantial amount of semi-natural flood plains still exist in Estonia. Large flooded areas are situated in the river basins of the Kasari, Pärnu, Suur-Emajõgi and Võhandu rivers (Kuresoo 1999).

Coasts

Estonia has a long, indented coastline of nearly 3,800 km. Estonia has over 1500 islands alone with 2540 km of coastline. Continuing tectonic uplift reaching up to 3 mm a year is a reason for creation of the new coastal wetlands and islets (Kuresoo 1999).

Wooded Meadows and Other Seminatural Landscapes

Meadows occur with thin topsoil on limestone bedrock and are mainly distributed in western Estonia and in the archipelago (Kuresoo 1999). Wooded meadows are characterized by exceptionally high biodiversity. Previously wooded meadows were the typical form of landscapes in western Estonia. Currently wooded meadows are rare because they have been replaced by agricultural lands. Alluvial meadows that are still mowed can be found in floodplains of Kasari, Halliste and Emajõgi rivers (Kuresoo 1999).

Estonian Arable Land Structure

The area of Estonia, without Lake Peipsi, Petserimaa, and areas east the Narva River, is 45 million hectares (Arvo 1999). Agricultural lands occupy 22 % or 130.8 thousand hectares of the total country area, (other lands occupy 36% including shrubbery 3.0% and swamp 7.4%).

Connection Between Land Cover and Geology

The prevalent types of sediment within the analyzed area originated during Pleistocene and Holocene periods. Older, mostly limestone, outcrops are located on coastal escarpments and may be neglected during the sediment analysis. The thickness of Quaternary cover is mostly greater than 5 meters, so pre-Quaternary bedrock can be neglected in the analysis.

Pleistocene sediments for use in the analysis can be divided into a few main lithological groups including:

a) Sand and gravel.

b) Silt, loam, clay.

c) Different kinds of till.

The most eminent geomorphologic elements on the analyzed area include:

a) End moraines.

b) Hilly moraine terrain.

c) Drumlins.

d) Eskers.

e) Kame fields.

f) Sand dunes.

g) Peat bogs.

Vegetation in Estonia has undergone a process of substantial changes throughout the last one thousand years. Today human land use has remodeled vegetation completely. The best soils are used for agriculture; the rest of the soils, which do not meet the requirements of agriculture, are used for forestry, peat or other purposes.

On the analyzed scenes the borders of sedimentologic and geomorphic features coincide with boundaries in the distinctive areas of land use. The general information obtained from analysis of the land use indicates that agricultural and pasturelands are located on sandy and loamy sediment. In contrast, forests are connected with bedrock including glacial tills and clays.

Concerning geomorphologic forms, forests are connected with different moraines, kames, eskers, drumlins and other types of hummocky landscape. Flat areas are in most cases used for agriculture. Genetically flat areas originated in front of the ice-sheets and are connected with limno-glacial, outwash or alluvial sediments.

Landsat T M Previous Studies

The analysis of the sediment and geomorphic features involving the use of Landsat TM data is still a fairly young field of research. Many large scale studies have been done before. Landsat TM data have been analyzed by many authors to obtain large scale results concerning land use, geology and geomorphology of different areas. The studies gave good results and were cost effective. A study made by Robinson and Beck (2000) used Landsat TM data to create a coherent geologic map of the remote places in Pakistan. Landsat TM data were used to create a spectral ratio images of bands 3/4, 5/4, and 7/5 displayed as red, green, and blue. The images were used in the interpretation of available geologic maps, limited field work, and biostratigraphic, lithostratigraphic, and radiometric data. A study by Rivard et al. (1992) used Landsat TM data to examine sediment and rock controls on spectral reflectance of outcrops in arid regions. In the study by White (1991) the Landsat TM images were used for geomorphological analysis of piedmont landforms in the Tunisian Southern Atlas. The author separated different erosional and accumulational landforms in the Southern Atlas region. The studies of Nichol (1991) and Lancaster (1990) used Landsat TM data to measure the extent and the dynamics of active dunes on deserts in Nigeria and Mexico. In the studies of Cherrill and Fuller (1994) Landsat TM images were used in the characterization of landscape composition in northern England.

Chapter 3

Image Processing

Processing of Landsat TM Scenes

Four Landsat TM scenes were selected (table 3) and acquired from EROS data center on writable CD's. The Landsat TM scenes were loaded into the PC from the writable CD's. The files were renamed to include an *.img extension for the use in IDRISI. The documentation files were made using the information from the header file *.hd for each scene (fig. 10).

A header file is included on writable CD's with the scenes and provides information about the scenes. The information in header files includes "pixels per line" that was used as columns and "lines per data file" that was used as rows in the documentation file. The pixel spacing [resolution] was 28.5 m, which is 0.0285 km. To determine the maximum X coordinate the number of the columns was multiplied by the resolution. To determine the maximum Y coordinate the number of the rows was multiplied by the resolution. The minimum X and Y coordinates were set at zero. In the documentation file the reference system was a plane grid. In the scenes, the maximum and minimum cell values were set up as 0 and 255. In the value units, Thematic Mapper bands were listed for the each file. Separate documentation files were created for each of the four scenes, because the numbers of the columns and the rows were different in each scene.

The four scenes included seven images representing seven spectral bands (table 4). Windows were extracted from each scene to make the further processing faster and to resample overlapping parts of the four scenes.

Scene Date	Scene ID	PATH/ROW	LANDSAT	Sun Elevation
1986/07/28	LT5188019008620910	188/19	LANDSAT 5	47
1986/06/26	LT5188019008617710	188/19	LANDSAT 5	51
1988/05/13	LT4189019008813410	189/19	LANDSAT 4	47
1986/07/03	LT5189019008618410	189/19	LANDSAT 5	51

Table 3. Landsat TM scene date, sun elevation, and ID.

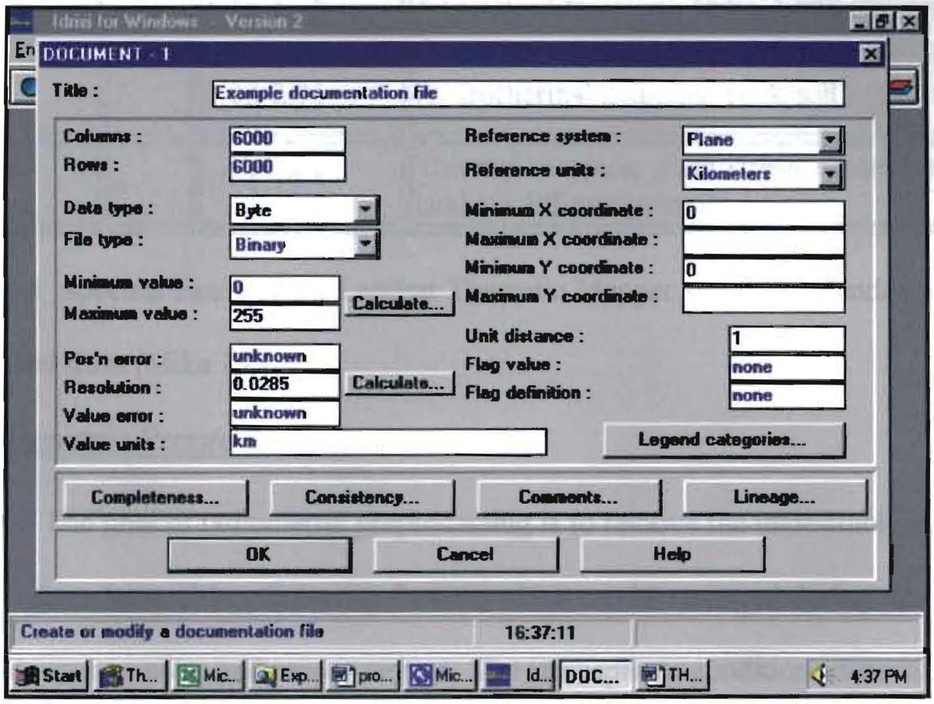

Fig. 10. Sample documentation file with data included from the header file.

Color	Band	Wavelength (μm)	Applications
Blue	1	0.45-0.52	Soil/vegetation and deciduous/coniferous forest differentiation, clear-water bathymetry.
Green	2	0.52-0.60	Vegetation growth/vigor, sediment estimation, turbid-water bathymetry.
Red	3	0.63-0.69	Crop classification, ferric iron detection, ice & snow mapping.
Near infrared	4	0.76-0.90	Biomass (vegetation) surveys, water-body delineation.
Mid infrared	5	1.55-1.75	Vegetation moisture, snow-cloud differentiation.
Mid infrared	7	2.08-2.35	Hydrothermal mapping, rock/soil type discrimination.
Thermal infrared	6	10.4-12.5	Thermal mapping, plant stress, urban/ non-urban landuse differentiation.

Table 4. Spectral bands of the Landsat Thematic Mapper and their intended applications. Adapted from (Mika 1997).

Radiometric Preprocessing

The goal of radiometric preprocessing is to remove the undesirable influence of atmosphere haze. Other distorting factors, which can be removed during this operation, include system noise and sensor motion. The atmospheric conditions distorting the images may include sun angle, cloud cover, water vapor, aerosols, topography, weather, time of the day, and vegetation conditions. Spectral bands 1, 2, 3, 4, 5 and 7 were haze corrected to remove distortions caused by atmospheric effects. The haze correction value was lessened or increased to receive a new minimal value equal to 1.0. (fig. 11) and was done using the module *Analysis /Mathematical Operations /Scalar*. For example, the atmosphere caused the minimal value to be 44 in the upper histogram (fig. 12). The lower histogram shows haze corrected atmosphere with minimum value at one.

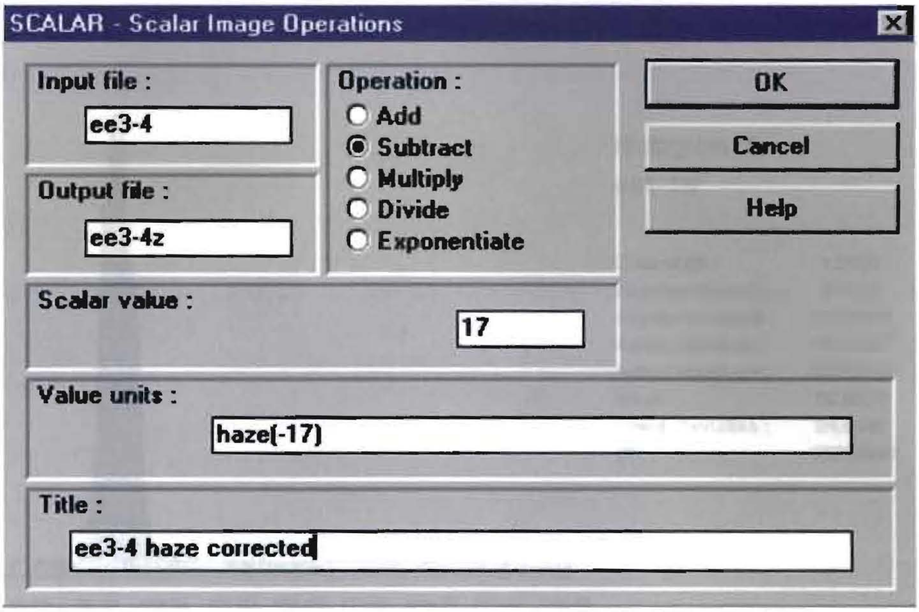

Fig. 11. Module Scalar used for haze correction of each spectral band.

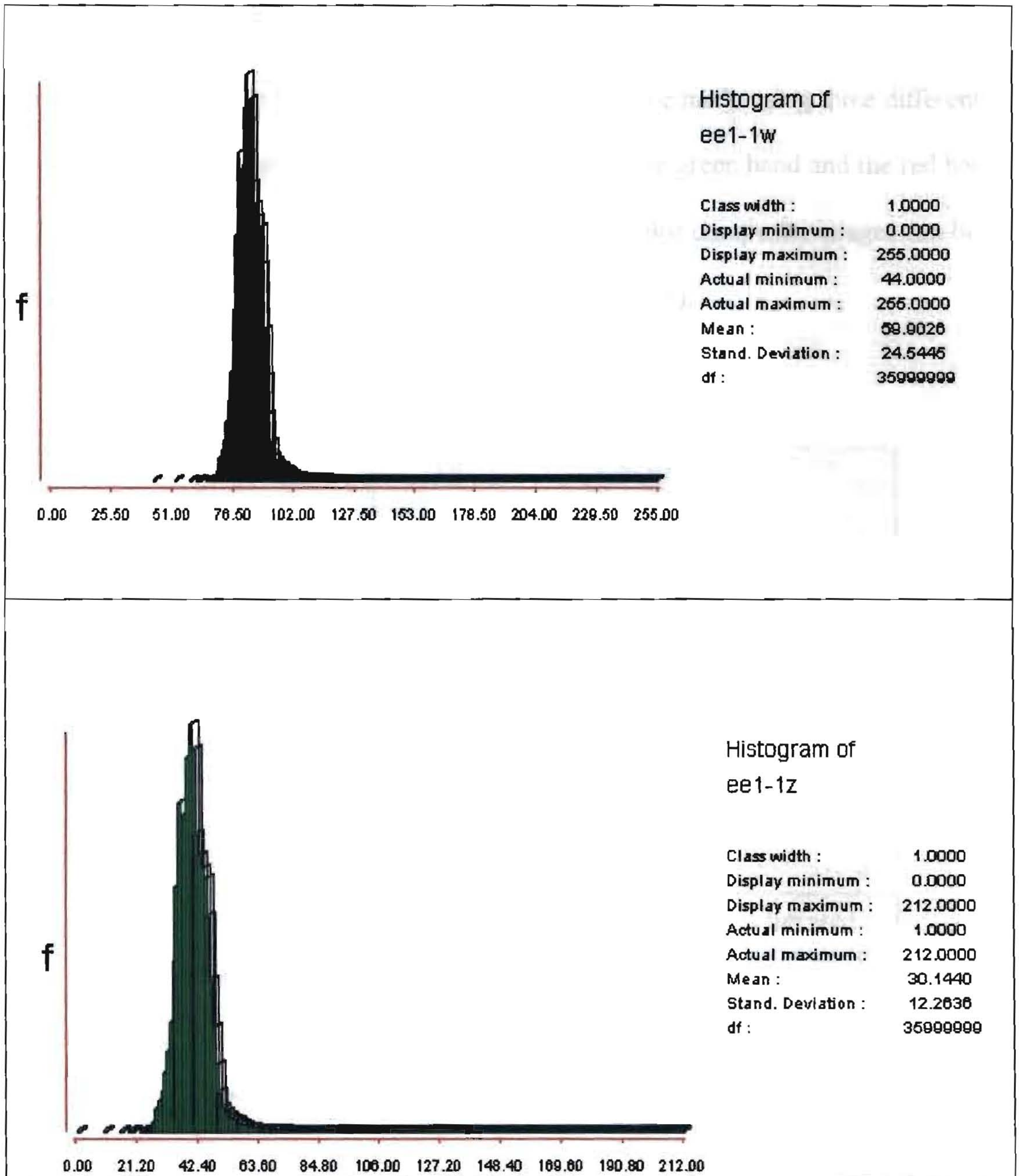

Fig. 12. Hazy atmosphere in band 1 of the EE1-1.img. The additional brightness of the atmosphere caused the minimum value to be 44 in the upper histogram. The lower histogram shows haze corrected atmosphere with the minimum value at one.

Composites

The combinations of TM bands 1, 2, 3, 4, 5 and 7 were used to enhance geologic and geomorphologic features. Composite images can be made using three different spectral bands, which are depicted as the blue band, the green band and the red band in the COMPOSIT module. Various natural and false-color composite images can be created (table 5). Examples are given below (figs. 13-16).

Instrument	Bands	Colors	Type
TM (4-5, 7)	1, 2, 3	B, G, R	Natural color
TM (4-5, 7)	2, 3, 4	B, G, R	Std. false color
TM (4-5, 7)	1, 2, 7	B, G, R	Special composite
TM (4-5, 7)	2, 3, 5	B, G, R	Special composite
TM (4-5, 7)	3, 7, 5	B, G, R	Special composite
TM (4-5, 7)	4, 5, 7	B, G, R	Infrared composite

Table 5. Some common TM band combinations for Landsat color-composite images. Aber (1999).

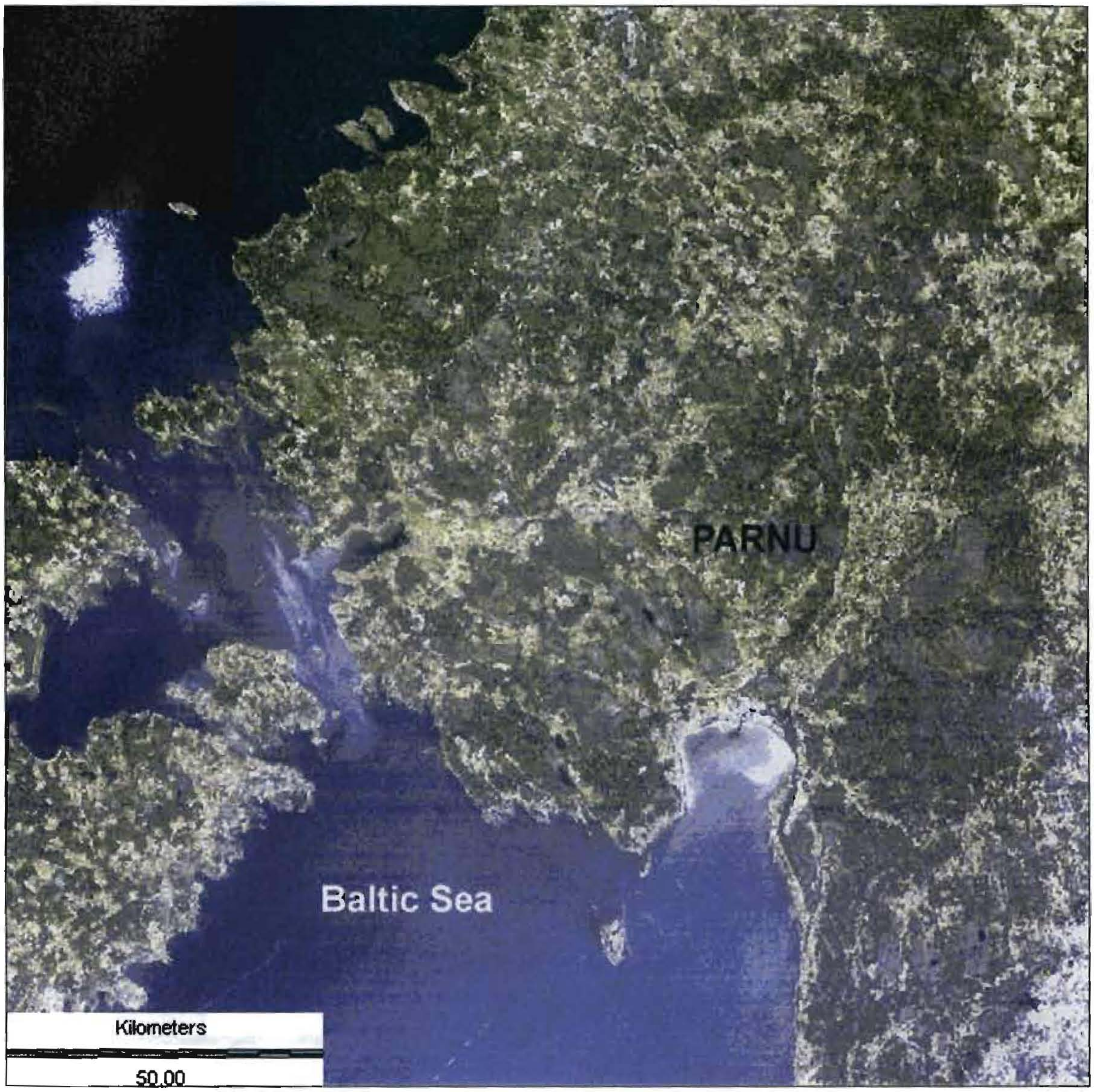

Fig. 13. Natural color-composite image of southwestern Estonia, 86/07/28 scene, Landsat 5. Bands 1, 2, 3 - blue, green and red. Active vegetation is green. Baltic Sea is shown in shades of blue.

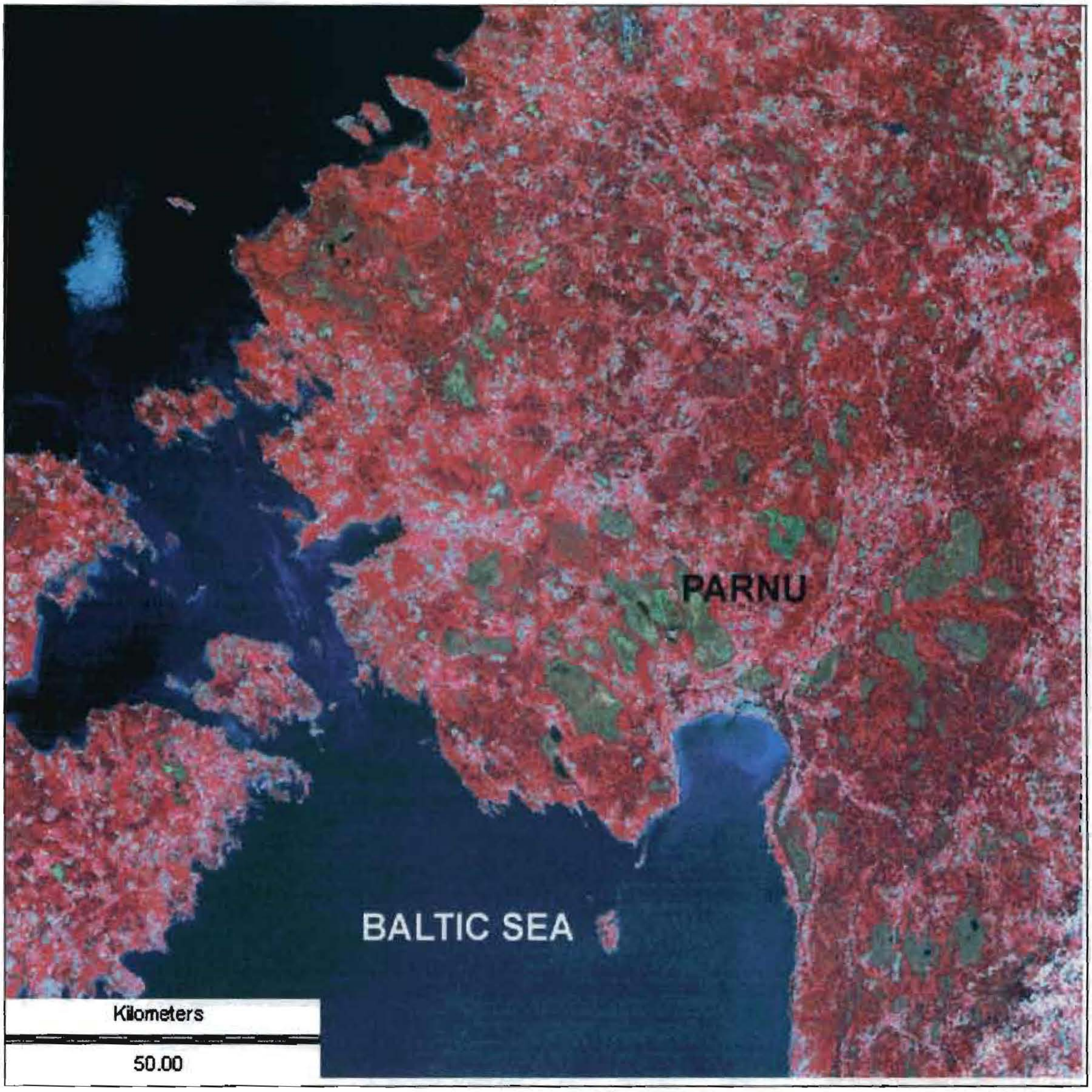

Fig. 14. Standard false-color composite image of southwestern Estonia, 86/07/28 scene, Landsat 5. Bands 2, 3, 4 - blue, green and red. Active vegetation is red. Baltic Sea is blue and black.

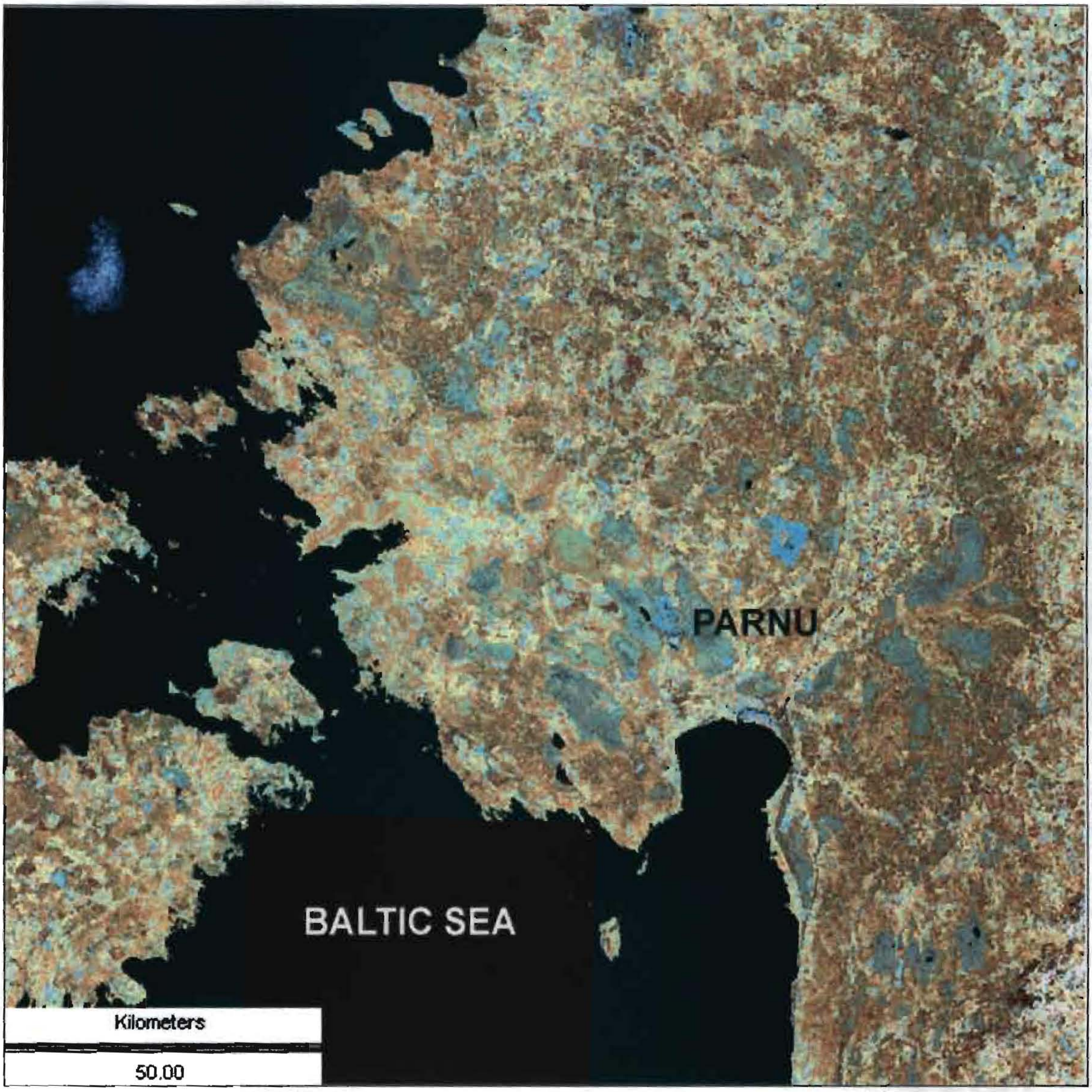

Fig. 15. Special color-composite image of southwestern Estonia, 86/07/28 scene, Landsat 5 Bands 7, 5, 4 - blue, green, and red. Active vegetation is green and brown. Baltic Sea is black.

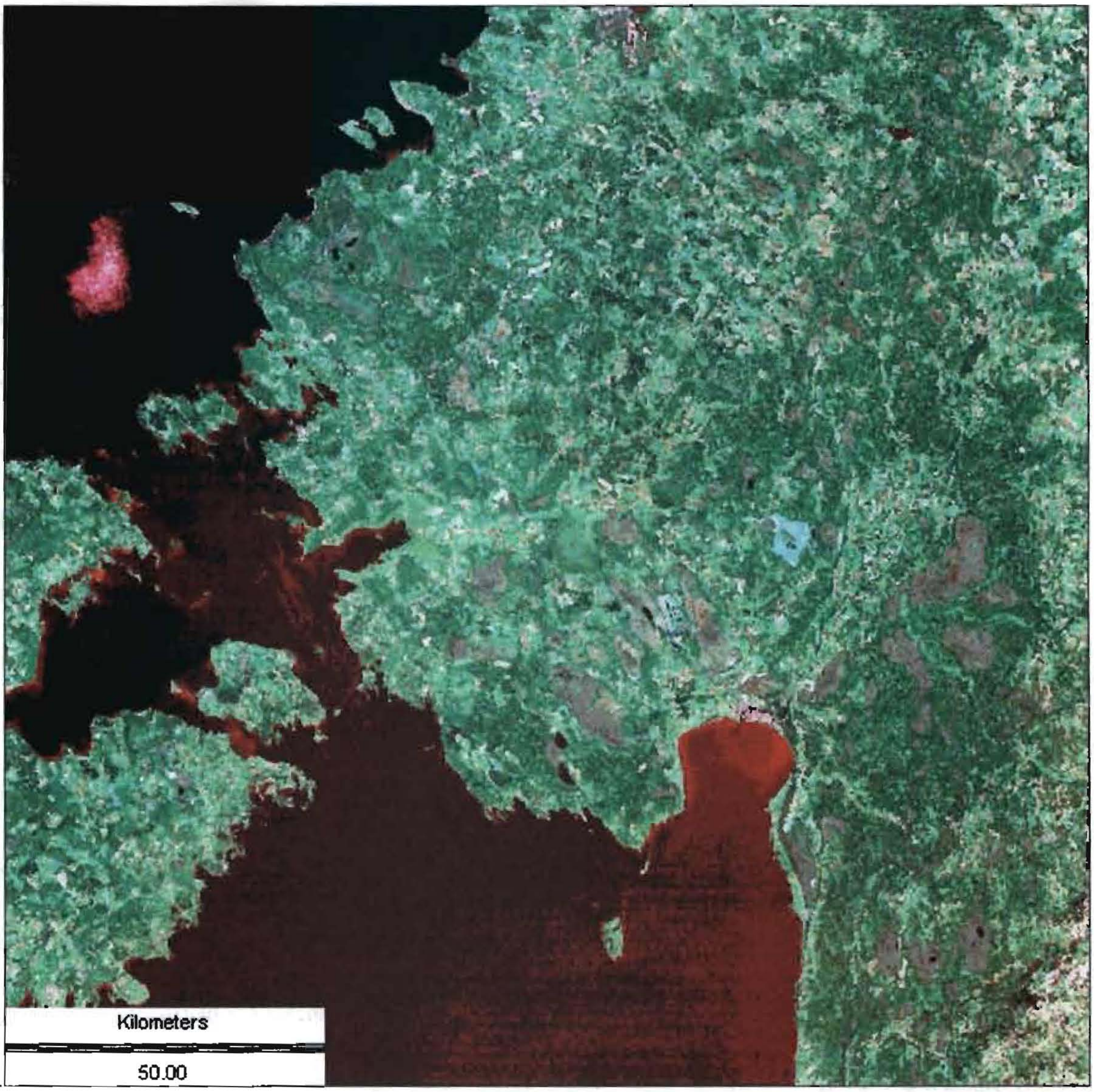

Fig. 16. Special color-composite image of southwestern Estonia, scene 86/07/28, Landsat 5. Bands 7, 5, 3 - blue, green, and red. Active vegetation is green. Baltic Sea is red-black.

Processing

The preprocessed files were used to create several types of processed images. First, NDVI (Normalized Difference Vegetation Index) was created in the OVERLAY module using the equation *first – second / first + second* for bands *4 – 3 / 4 + 3* (Jensen 2000). On the NDVI scenes the most active vegetation is depicted as green. The more vigorous vegetation, the darker green is the pixel. Yellow color depicts less active vegetation and sometimes man-made features. The brown depicts bare soils, water bodies, and some man-made features. To overcome differences in NDVI values caused mostly by temporary climatic and seasonal conditions, NDVI indices were made for all available data sets (figs. 17-20).

The NDVI processed images were used to create composite images composed of band 2 as blue, NDVI scene as green, and band 5 as red (fig. 21). For use in COMPOSIT module the NDVI scenes were converted to byte-binary format. The composite windows (2, NDVI, 5) were processed in the module HARD CLASSIFIER / CLUSTER (fig. 22). Another operation undertaken on the same composite windows was processing in the ISOCLUST module (fig. 23). Six single bands and the composite NDVI were used in isocluster analysis. The number of classes was set up as 16 in the isocluster analysis. The same operation was repeated for the color-composite scene made of bands 3, 4, and 5. To receive generalized images the RECLASS module was utilized (fig. 24). The new pixel values were set up for the pixels representing similar objects. For example all water bodies received a new value equal 0.

To isolate the forest areas several different methods were derived. The first method, uses the isocluster scene composed of the bands 1, 2, 3, 4, 5, 7 and false-color composite scene 345. The ISOCLUST module performs unsupervised classification method, using clustering algorithm to form numerical clusters of pixels based on spectral locations (Idrisi-help).

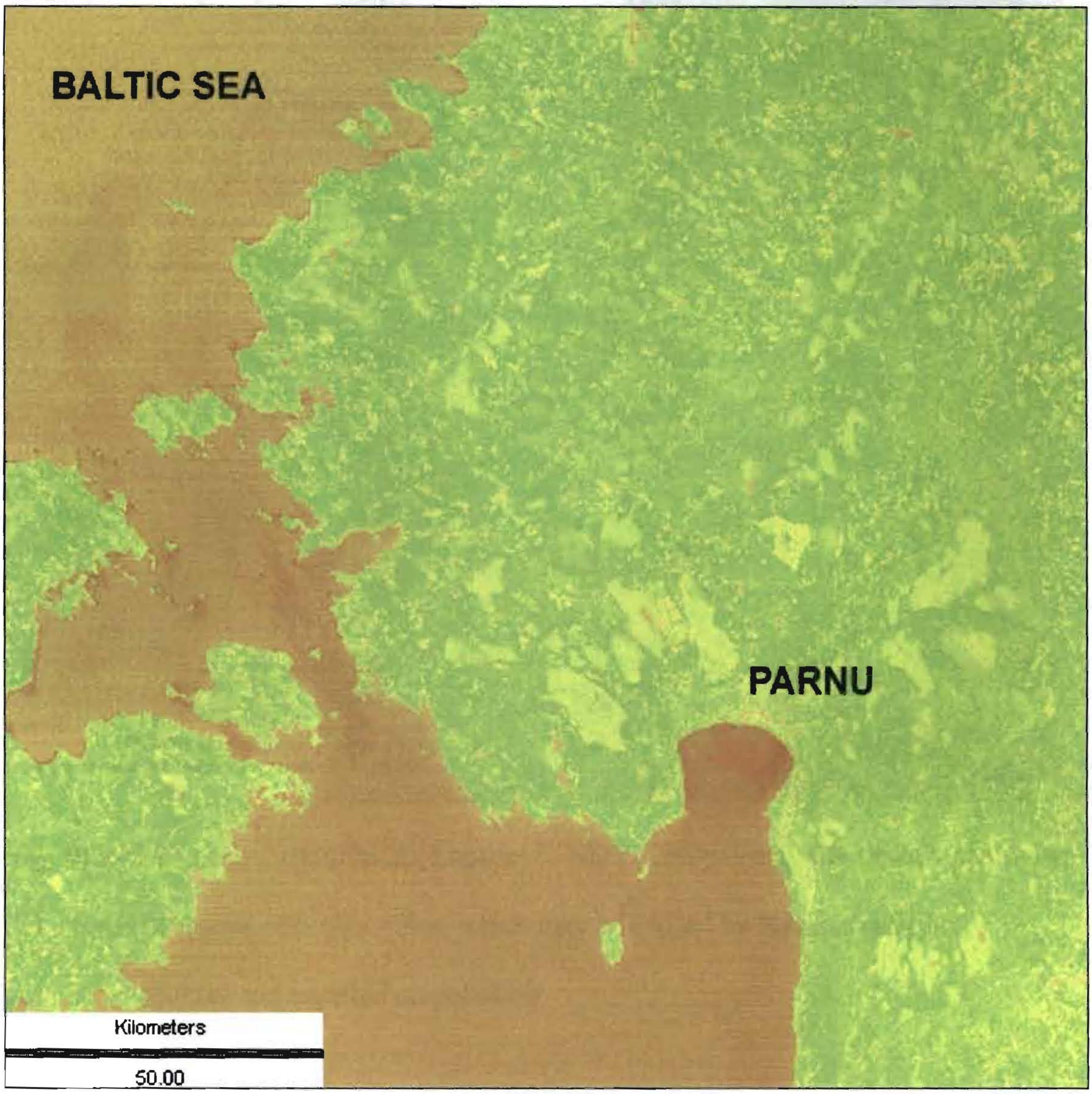

Fig. 17. NDVI image, 86/07/28, Landsat 5. NDVI 256 palette. Dark green color depicts vigorous vegetation. Yellow color depicts less active vegetation and sometimes man-made features. Brown color depicts bare soils, water bodies, and some man-made features.

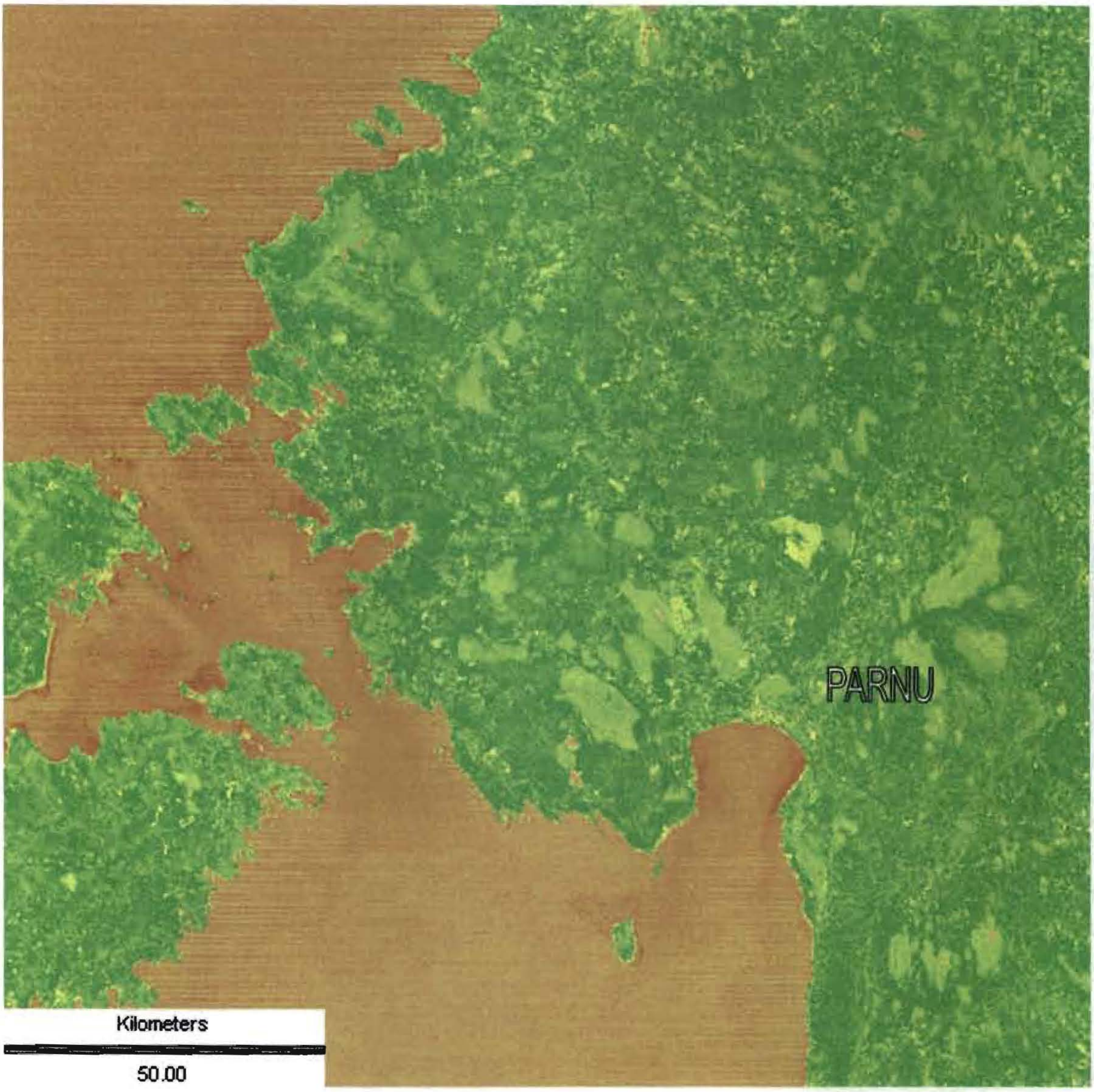

Fig. 18. NDVI image, 1986/06/26, Landsat 5. NDVI 256 palette. The shallow sea shows differences in shades of brown color, which may be caused by features including suspended silt/clay and possible oil pollution.

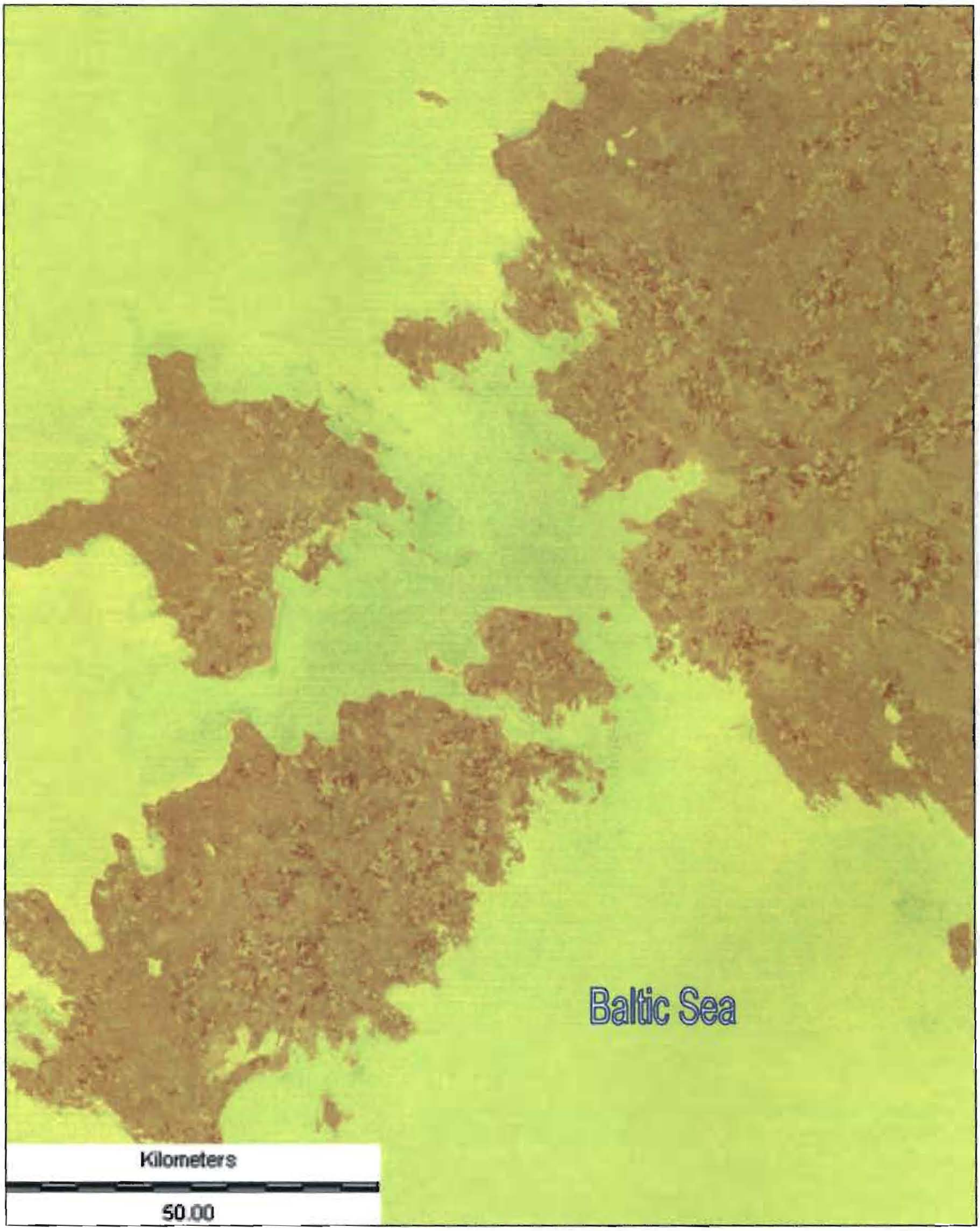

Fig. 19. NDVI image, 1988/05/13, Landsat 4. NDVI 256 palette.

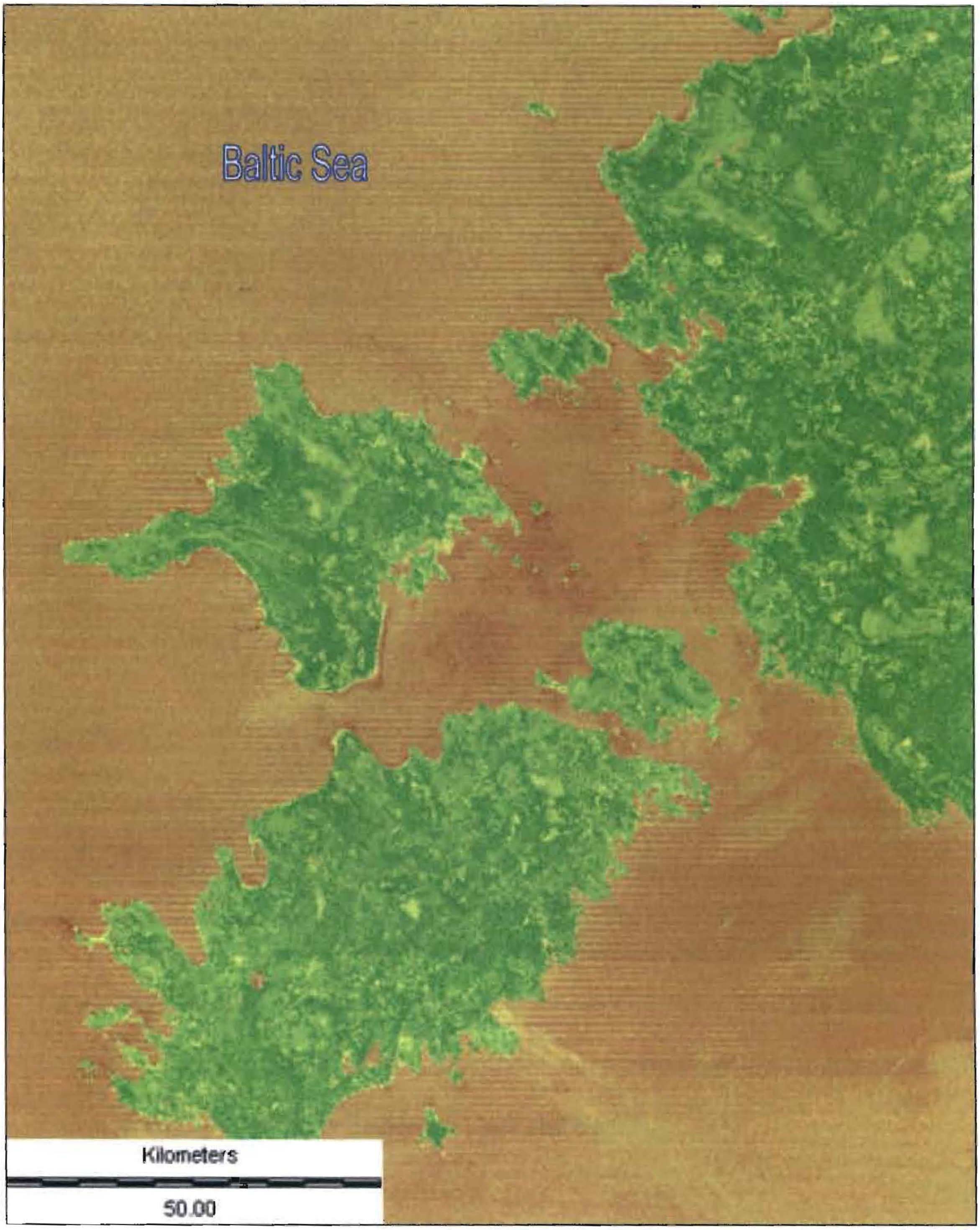

Fig. 20. NDVI image, 1986/07/03, Landsat 5. NDVI 256 palette. The shallow sea shows differences in shades of brown color, which may be caused by features including suspended silt/clay and possible oil pollution.

Fig. 21. Special color-composite image of southwestern Estonia, 86/07/28 scene, Landsat 5. Bands 2, NDVI, 5 - blue, green, and red. Active vegetation is green and brown. Baltic Sea and water bodies are black and blue.

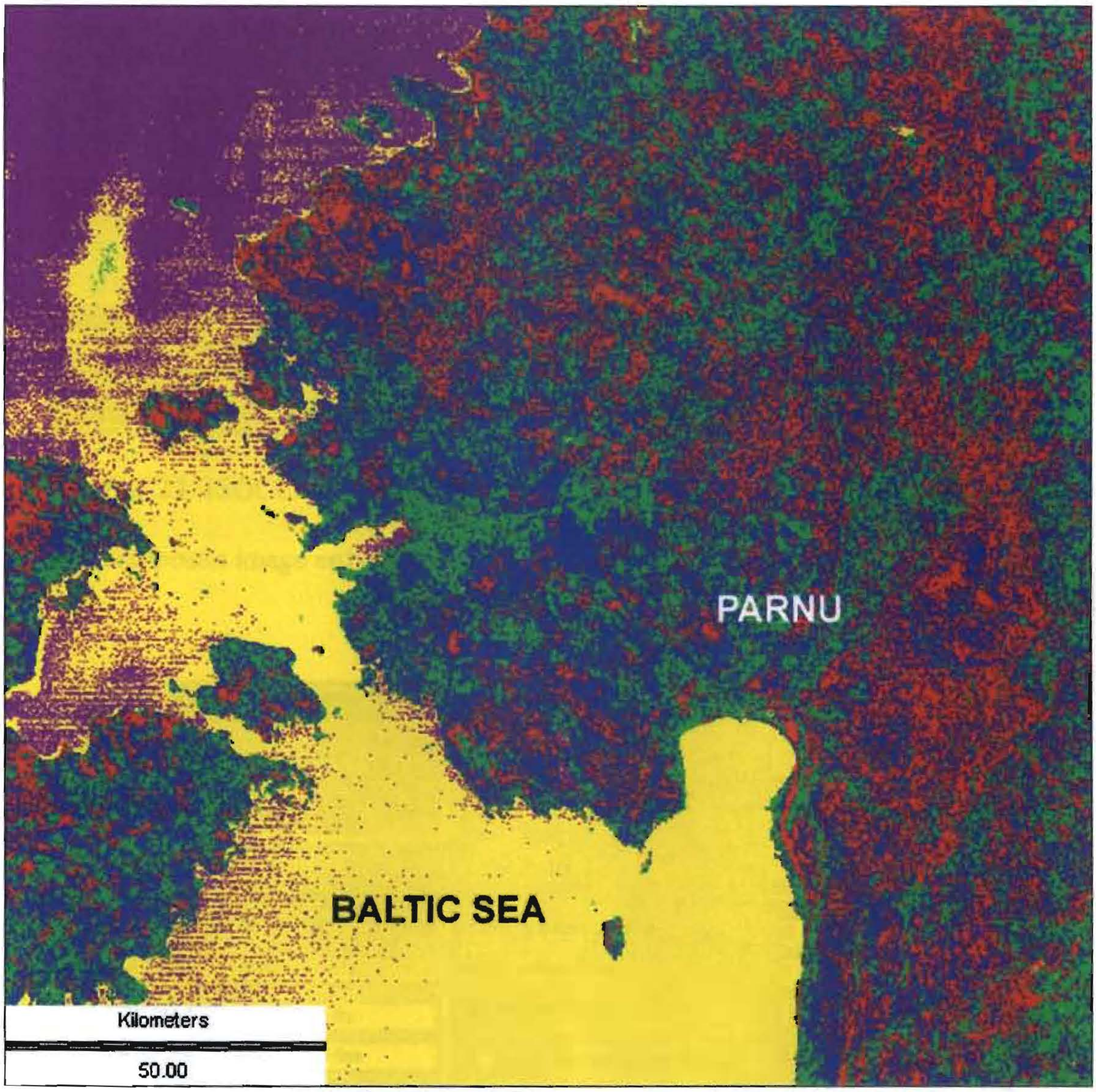

Fig. 22. Special-color composite image, 86/07/28 scene, Landsat 5. Bands 2, NDVI, 5 - blue, green, and red processed in the CLUST module. Forest is blue and red, agricultural land use is green.

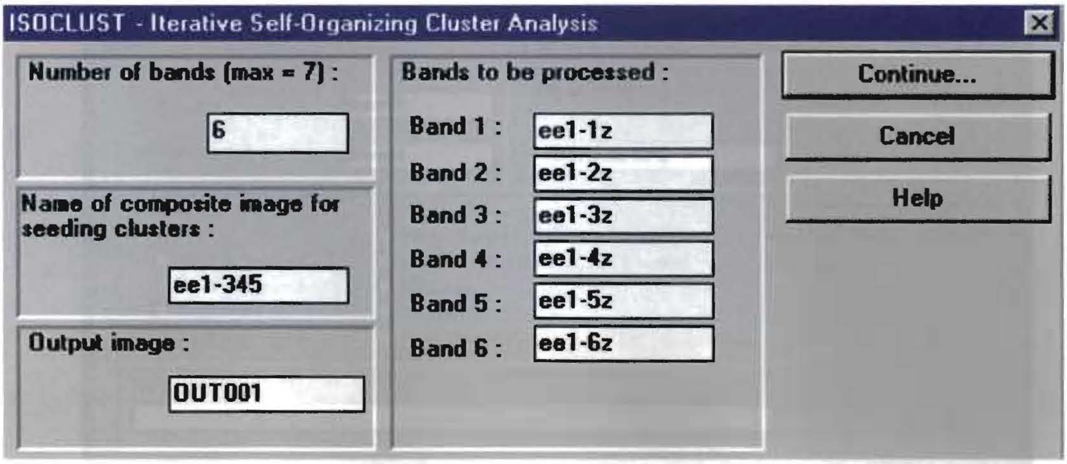

Fig. 23. ISOCLUST module with processed bands 1,2,3,4,5 and 7, with composite image ee1-345.

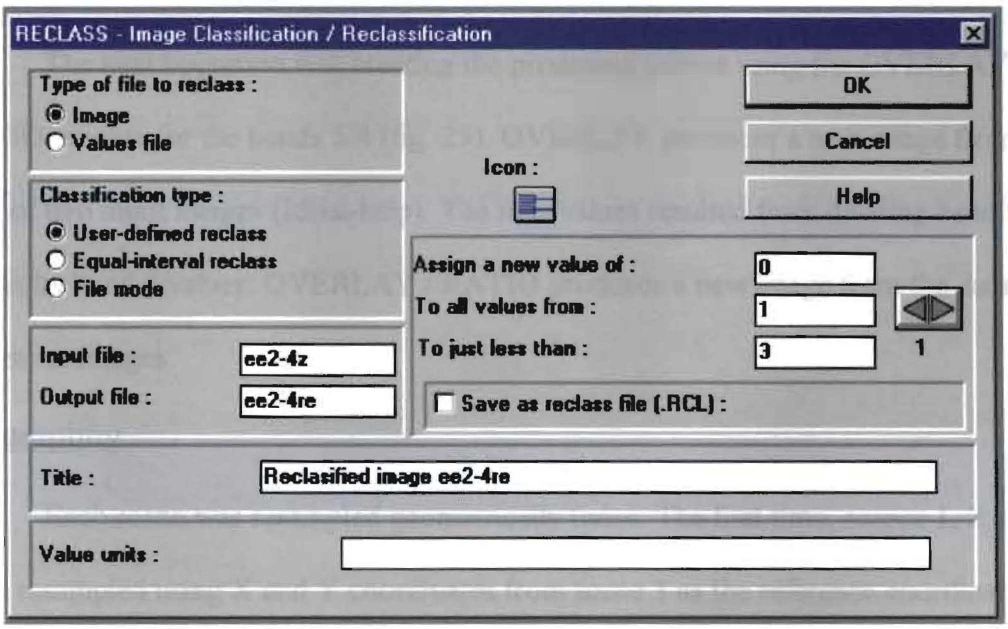

Fig. 24. RECLASS module. New value of zero was set up for the pixels having values from 1 to 3.

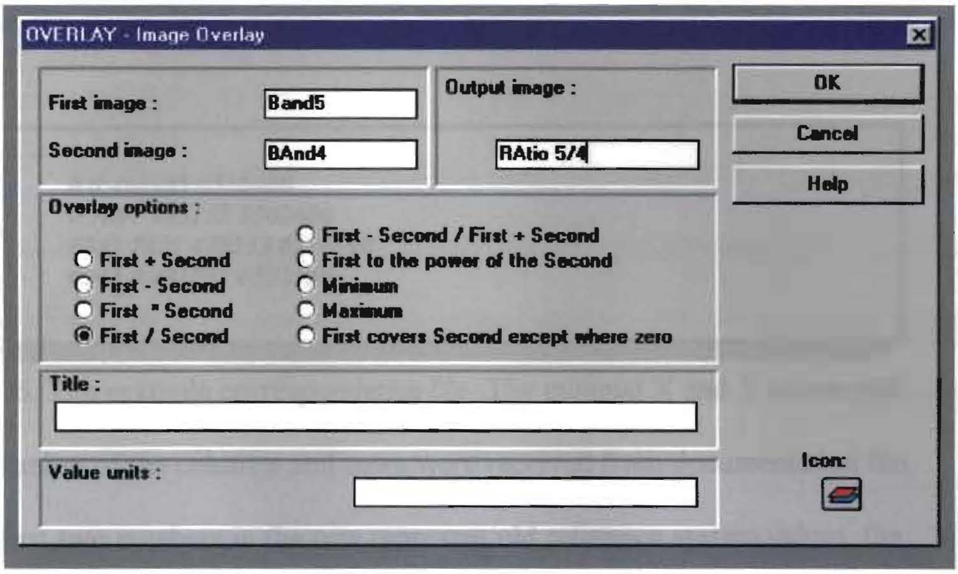

Fig.25. OVERLAY Module --Ratio for the TM bands 5/4.

The next operation was creating the processed scenes using the OVERLAY / RATIO module for the bands 5/4 (fig. 25). OVERLAY produces a new image from the data of two input images (Idrisi-help). The new values resulted from dividing band 5 values by band 4 values. OVERLAY / RATIO produces a new image from the data of two input images.

Resampling

Each scene was resampled geometrically twice. The first time, scenes 1, 2, and 4 were resampled using X and Y coordinates from scene 3 as the reference coordinates.

RESAMPLE registers the data in one grid system to a different grid system covering the same area (Idrisi-help). During the resample operation, the nearest-neighbor option was used. The RESAMPLE module uses polynomial equations to

```
4
    0 0 496905 6516460
    0 7691 483155 5502600
    6245 7691 478533 6514590
    6245 0 497015 6522950
```

Fig. 26. The example correspondence file. The minimal X and Y values and the number of the columns and rows were received from documentation file. The first two numbers in the row represent old reference system values, the last two numbers in the row represent a new reference system values.

transform one grid system into another grid system. For the purpose of resampling, correspondence ASCII files were created. The correspondence file contains the coordinates of control points in two different reference systems. Idrisi uses coordinates in the correspondence file in RESAMPLE to create a function with which to map the entire image to the desired georeferencing system (Idrisi-help).

Scenes were resampled using Universal Transverse Mercator - UTM coordinates determined from the Digital Elevation Model (DEM) of Estonia. The goal of the second resampling was to create overlapping images composed of two information layers: DEM and TM scenes. Correspondence files containing old and new coordinates for the original and resampled scenes were made in the EDIT module (fig. 26). The equivalent points on the TM scene and on the DEM were determined to receive pairs of the old and new coordinates.

In the resampled scenes, the reference system was changed from a plane grid to a UTM Transverse Mercator reference system. The process of resampling determines the relation between the output cell value and the input cell value. For the resampling of the TM scenes the nearest-neighbor interpolation was used, which designates the values of the input cell closest to the position in the output cell (fig. 27). The bounding UTM coordinates were determined from the DEM map of Estonia. The bounding points were located outside of the resampled window.

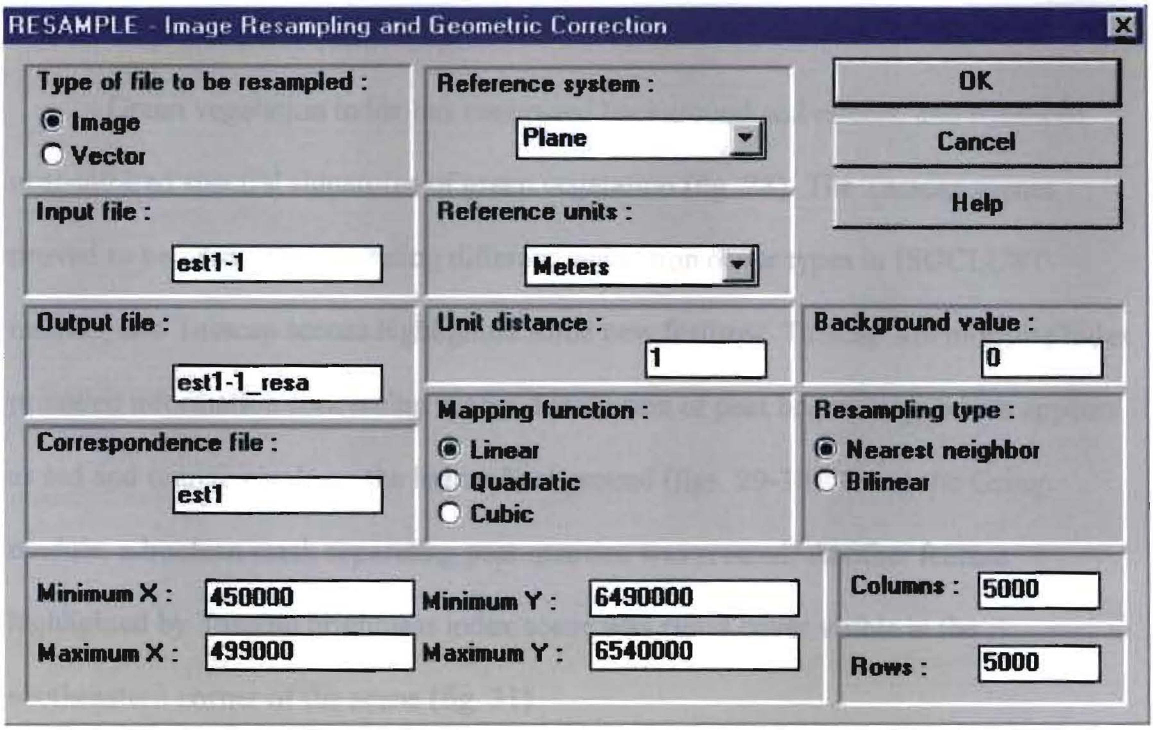

Fig.27. RESAMPLE module. The maximum and minimum values and the number of columns and rows were taken from a documentation file.

Tasscap

The TASSCAP module can be used to determine annual changes in vegetation indices. TASSCAP is a transformation of 6 bands of TM data (excluding the thermal band) using the process to extract four new index bands. It extracts four new index bands known as Soil Brightness Index (SBI), which is the soil background brightness index, Soil Moisture Index (SMI), Green Vegetation Index (GVI), which highlights green vegetation cover, and Yellow Vegetation Index (YVI), which depicts information on vegetation that is decaying or drying out. The Non Such Index (NSI) is associated with atmospheric noise (Idrisi-help).

Green vegetation index has minimized background soil effects, and enhanced near-infrared spectral signatures of green vegetation (fig. 28). The Tasscap scenes proved to be useful for separating different vegetation cover types in ISOCLUST module, and Tasscap scenes highlighted some new features. Tasscap soil moisture index provided information concerning spatial distribution of peat bog mining, which appears as red and orange pixels on the lighter background (figs. 29-30). Using the Group module, a boolean mask separating peat quarries was created. Another feature highlighted by Tasscap brightness index scene was cloud cover visible in the southeastern corner of the scene (fig. 31).

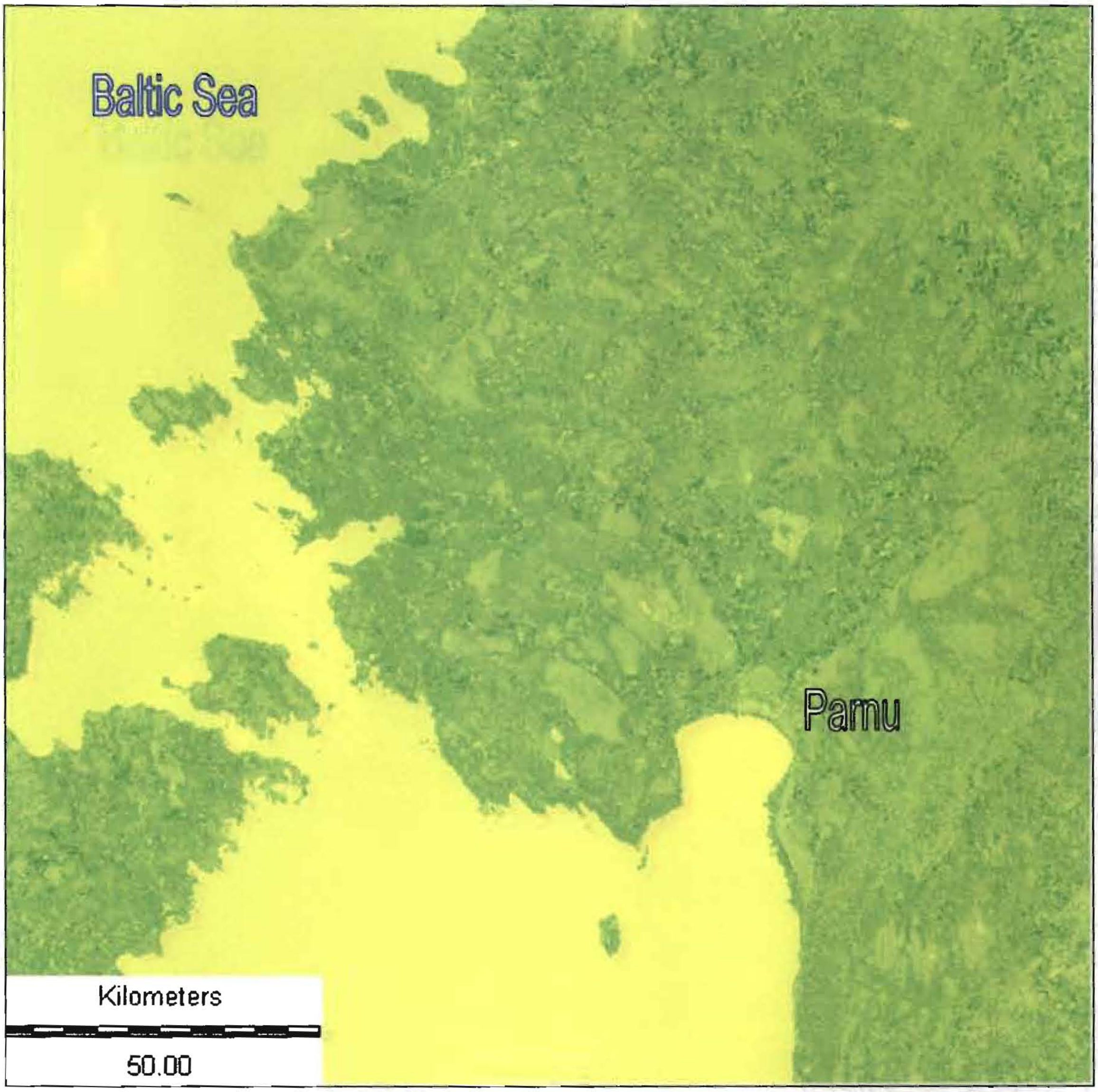

Fig. 28. Tasscap greenness index image of the Estonia, 86/07/28 scene, Landsat 5. NDVI 256 palette. Dark green color depicts vigorous vegetation. Yellow color depicts less active vegetation and sometimes man-made features. Brown color depicts bare soils, water bodies, and some man-made features.

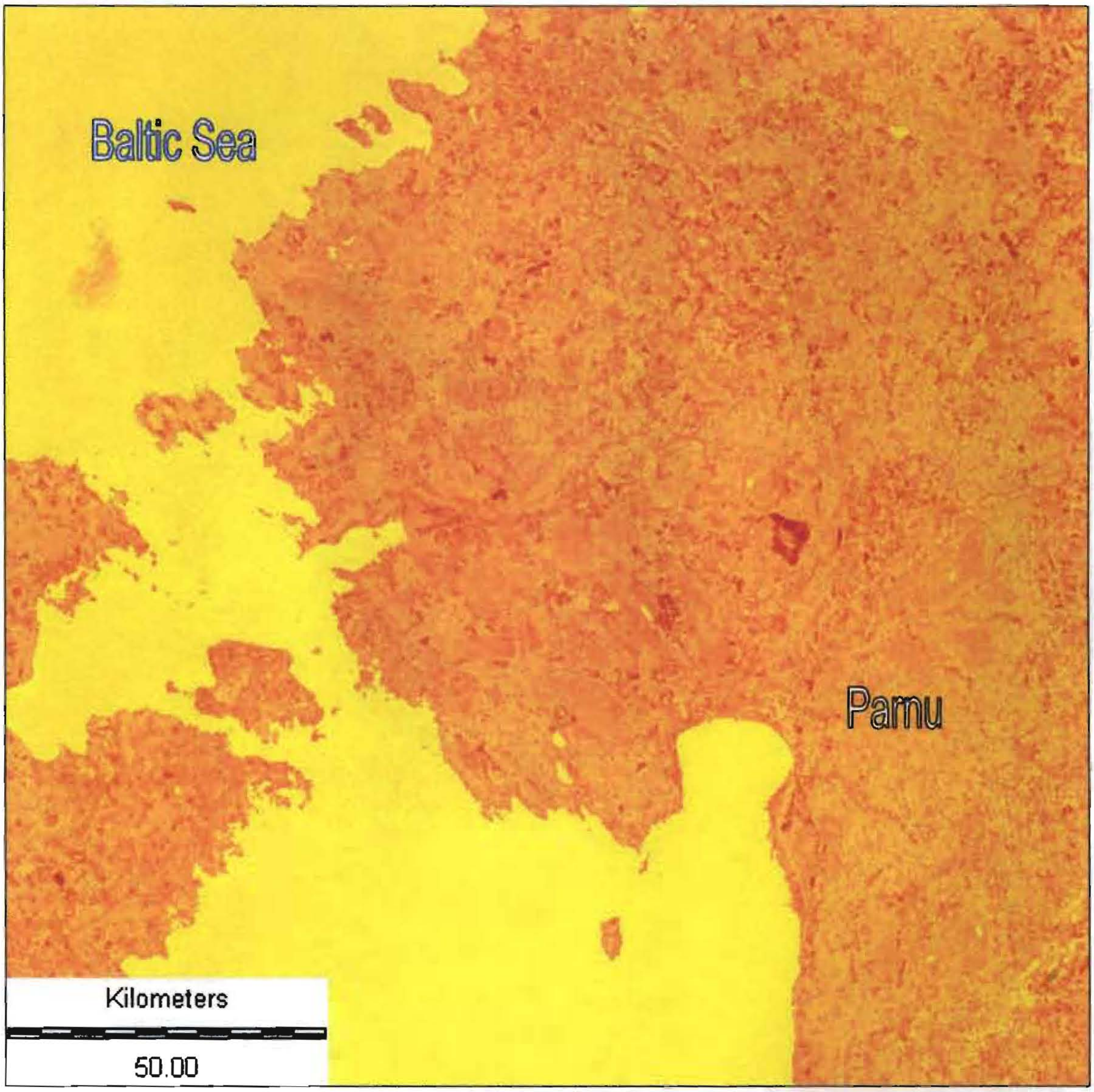

Fig. 29. Tasscap moisture index image of the Estonian scene, 86/07/28 Landsat 5. Idrisi 256 palette. The dark red color depicts features having more moisture.

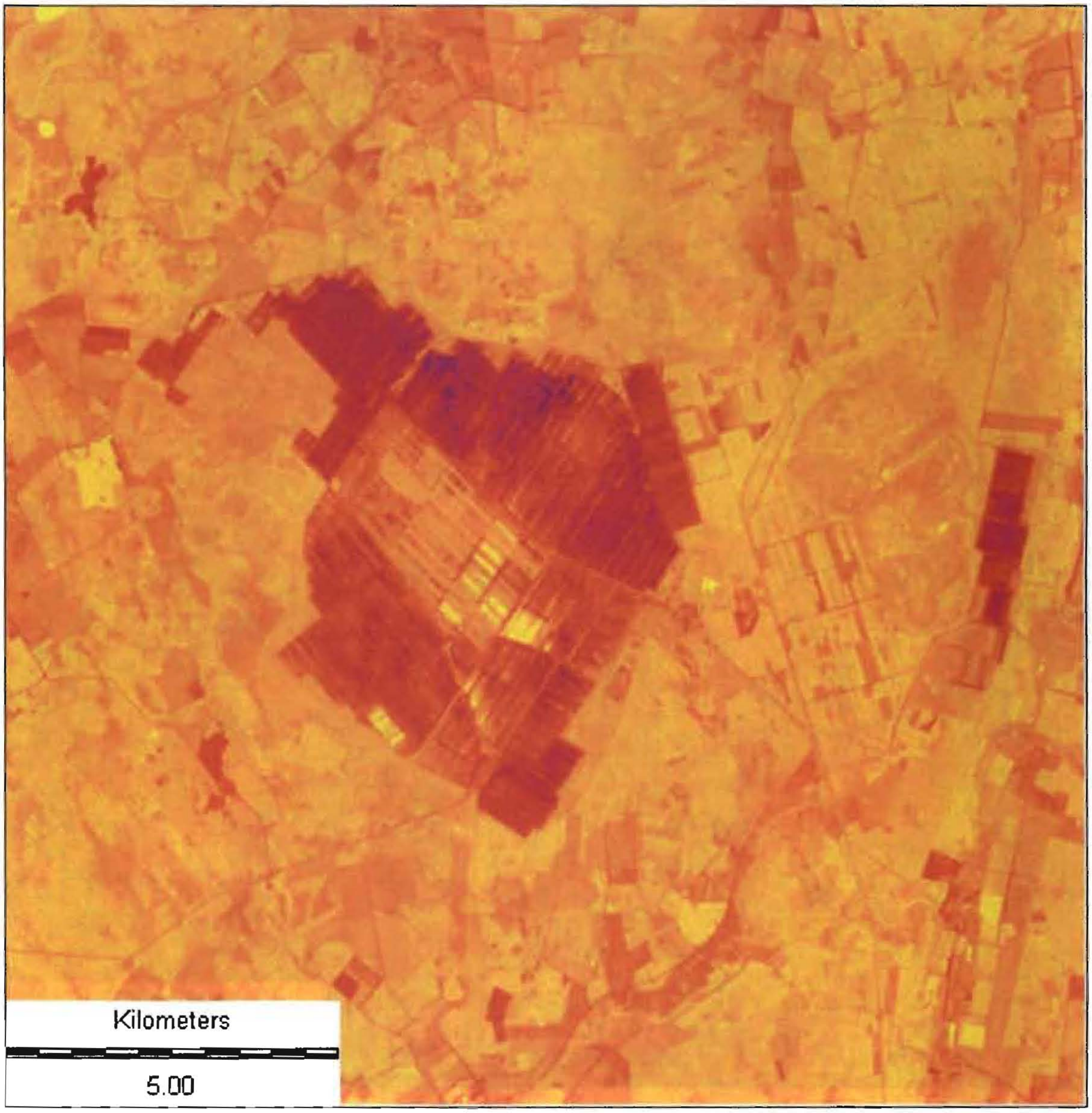

Fig. 30. Tasscap window from moisture index image of the Estonia, 86/07/28 scene, Landsat 5. Idrisi 256 palette. Peat mining is the eminent feature on the image.

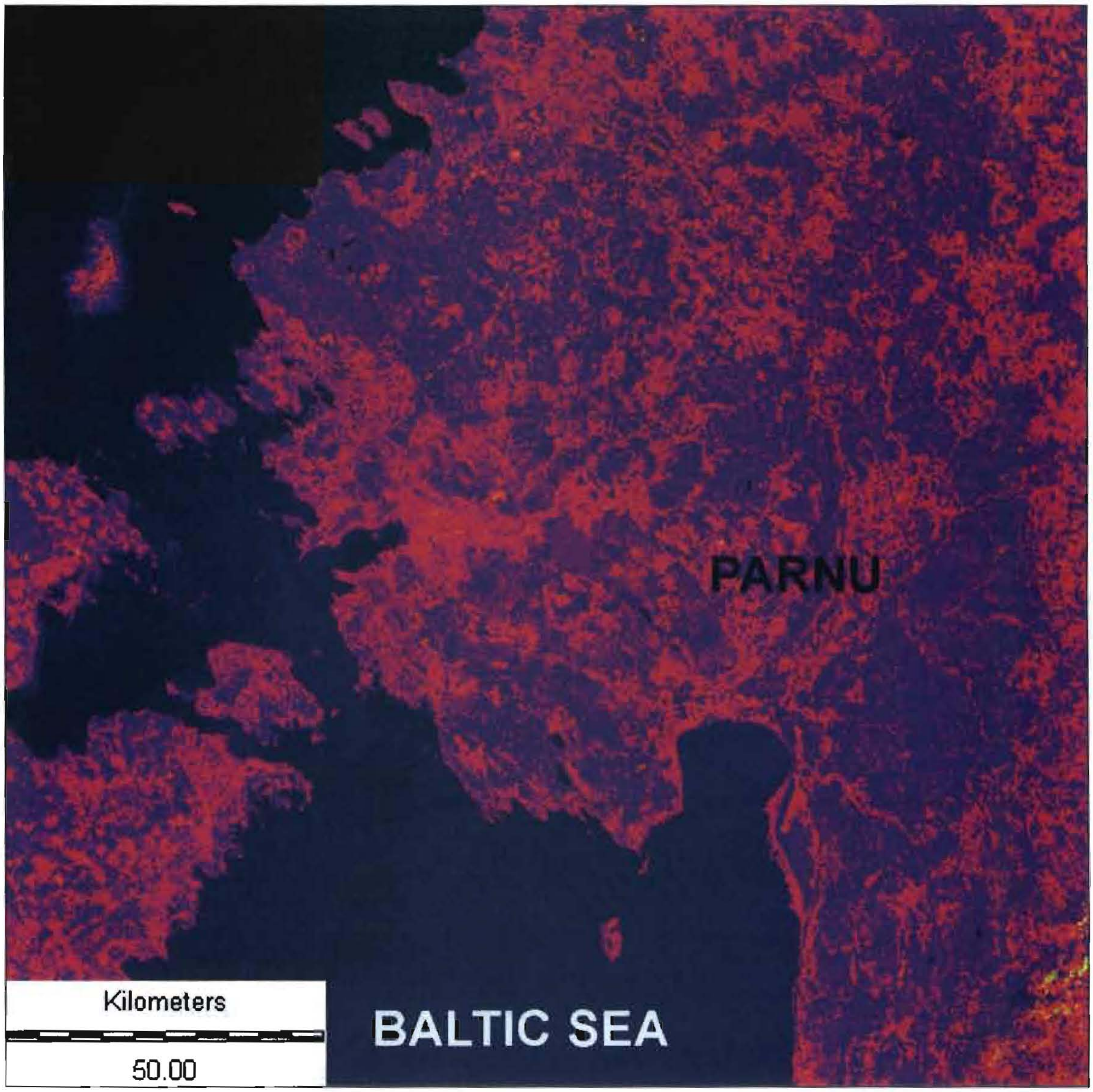

Fig. 31. Tasscap brightness index image of the Estonia, 86/07/28 scene, Landsat 5. Idrisi 256 palette. Cloud cover in southeast corner highlighted as green and orange pixels. The blue color depicts less bright features. Pink color depicts more bright features.

Digital Elevation Model

Digital Elevation Model (DEM) is a term used to refer to an image, which stores data that can be envisioned as heights on a surface. Although the grid structure breaks up the surface into cells of uniform character, the data are considered to come from an underlying continuous surface (Idrisi-help).

Digital elevation original data were in *Arc Info* export format. For use in Idrisi all elevation arcs were imported into *Arc View* SHAPE format. In Shape format information included in the database attached into Shape file is also saved.

The next operation executed in IDRISI was creation of INITIAL files for every map sheet – 25 x 25 km. The extreme X and Y values were defined manually and the single cell size was set up as 50m. The following operation was rasterizing imported contours- shape files. In the DATABASE WORKSHOP rasterized images were linked into Database. Next field values received from the Height field in the Database Workshop were assigned into images. The SHAPEIDRISI makes height fields "DOUBLE" instead of INTEGER. To overcome this problem a new Integer field was calculated from the HEIGHT field.

In Database Workshop CALCULATE SQL –module SQL expression was used:

UPDATE [database]

SET [new_field] = [old_field]

[old_field] here is considered as the field HEIGHT, brackets are used to mark syntax entities.

After all these operations an image was ready for DEM interpolation. For the purpose of interpolation the image corner heights had to be estimated and processed in the INTERCON module. The resulting Idrisi DEM is ready for the overlaying with the TM scene in the OVERLAY module. The results of the operation were not used in the research, because the DEM files did not have the sufficient resolution.

Chapter 4

Processing of Selected Land Cover Features

Water

The preprocessed scenes were used for the analysis leading to recognition of the different geological features. In the beginning, processing methods were focused on the general depiction of different kinds of vegetation, as well as on discrimination between water bodies and land. The best results for separating the water bodies were achieved by using different composite scenes which included the near infrared band four (table 4).

The composite scene showing water bodies best was composed of the bands 3 - blue, 4 - green, 5 - red. To extract water bodies the method of supervised classification was used based on the 345 composite image. Pixels with spectral signatures larger than 14 were masked, and displaying the mask scene a special color palette was created called "water." The water palette has only two classes. Class one shown on the scene as blue encompasses pixels having spectral signatures from 0-14 representing water bodies. Class two is shown on the scene as green and encompasses all the pixels having values from 15 to 255 representing the land area (fig. 32).

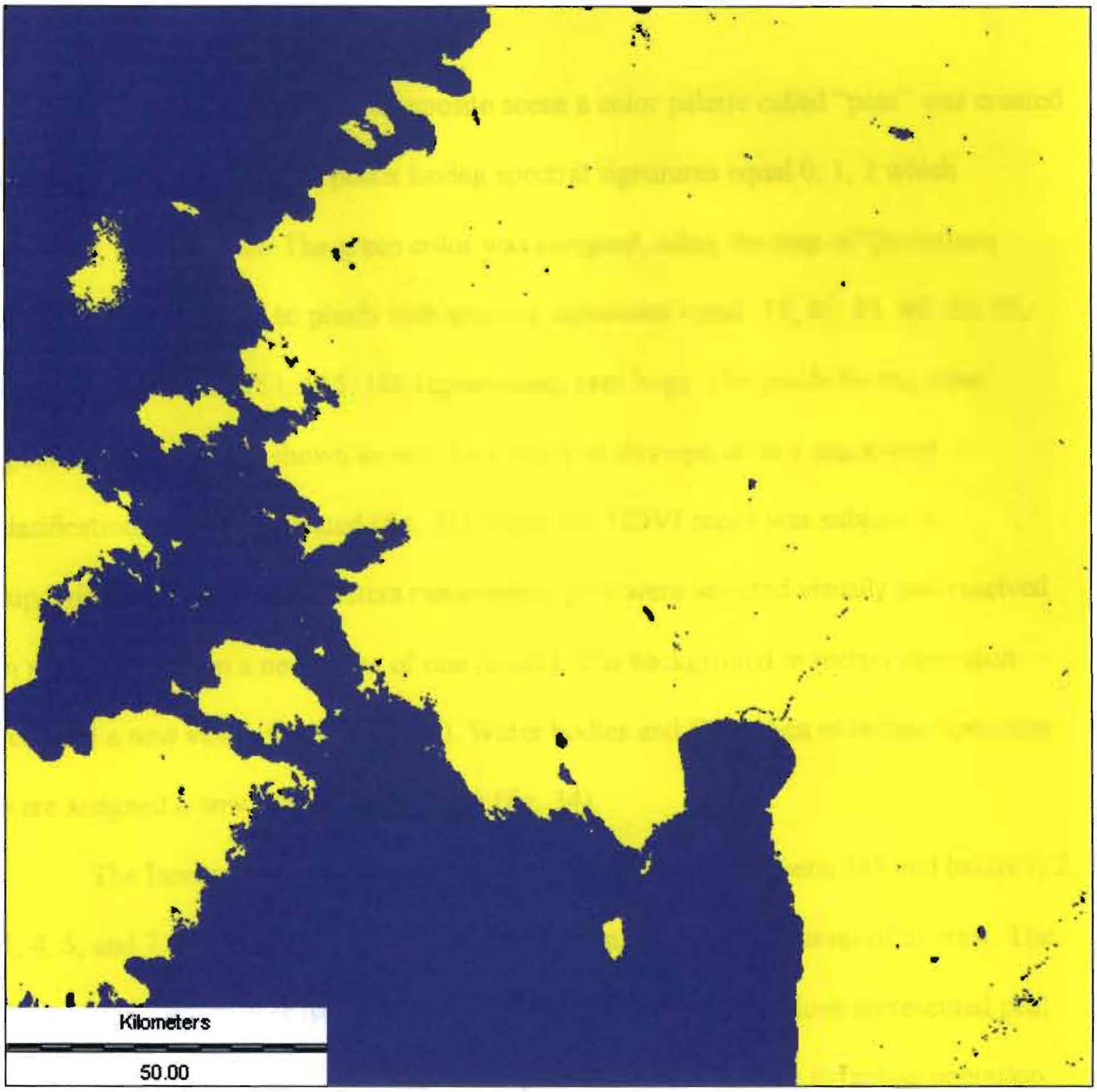

Fig. 32. Boolean image of the Estonian 345 composite scene, 86/07/28, Landsat 5. Supervised classification. Water bodies are blue, the other features are green.

Peat

Next, for the 345 color composite scene a color palette called "peat" was created assigning the black color to pixels having spectral signatures equal 0, 1, 2 which represent water bodies. The green color was assigned, using the map of Quaternary deposits (Kajak 1993), to pixels with spectral signatures equal: 79, 80, 85, 86, 92, 93, 122, 123, 128, 129, 164, 165, 166 representing peat bogs. The pixels having other spectral signatures are shown as red. As a result of this operation a supervised clasification scene was created (fig. 33). Next, the NDVI scene was subject to supervised classification. Clusters representing peat were selected visually and received in reclass operation a new value of one (black). The background in reclass operation recieved a new value of zero (yellow). Water bodies and Baltic Sea in reclass operation were assigned a new value of two (blue) (fig. 34).

The Isocluster image composed of the color-composite scene 345 and bands 1, 2, 3, 4, 5, and 7 (fig. 35) was subject to interpretation, to isolate the areas of interest. The study areas were further isolated by determining, which cluster values represented peat bogs. Pixels representing peat were selected visually. Peat clusters in reclass operation received a new value of 1 (black). Background pixels received in reclass operation a new value of 0 (white). Baltic Sea and water bodies received a new value of 12 (blue). As a result of this operation a classified scene was created (fig. 36). The classified image (fig. 36) was multiplied by the NDVI values which left all other land values as zero (fig. 37). The operation was repeated for each of the four scenes.

The visual interpretation of the images (figs. 38-39) highlights the following facts concerning peat bogs and their distribution. The density of peat bogs is much greater in the southern part of the analyzed scene compared to the northern part of the

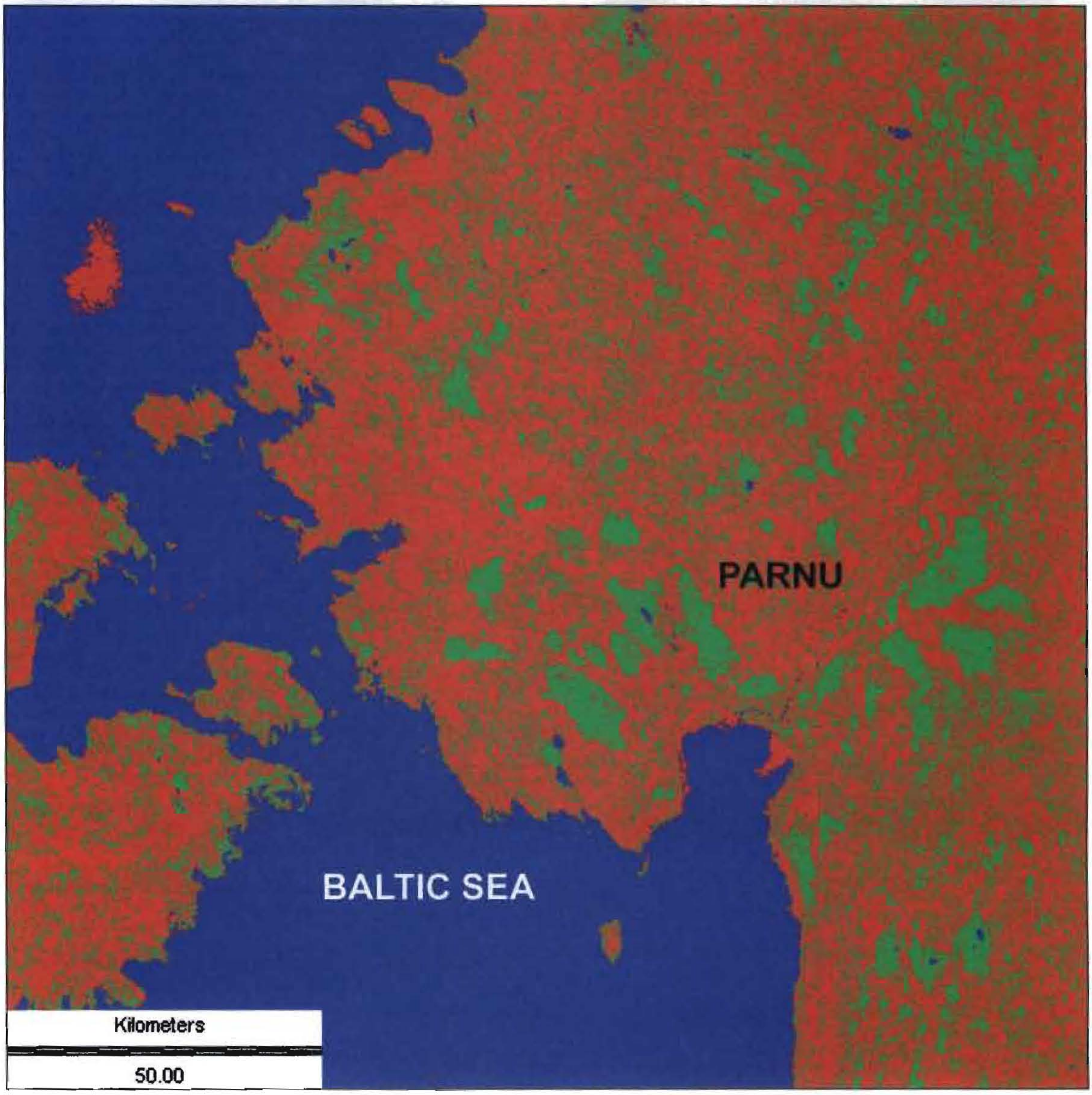

Fig. 33. Classified image of the Estonia 345 composite scene, 86/07/28, Landsat 5. Supervised classification. Peat bogs are green, the other land features are red. Baltic Sea and water bodies are blue.

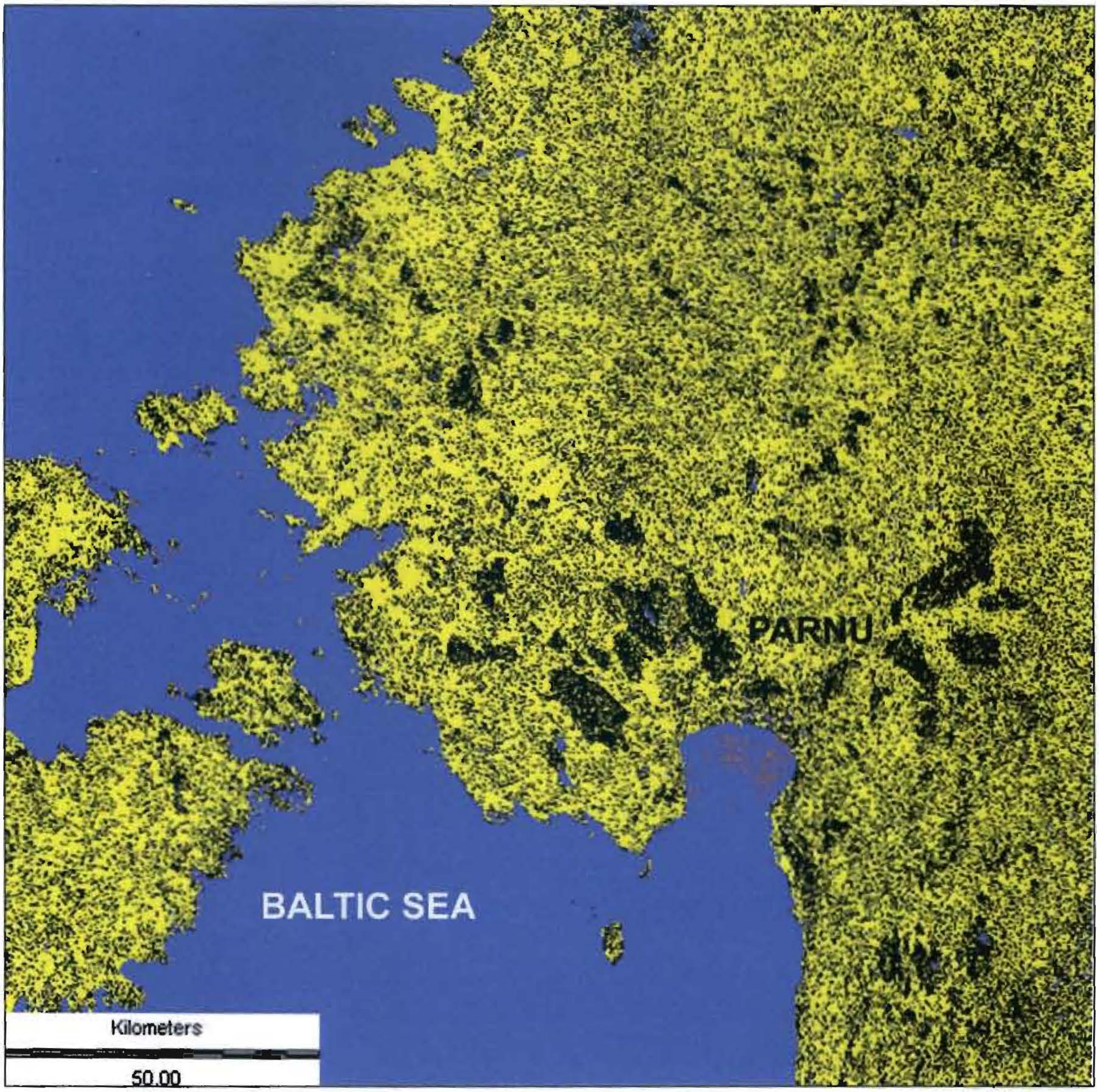

Fig. 34. NDVI image of the Estonian scene, 86/07/28, Landsat 5. Supervised classification. Peat bogs are black, water bodies are blue, other features are yellow.

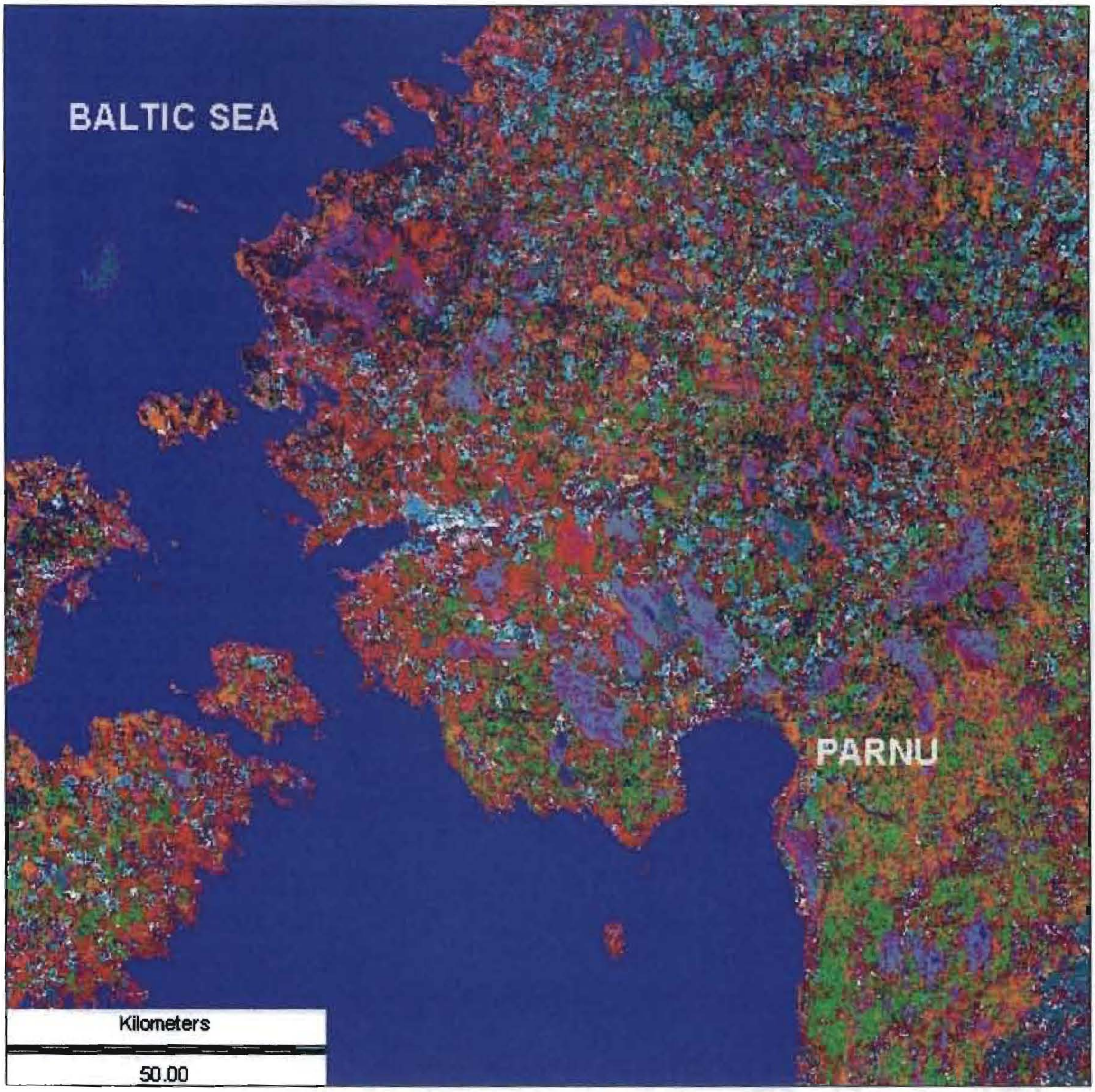

Fig. 35. Isocluster image of the Estonian 345 composite scene, 86/07/28, Landsat 5 as background image, and bands 1, 2, 3, 4, 5, and 7. Unsupervised classification; peat bogs are depicted in shades of pale blue and purple.

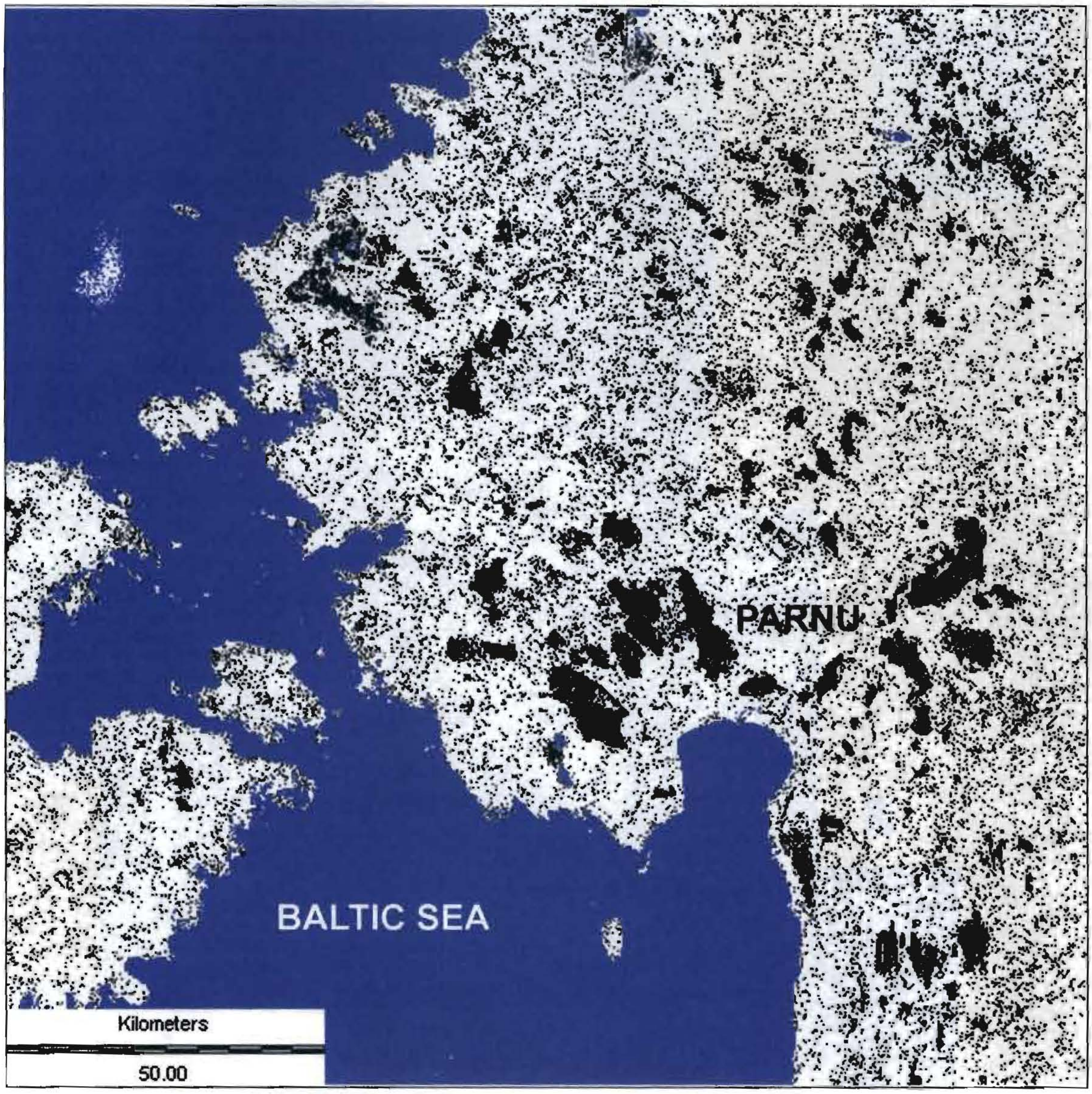

Fig. 36. Mask of isocluster image of the Estonia 345 composite scene, 86/07/28, Landsat 5, as background image, and bands 1, 2, 3, 4, 5, and 7. Supervised classification. Peat bogs are black. Background is white, water bodies and Baltic Sea are blue.

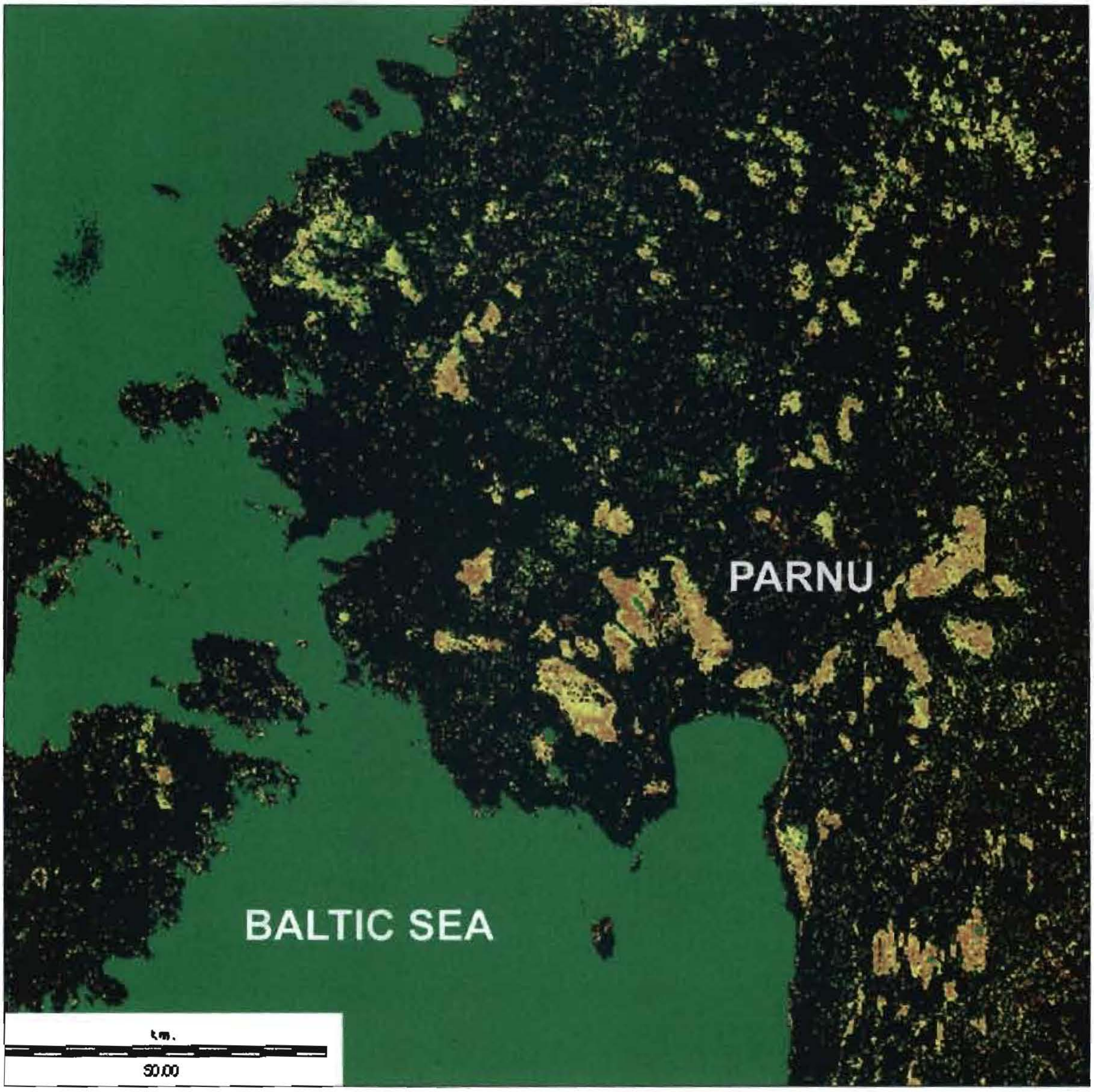

Fig. 37. Classified isocluster scene. Clusters representing peat were grouped and multiplied by NDVI values. NDVI 256. palette. Scene 86/07/28, Landsat 5. Peat appears in yellow-brown colors; water bodies are green.

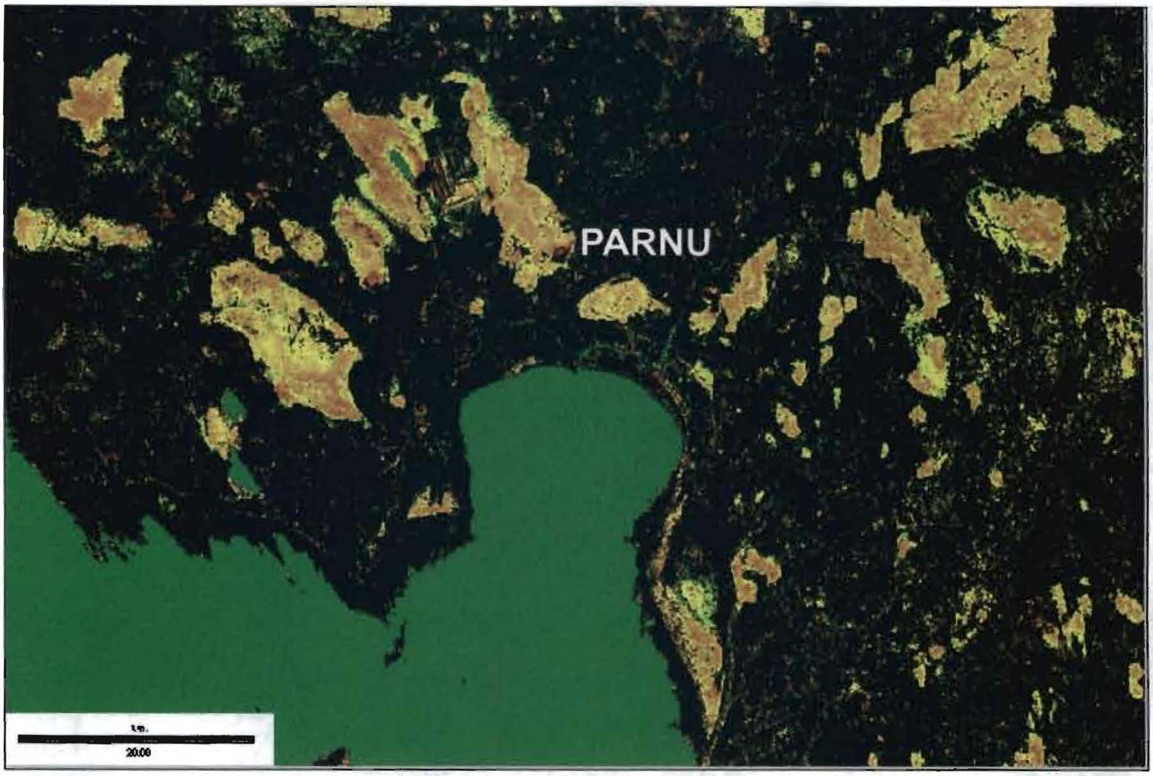

Fig. 38. Window from classified isocluster scene. In the center of a peat bog vegetation has lower NDVI values (brown) compared to external parts of a peat bog with higher NDVI values (yellow).

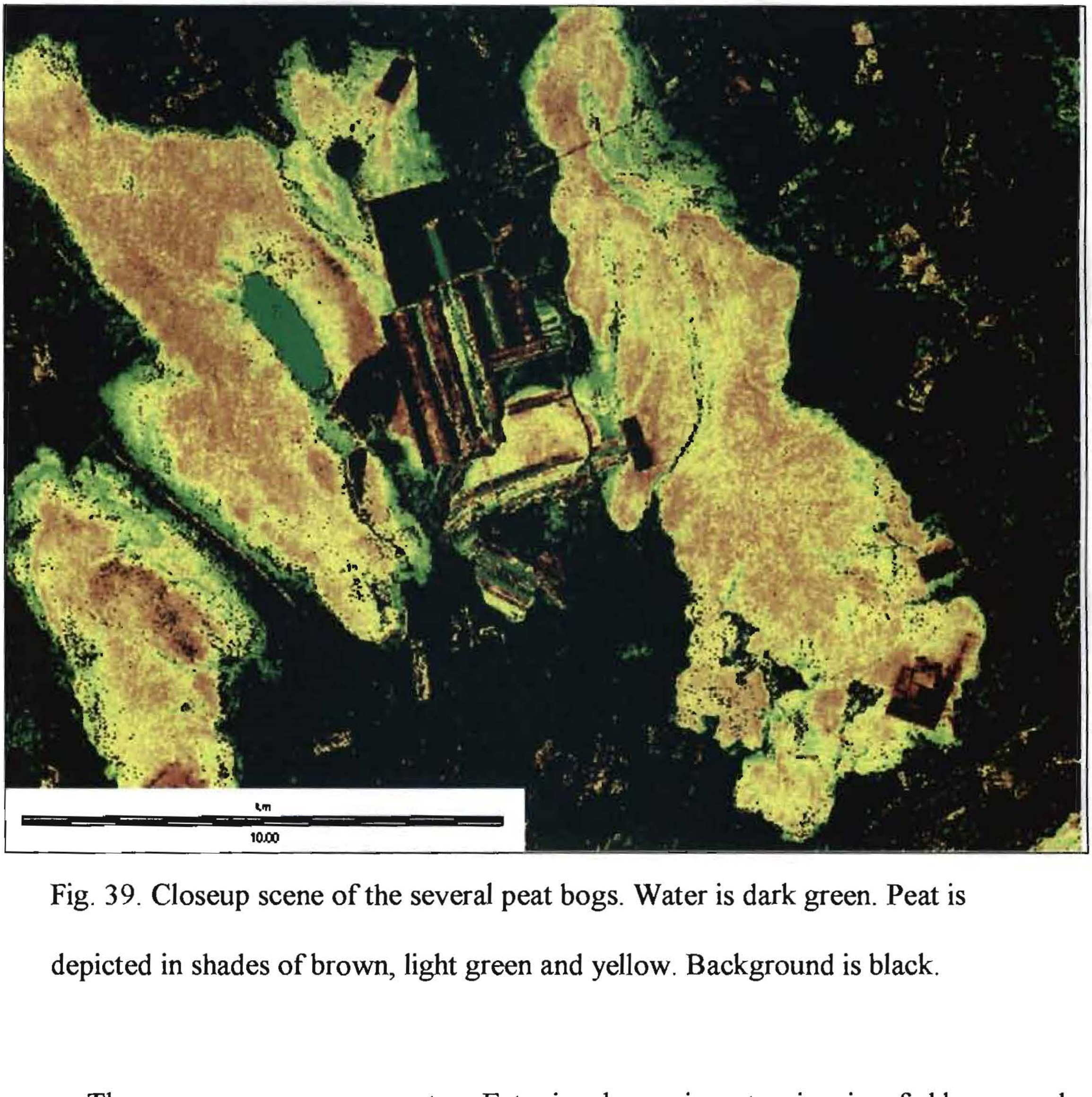

Fig. 39. Closeup scene of the several peat bogs. Water is dark green. Peat is depicted in shades of brown, light green and yellow. Background is black.

scene. The scene encompasses western Estonia where minerotropic mires fed by ground and surface water are predominant. The boundary between peat land genetic provinces coincides with extension of the maximal Baltic Sea transgression is not included on the analyzed scenes. The NDVI mask highlights usually two zones of vegetation present in the typical bog. The internal zone, composed of less "active" vegetation, has lower NDVI values, and the external zone, composed of more "active" vegetation, has higher NDVI values (fig. 39).

Peat mining activity was extracted from Tasscap moisture index (figs. 29, 30). Peat mines were further isolated by determining, which cluster values represented peat mining. Pixels representing peat mining were selected visually. Peat clusters in reclass operation received a new value of 1 (yellow). Background pixels received in reclass operation a new value of 0 (black). Baltic Sea and water bodies received a new value of 12 (blue) (fig. 40).

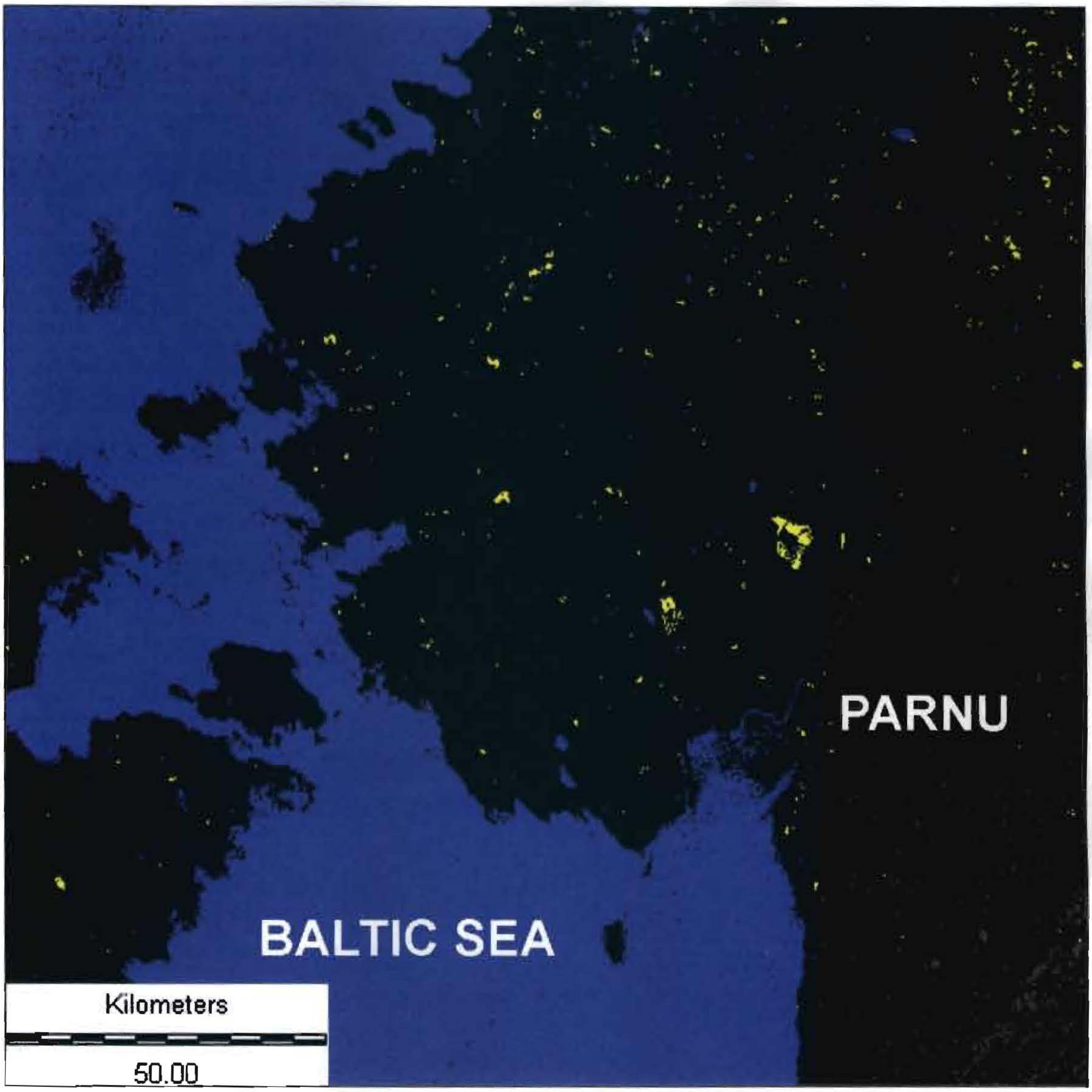

Fig. 40. Classified Tasscap moisture index scene. Clusters representing peat quarries were grouped (yellow), background is black. Scene 86/07/28, Landsat 5.

Forest

The forest areas were isolated from the isocluster image by determining which cluster values represented the forest. The values were determined by visual interpretation of the isocluster 345 scene. Using the Reclass module a classified image was made from the scene. Pixels having values 3, 4, and 8 representing forest received a new value of 1 (green), the areas of other land use received a new value of 0 (black) (fig. 41). The next step was isolating different types of the forests, based on cluster values in the Isocluster scene.

The three basic clusters of forested areas represent different forest types. Using the method described above three new classified masks of different forest types were created. The distribution of cluster 8 (fig. 42) coincides with spatial distribution of the sandy sediment on the geological map of Estonia. This forest is assumed to be mostly pine (personal communication Kalm, 2000). The forest type having cluster value 4 (fig. 43) is much more common in the southern part of the scene. The distribution of the forested areas coincides with the sandy and till sediment. Figs. 42 and 43 indicate the close connections between bedrock and land cover.

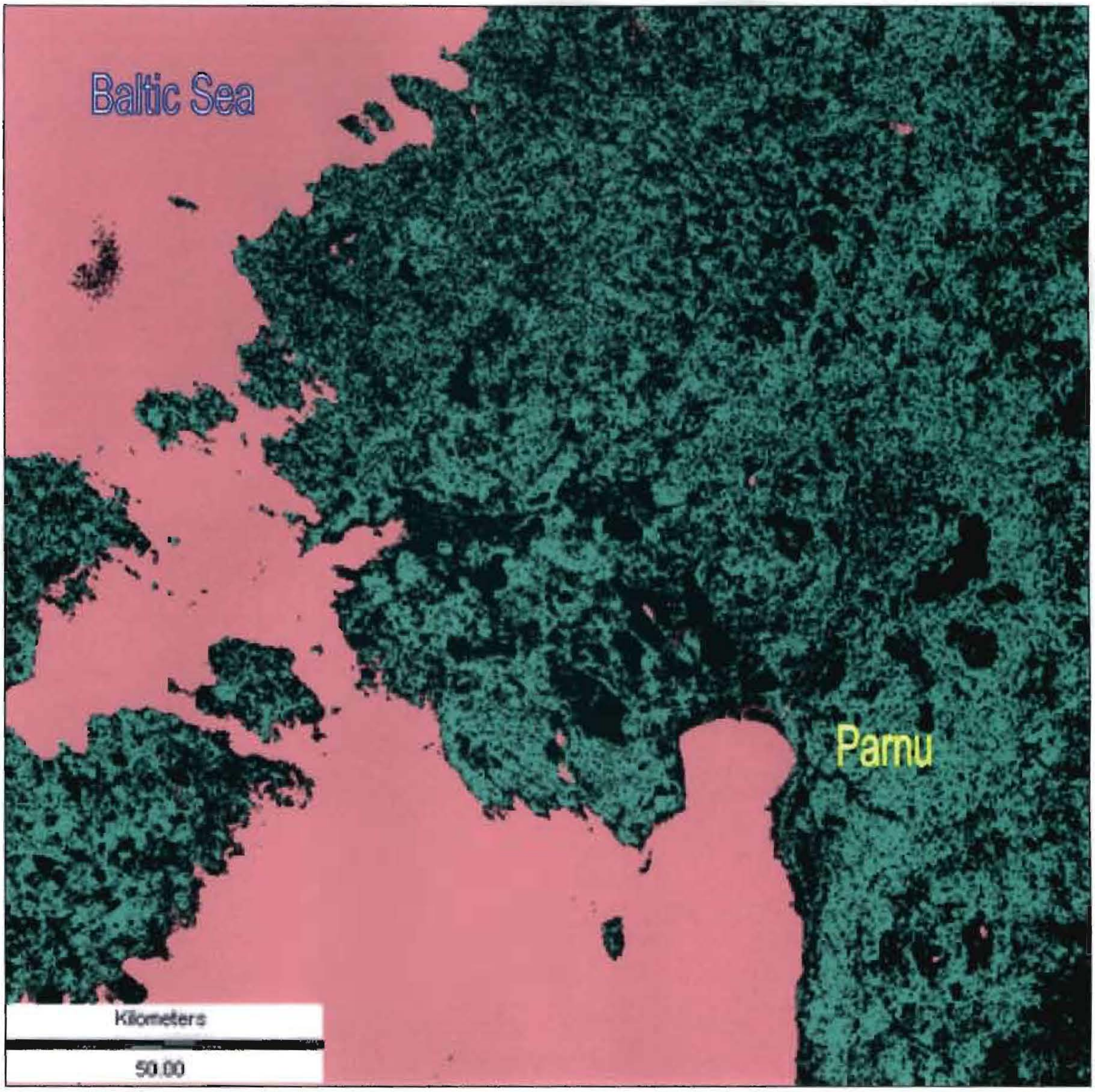

Fig. 41 Classified isocluster scene. Clusters representing forest were reclassed and received a new value of 1 (green pixels). Water bodies are pink, other land cover is black. Qual256 palette. Scene 86/07/28, Landsat 5.

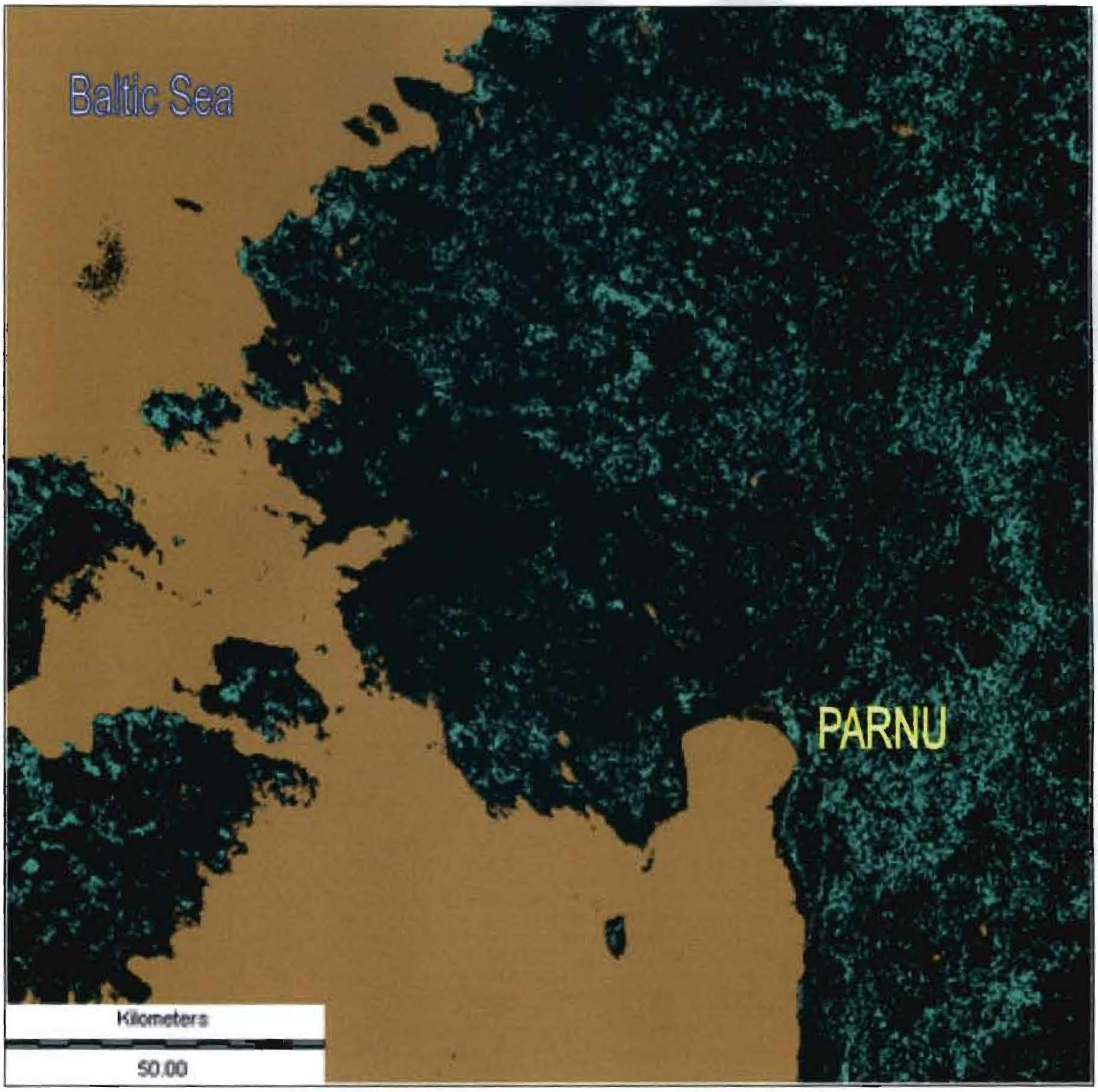

Fig. 42. Classified isocluster scene. Clusters having value 8 were reclassed and received a new value of 1 (green pixels). Background is black. Qual256 palette. Scene 86/07/28, Landsat 5. The distribution of the forested areas coincides with the sandy sediment, according to the map of Quaternary deposits (Kajak, K. 1993).

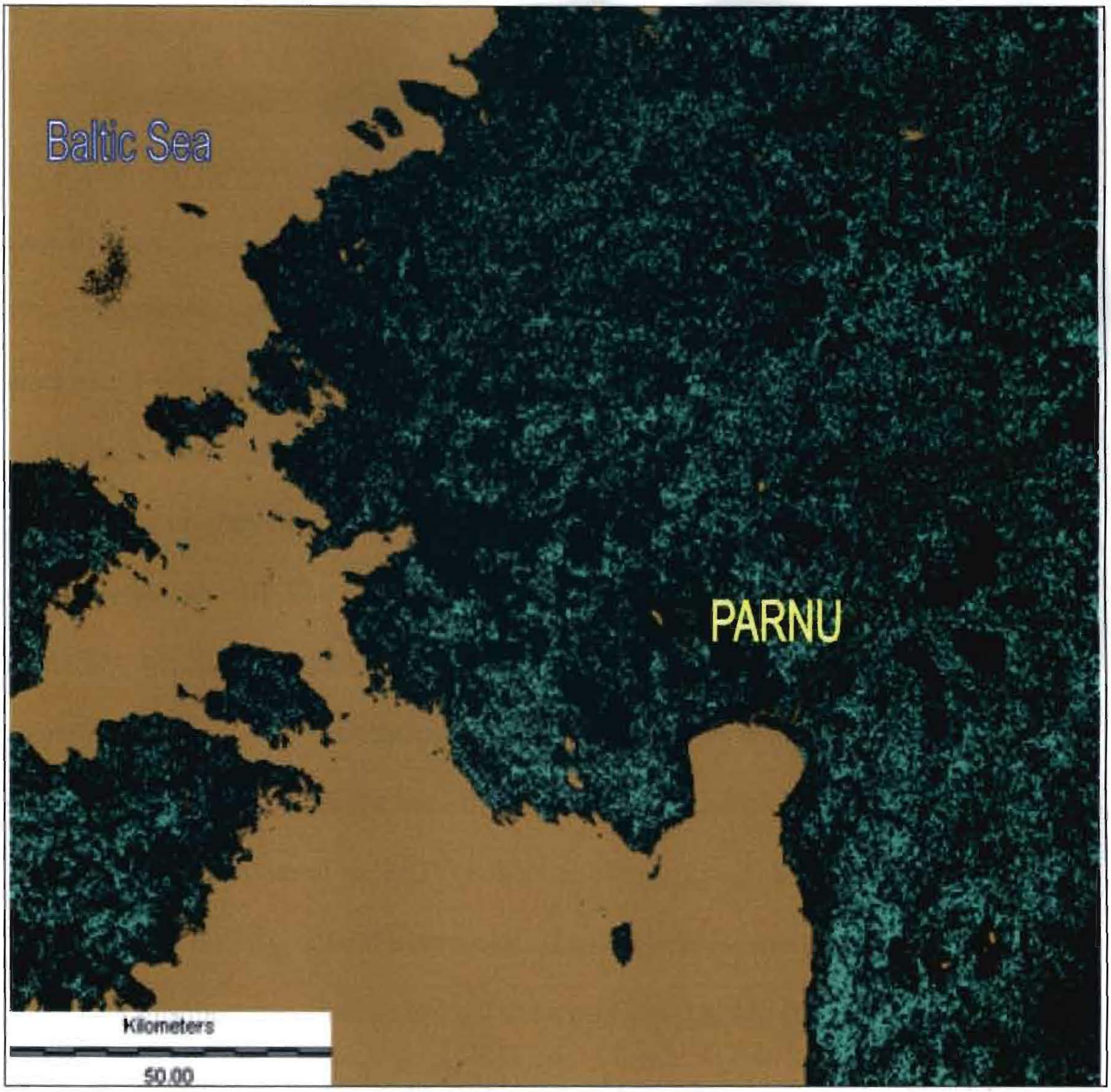

Fig. 43. Classified isocluster scene. Clusters having value 4 were reclassed and received a new value of 1 (green pixels). Background is black. Qual256 palette. Scene 86/07/28, Landsat 5. Forest having cluster value 4 is much more common in southern part of the scene. The distribution of the forested areas coincides mostly with till sediment, according to the map of Quaternary deposits (Kajak, K. 1993).

Till and Sand

The distribution of till and sand on the Landsat scene is one factor that controls the spatial distribution of the land-use types. Generally till is a sediment type which is used for forestry (personal communication Kalm, 2000). The distribution of the sand was extracted from the background (fig. 44). On the scene 86/07/28, the distribution of isocluster 8 coincides with the distribution of areas covered by sand. The forest isocluster 8 scene (fig. 44) was multiplied in OVERLAY module by NDVI, or band 4, values of the clusters (figs. 45-46). The same procedure was repeated for the rest of datasets (figs. 48, 50). The forest type represented by cluster 8 is probably composed of pine trees, which are common in the similar settings. The histogram of the spectral signature of pine is shown on the (fig. 47). The overlay operation allowed identification of the spectral signatures of the trees in the forest, what is depicted on the histograms showing the disrtibution of the NDVI values on the scenes. (figs. 49, 51).

During the study of different forest types in southwestern Estonia, isocluster method of unsupervised analysis proved to be useful during the process of separating the forest, coinciding with till sediment, from the background. The datasets used for the forest analysis come from May, June and July. As a result of the research, it appeared that July scenes were the most useful for the forest classification. Estonia with relatively cold climate has the maximum vigor of vegetation in late June and July. The NDVI values of different tree species are the most diverse during this period of time. The different isocluster scenes made of the same data sets, with different color composite scenes as a background have different amount of information depending on the color

Fig. 44. Classified isocluster scene Scene 86/07/28, Landsat 5. Clusters having value 8 were reclassed and received a new value of 1 (brown pixels) and were multiplied by NDVI value. Background is black. NDVI 256 palette. The distribution of the forested areas coincides with sandy sediment.

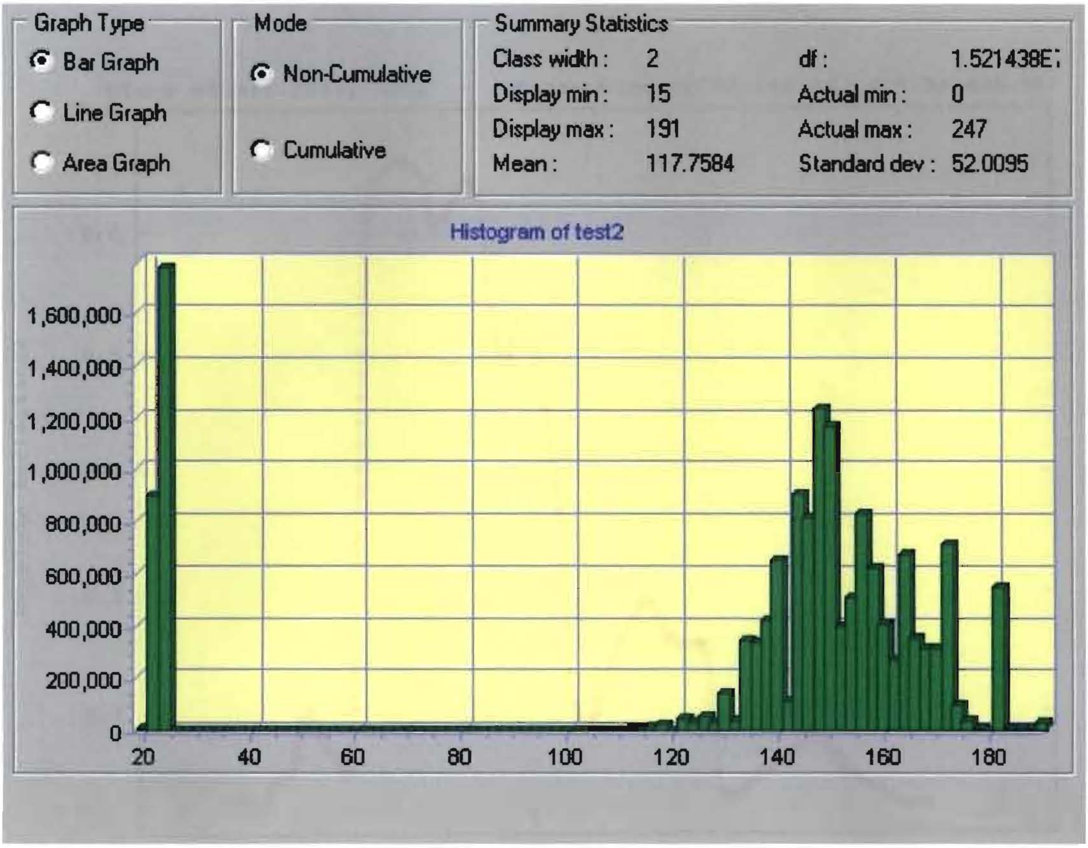

Fig. 45. Histogram of the classified isocluster scene where cluster 8 was multiplied by the NDVI values. The NDVI mean spectral value is 155. The distribution of spectral signatures of the forest resembles histogram of the scene 1986/06/26.

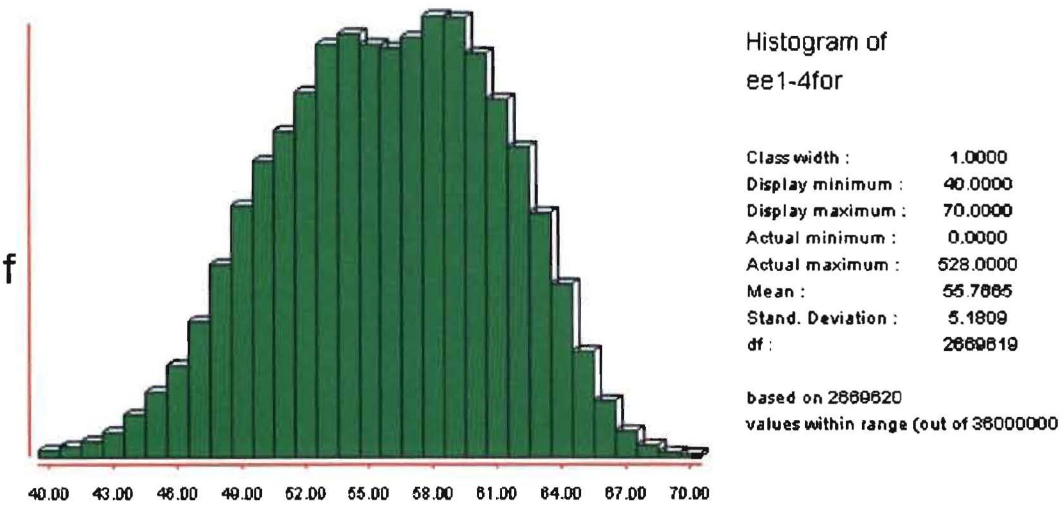

Fig.46. Histogram of the classified isocluster scene where cluster 8 was multiplied by the values taken from band 4 (NIR). The NIR mean spectral value is 55.5.

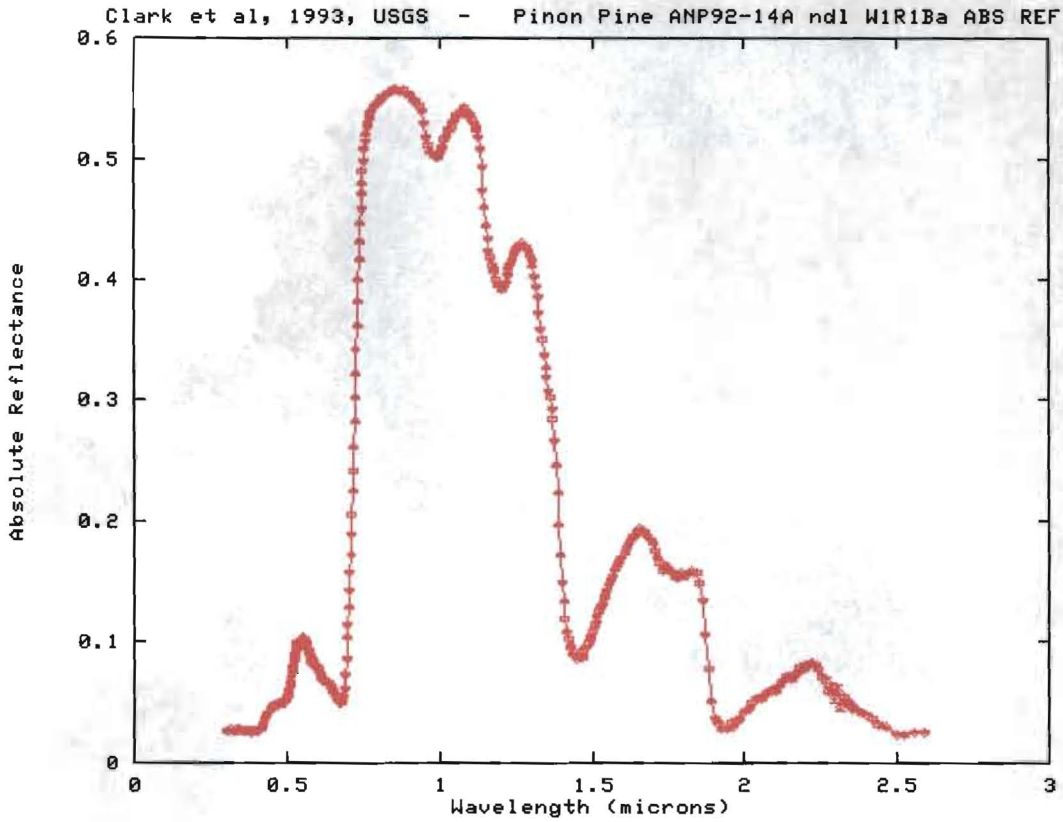

Fig. 47. Pine tree spectral signature. The isocluster class 8 most probably coincides with pine forest, which is common on sand dunes and on till sediment. (USGS Digital Spectral Library).

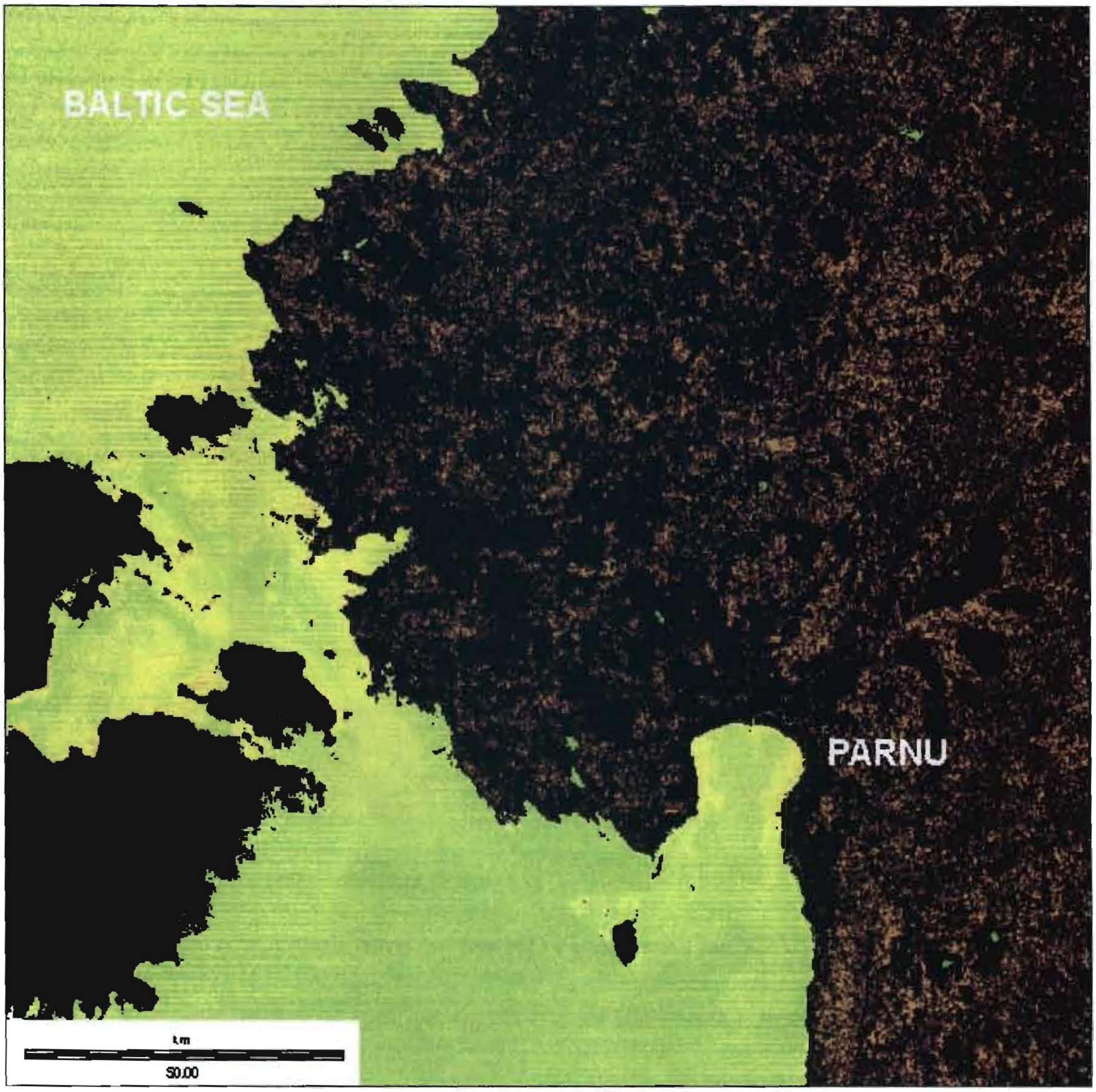

Fig. 48. Classified isocluster image of the Estonia. Scene 1986/06/26, Landsat 5, unsupervised classification. Composite scene (band 3, band 4, band 5) blue, green and red, as background image, and bands 1, 2, 3, 4, 5, and 7. Clusters having value 6 were reclassed and received a new value of 1 (brown pixels) and were multiplied by NDVI value. Background is black. NDVI 256 palette. The distribution of the forested areas coincides, in many places, with till sediment.

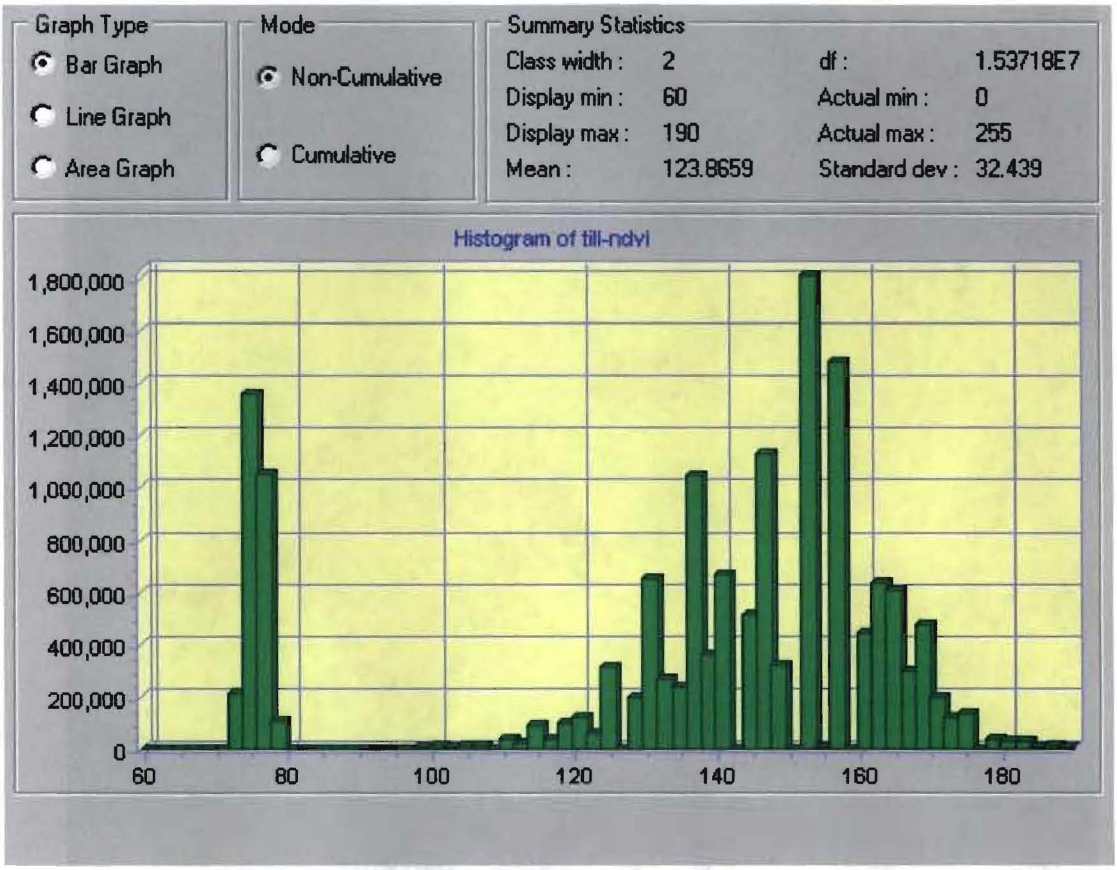

Fig. 49 Histogram of the classified isocluster 1986/06/26 scene, values based on masking. Cluster 6 was multiplied by the NDVI values. The NDVI mean spectral value is 123.8. The distribution of spectral signatures of the forest resembles histogram of the scene 86/07/28.

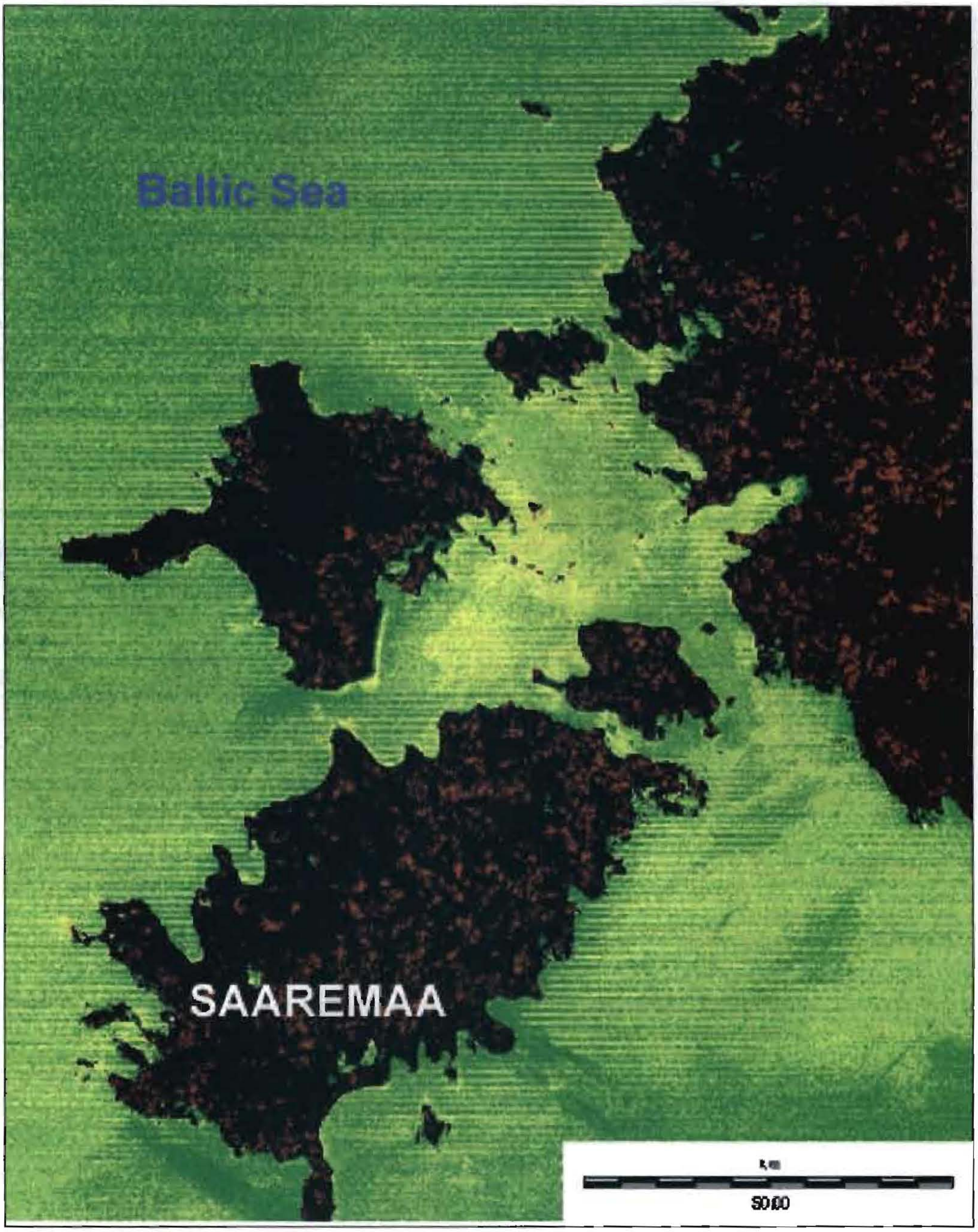

Fig. 50. Scene 1986/07/03. Isocluster mask of western Estonia, unsupervised classification. Composite scene (band 3, band 4, band 5) blue, green and red, as background image, and bands 1, 2, 3, 4, 5, and 7. Landsat 5. Clusters having values 13 and 16 were reclassed and received a new value of 1 (brown and green pixels) and were multiplied by NDVI value. Background is black. NDVI 256 palette. The distribution of the forested areas coincides, in many places, with the sandy and till sediment

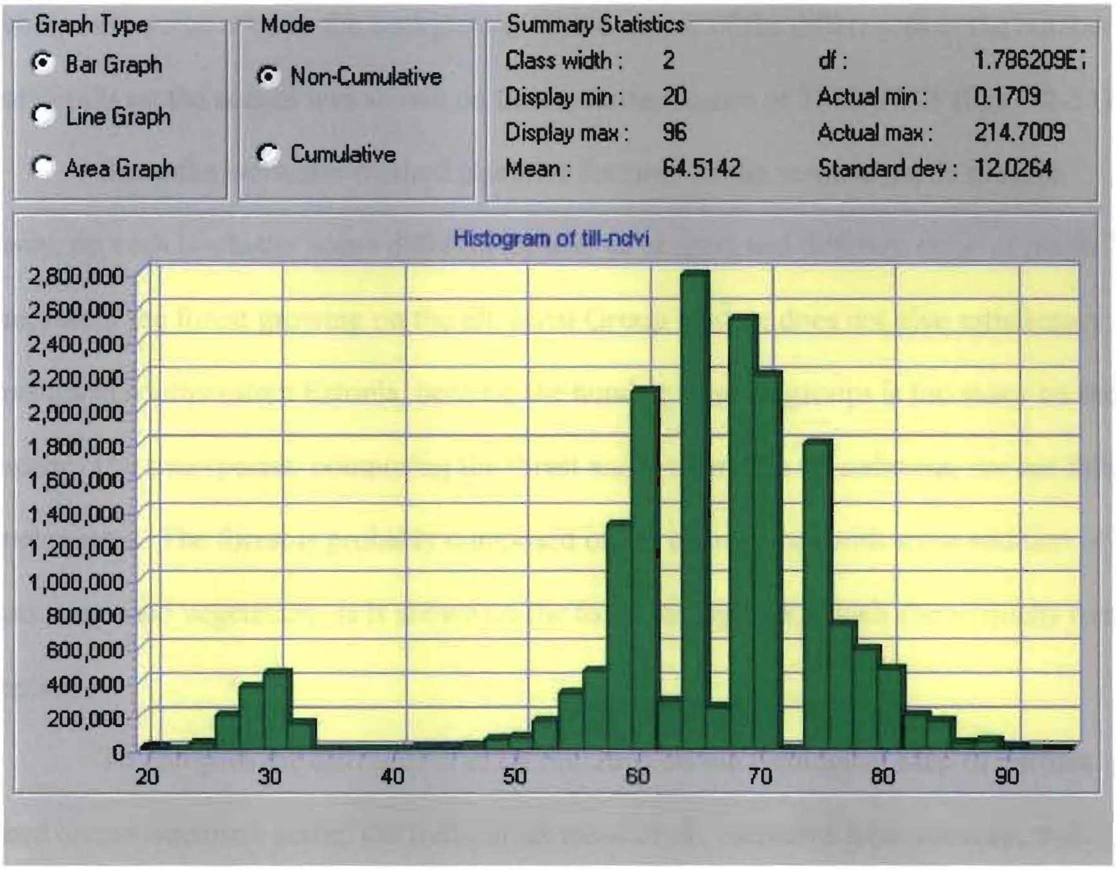

Fig. 51. Histogram of the classified isocluster 1986/07/03 scene, values based on masking. Clusters 13 and 16 were multiplied by their NDVI values. The NDVI mean spectral value is 64.5. The distribution of spectral signatures of the forest resembles histogram of the scene 86/07/28.

composite scene used as the background. The example of the differences in the number of details on the scenes was shown on the isocluster scenes of 1986/07/03 (figs. 52-53).

Since the isocluster method classifies features on the scene in partly random way, on each isocluster scene different number of clusters and different color of pixels represent the forest growing on the till. Idrisi Group module does not give satisfactory results in southwestern Estonia, because the number of small groups is too many on the scene. The tree species, composing the forest and growing on till sediment, are not fully recognized. The forest is probably composed of the spruce trees with some addition of unrecognized vegetation, as is shown on the forest histograms, which show usually two spikes.

To compare the distribution of till outcrops on the Geological Map of Estonia and on the isocluster scene, the transparent mask of till, extracted from the map, was overlayed on the isocluster scene (fig. 54).

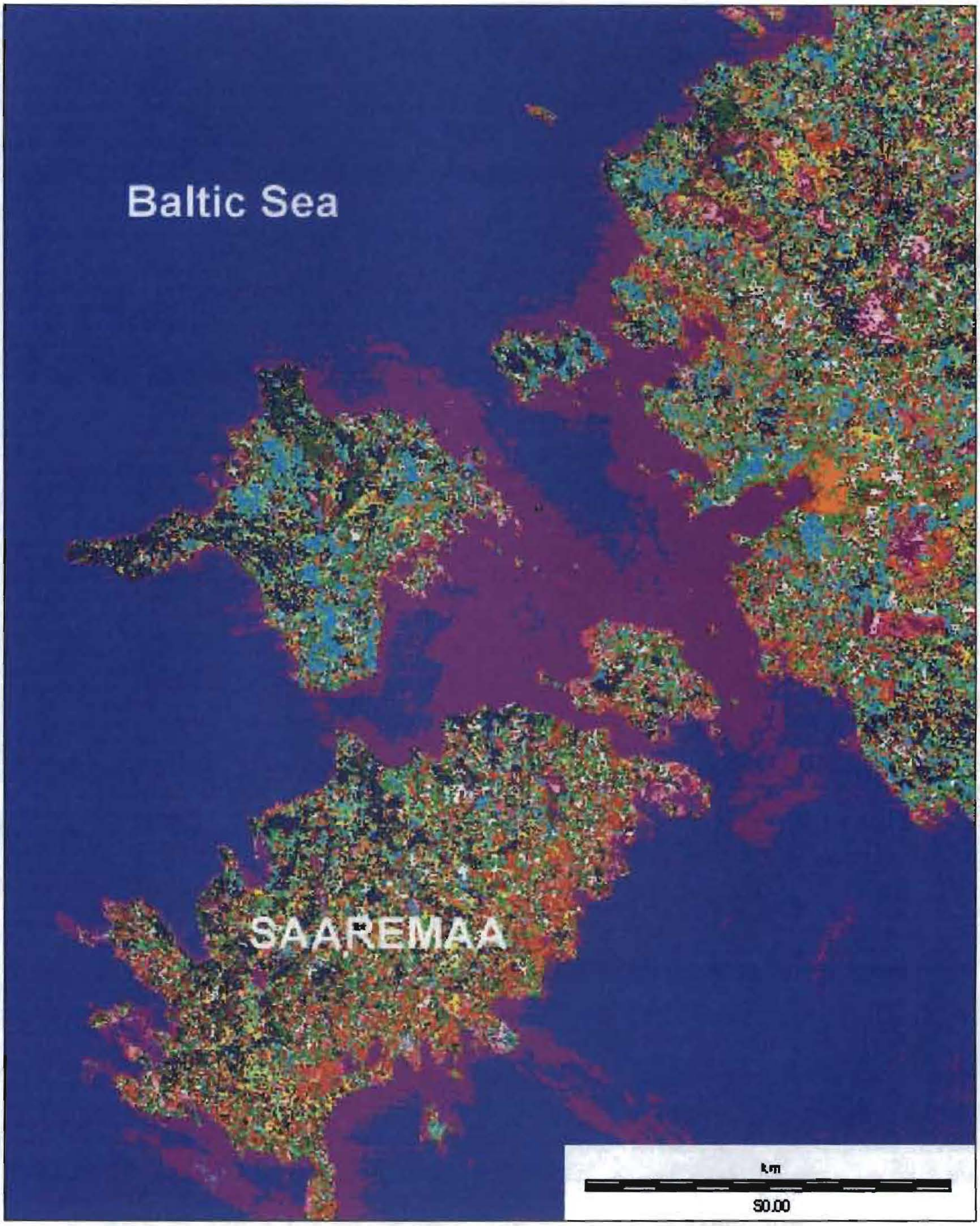

Fig. 52. Isocluster scene 1986/07/03, Landsat 5. Isocluster scene composed of the color composite image (band 3, band 4, band 5) blue, green and red, as background composite image, and six bands 1, 2, 3, 4, 5 and 7. Forest is composed of the green and brown pixels. Peat bogs are gray and violet, other colors represent agricultural lands and other types of land use. The number of different features, which are possible to be extracted from the scene depends on the background color composite scene used in the isocluster operation.

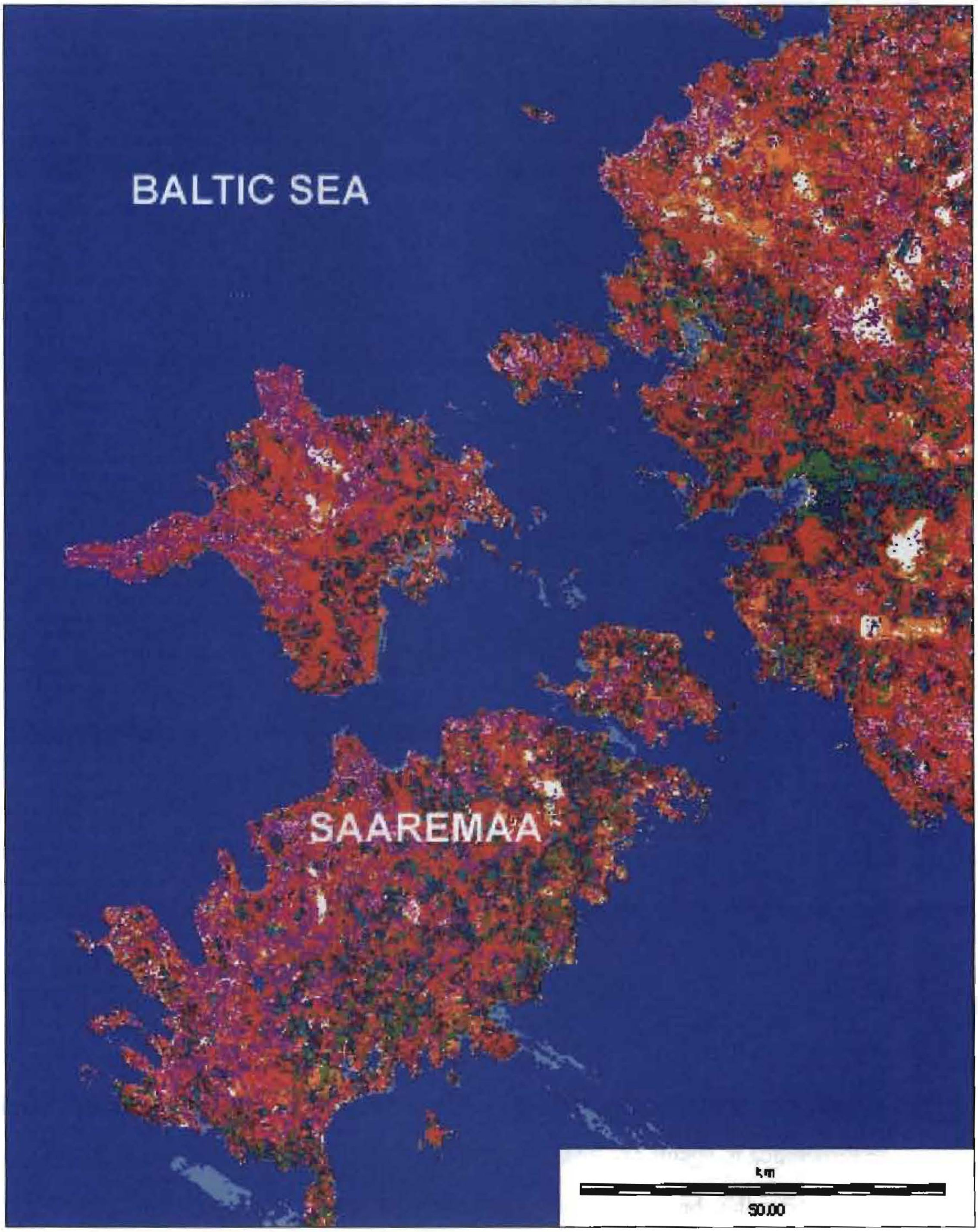

Fig. 53. Isocluster scene 1986/07/03, Landsat 5. Isocluster scene composed of the color composite image (band 2, NDVI-scene, band 5) blue, green and red, as background composite image, and six bands 1, 2, 3, 4, 5 and 7. Forest is composed of the red and brown pixels. Peat bogs are white red and green, other colors represent agricultural lands and other types of land use. The number of different features, which are possible to be extracted from the scene, depends on the background color composite scene used in the isocluster operation.

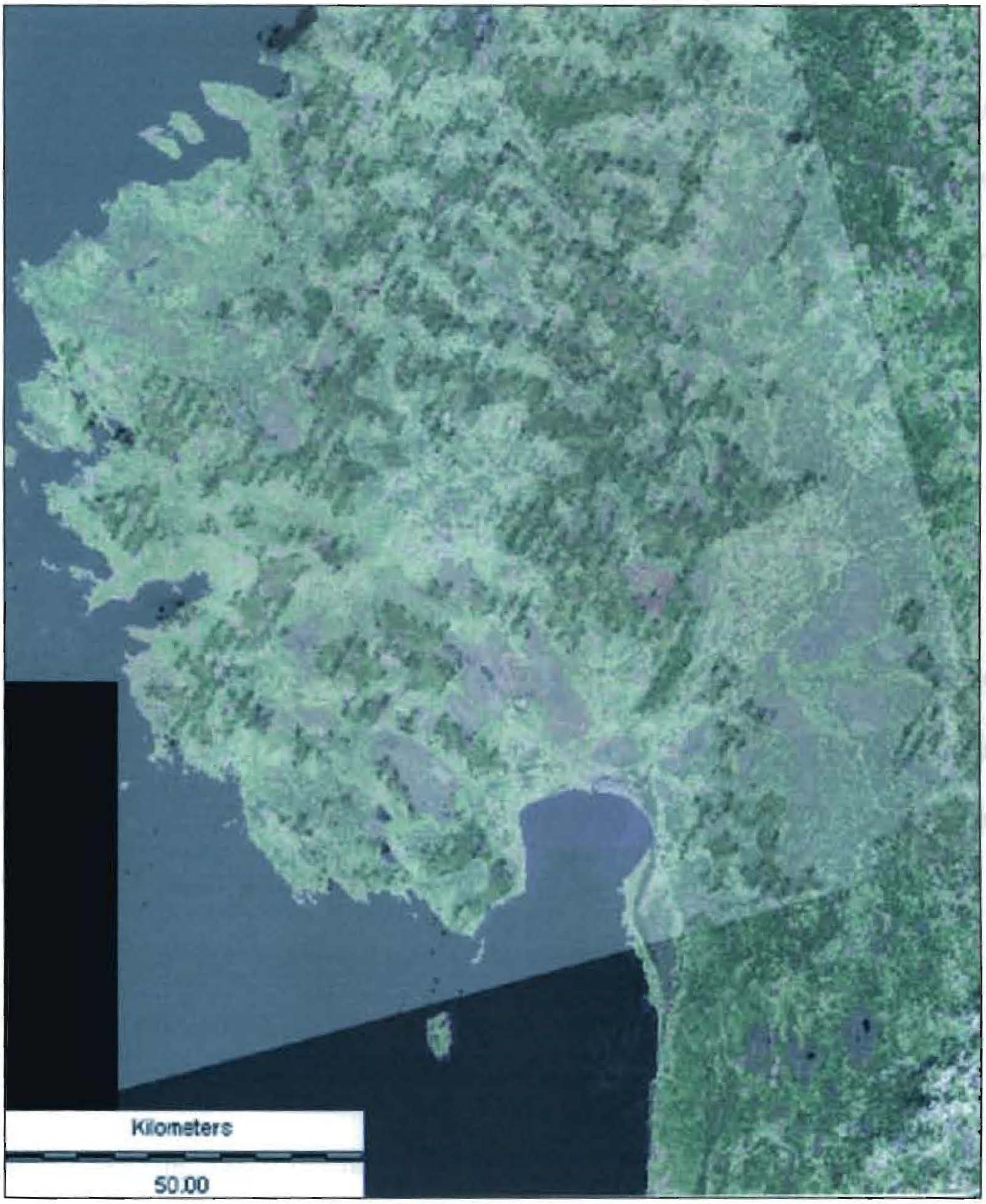

Fig. 54 Transparent mask representing till outcrops extracted from the Geological map of Estonia overlaid on top of the false color composite scene 345 image of southwestern Estonia, 86/07/28 scene, Landsat 5. Bands 3, 4, 5 - blue, green, red. Till is brown, forest is brown and green, Baltic Sea is black. The spatial distribution of till sediment on the map in majority of the places coincide with the distribution of the spruce forest on the Landsat TM scene.

End moraines and marginal eskers

Several end moraine ridges are located on the Landsat scene. Three different ice sheet lobes indicated as numbers 1, 2, and 3, were left by Pandivere and Palivere stadials of deglaciation (fig. 55). The end moraines and marginal eskers are together with dunes the most common natural linear features visible on the analyzed scene.

In most of the places the end moraines and marginal eskers are visible on the Landsat scene as borders between different types of land use (figs. 56-60). Usually, the land in front of the end moraine or marginal esker terrain is used for agricultural purpose (fig. 56). The arable lands in front of the end moraines are usually covered by loamy silty soil and in some cases sandy sediment. Moraines and areas behind moraine ridges are usually blanketed by till or sand. Till sediment coincides with forest cover. Peat bogs are very common features located behind moraine ridge (fig. 58). Many cultural features especially roads are located on the moraine ridges (fig. 60).

From the several moraine ridges left by stagnating ice sheet lobes, the author selected three lobes, which are the most prominent on the analyzed scene. Lobe number 1 left during Pandivere deglaciation stadial is the easiest to be recognized on the isocluster scene (fig. 55). It reaches the farthest to the south, and it is eroded by runoff in the most distal southern part. Lobe number 3, the youngest, was created in the final part of the Palivere stadial of deglaciation. In many places as the highest point on the wet terrain, moraine ridge number 3 is used as a road route. The end moraines are impossible to be extracted directly from the Landsat scene. The separation of end moraines is possible based on interpretation of the different types of land use and vegetation cover.

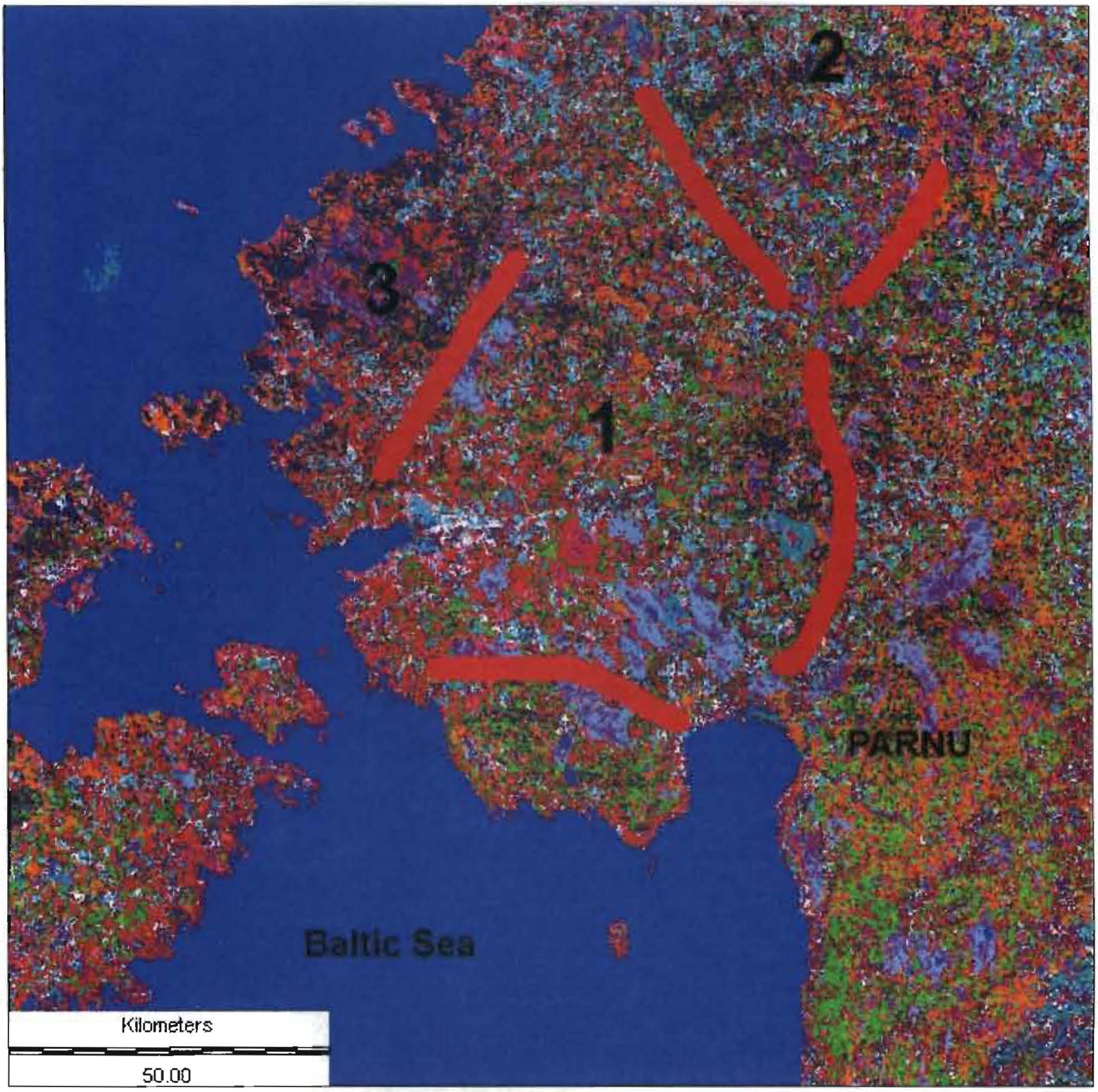

Fig. 55. Isocluster image of the southwestern Estonia 345 composite scene, 86/07/28, Landsat 5 as background image, and bands 1, 2, 3, 4, 5, and 7. Unsupervised classification. End moraines are highlighted as red lines. The numbers 1, 2 and 3 represent ice sheet lobes left during different stages of deglaciation. Number 1 and 2 - marginal moraines left by Pandivere stadial of deglaciation. Number 3 - marginal moraines left by Palivere stadial of deglaciation (Raukas and Teedumae 1997).

Fig. 56. Window from false-color composite scene 345 image of southwestern Estonia, 86/07/28, Landsat 5. Bands 3, 4, 5 - blue, green, red. End moraine ridge (highlighted as black line) is the border between two different types of land use. In front of the ridge (right) arable land, behind (left) forest and peat bogs. The difference between different types of land use is visible mostly in different shapes (agricultural lands have regular shapes, forest has irregular shapes), and in different colors.

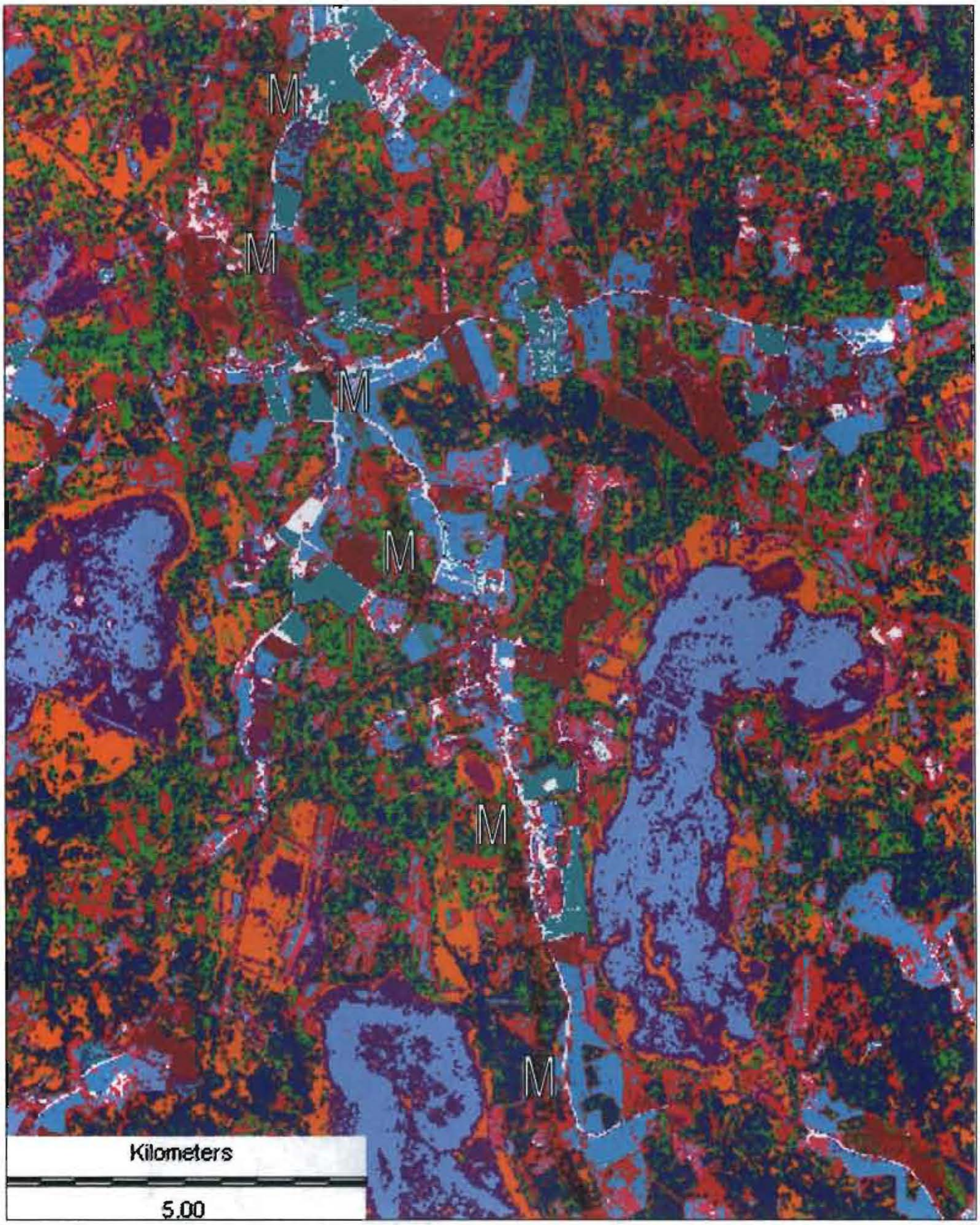

Fig. 57. Window from isocluster image of the Estonia 345 composite as background image, and bands 1, 2, 3, 4, 5, and 7. Scene 86/07/28, Landsat 5, unsupervised classification. End moraine is highlighted as red line and "M" letters. Red and brown pixels represent coniferous forest. Arable land is light blue and red, peat bogs are violet. The end moraine is the border separating two different types of land use - forestry and agriculture.

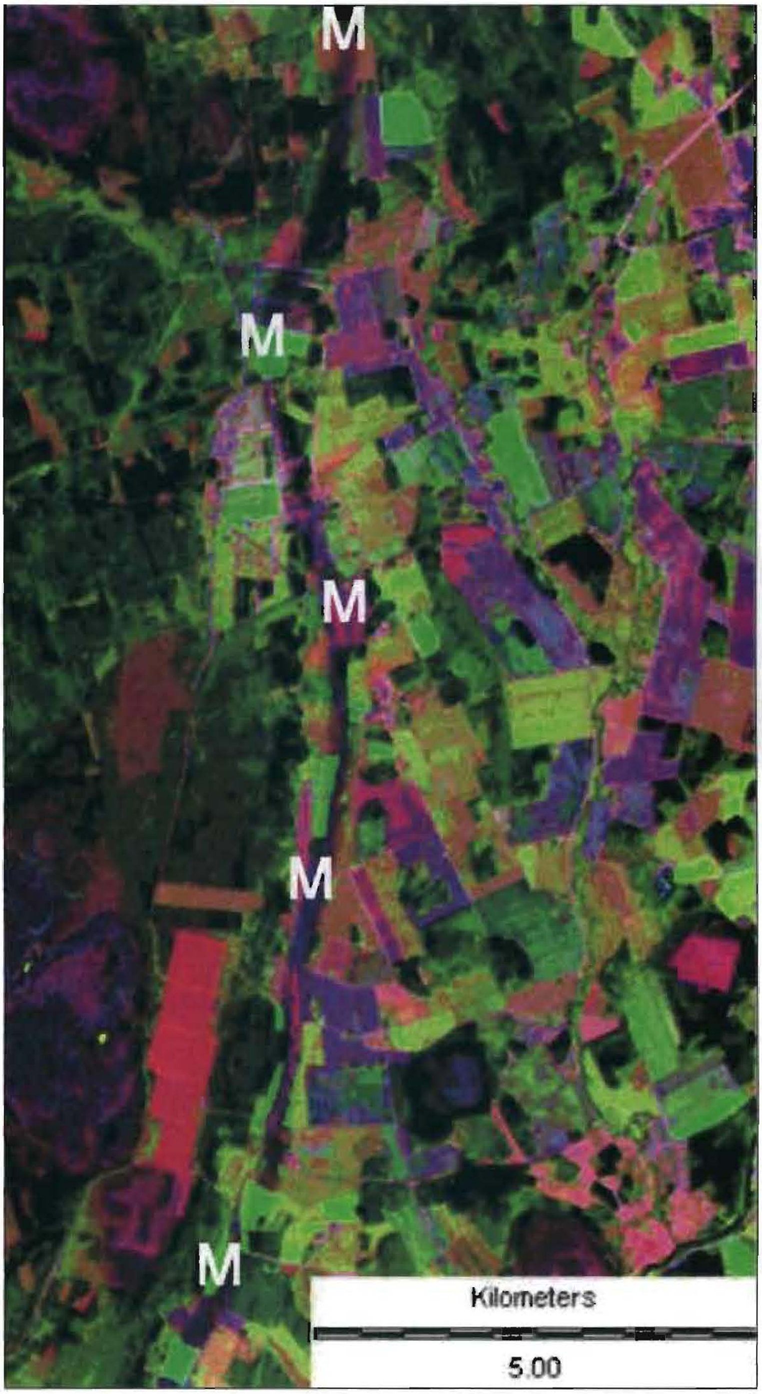

Fig. 58. Window from false-color composite scene 345 image of southwestern Estonia, 86/07/28, Landsat 5. Bands 3, 4, 5 - blue, green, red. End moraine ridge is the eminent linear feature on the scene highlighted as violet line and letters "M". The road route uses the end moraine as the highest elevated terrain on the scene.

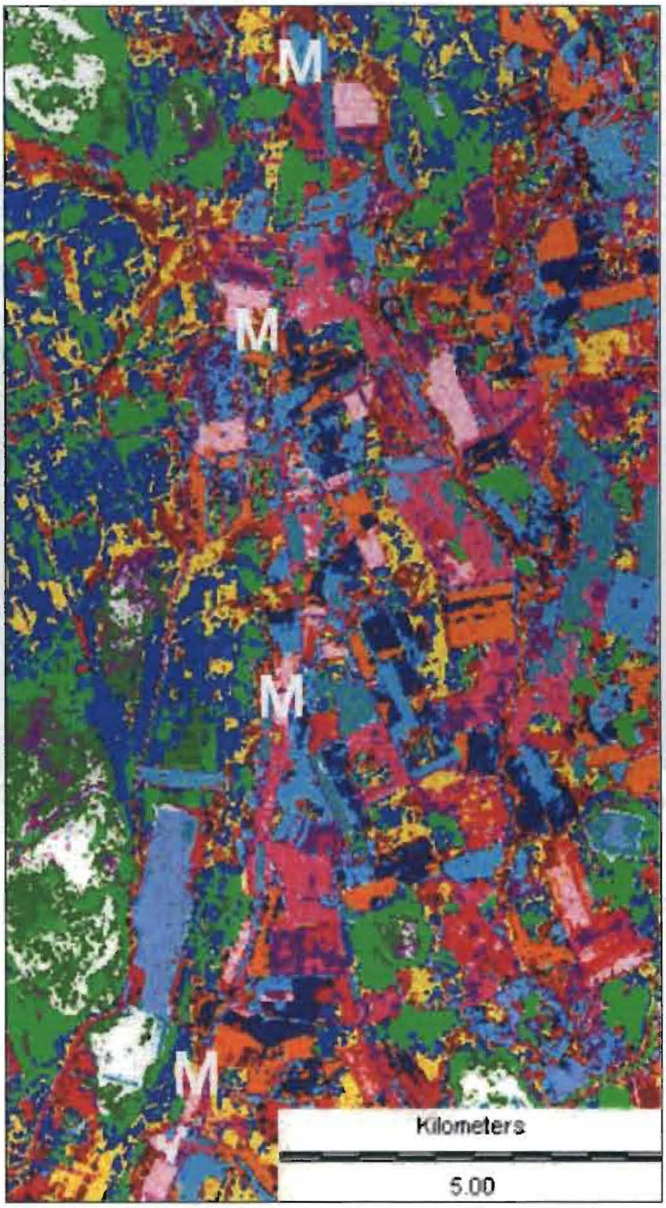

Fig. 59. Window from isocluster image of the Estonia 345 composite as background image, and bands 1, 2, 3, 4, 5, and 7. Scene 86/07/28, Landsat 5, unsupervised classification. End moraine is the border between two different types of land use. On the east side of the scene are prevalent polygonal shapes of agricultural landuse features. The western part of the scene located behind the moraine ridge has prevalent irregular land use features. Compare previous (fig. 58).

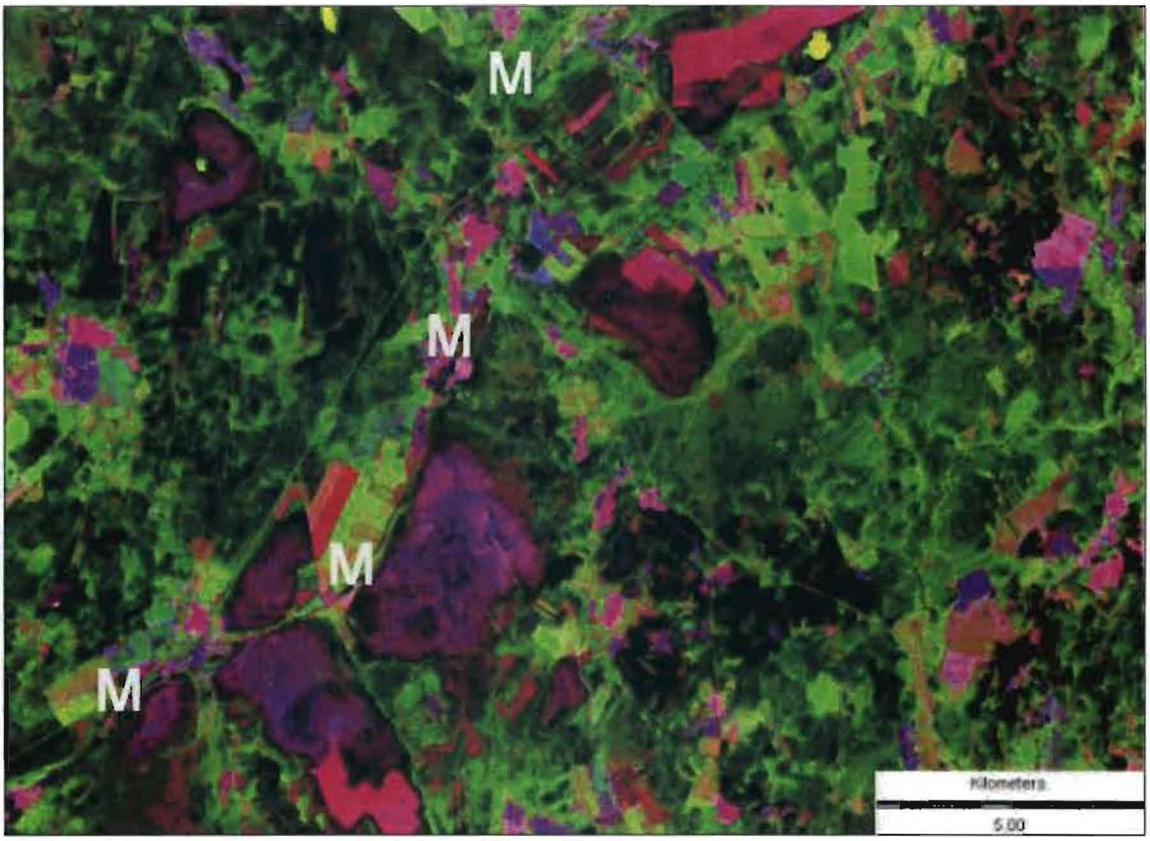

Fig. 60. Window from false-color composite scene 345 image of western Estonia, 86/07/28, Landsat 5. Bands 3, 4, 5 - blue, green, red. End moraine ridge, highlighted as "M" letters creates the road route.

Drumlins

Drumlins mostly form tear-drop shape formations on the distal sides of the bedrock elevations, and in depressions where the glacier had disintegrated into different lobes moving with different speeds (Raukas and Teedumae 1997). Several drumlin fields are located on the analyzed scene. The biggest drumlins are located in the southwestern part of the scene, in coastal vicinity. On the window scene (fig. 61) are located two drumlins highlighted with black lines. The eastern drumlin is difficult to be recognized on

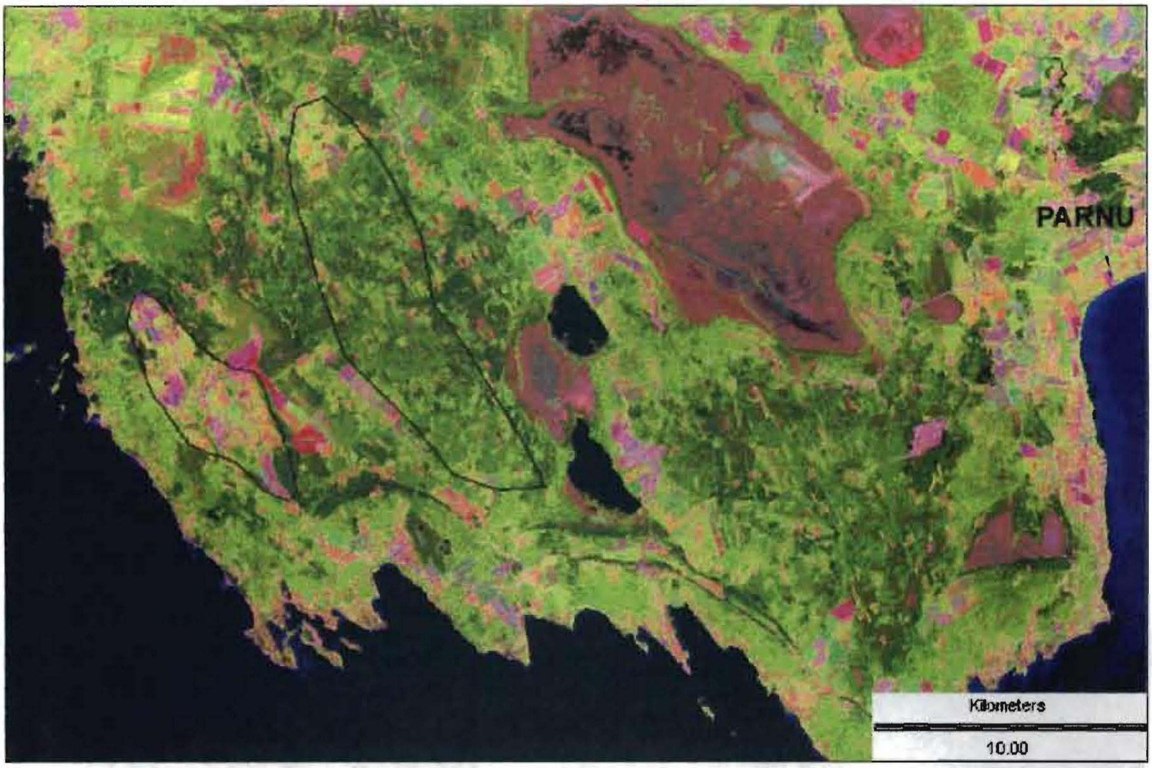

Fig. 61. Window from false-color composite scene 345 image of southwestern Estonia, 86/07/28, Landsat 5. Bands 3, 4, 5- blue, green, red. Drumlins are highlighted as a black line. The western drumlin highlighted by distinctive borders of land-use pattern.

the Landsat TM scene. The western drumlin is better preserved and creates a distinctive pattern in land use. The drumlin is covered by agricultural fields and is surrounded from north, south, and west by different type of land use - mostly forest. The differences in land-use pattern are connected with different types of soils blanketing the analyzed scene. The drumlin is composed of glaciofluvial sediment surrounded by till (Kajak 1993). For agricultural use, glaciofluvial sediments are preferable to till. The isocluster scene (fig. 62) shows the differences in the land-use pattern in a dramatic way. The drumlin is composed of cluster numbers 12 and 16, which coincide with agricultural type of land use. The surrounding drumlin clusters coincide with till and usually are used for forestry.

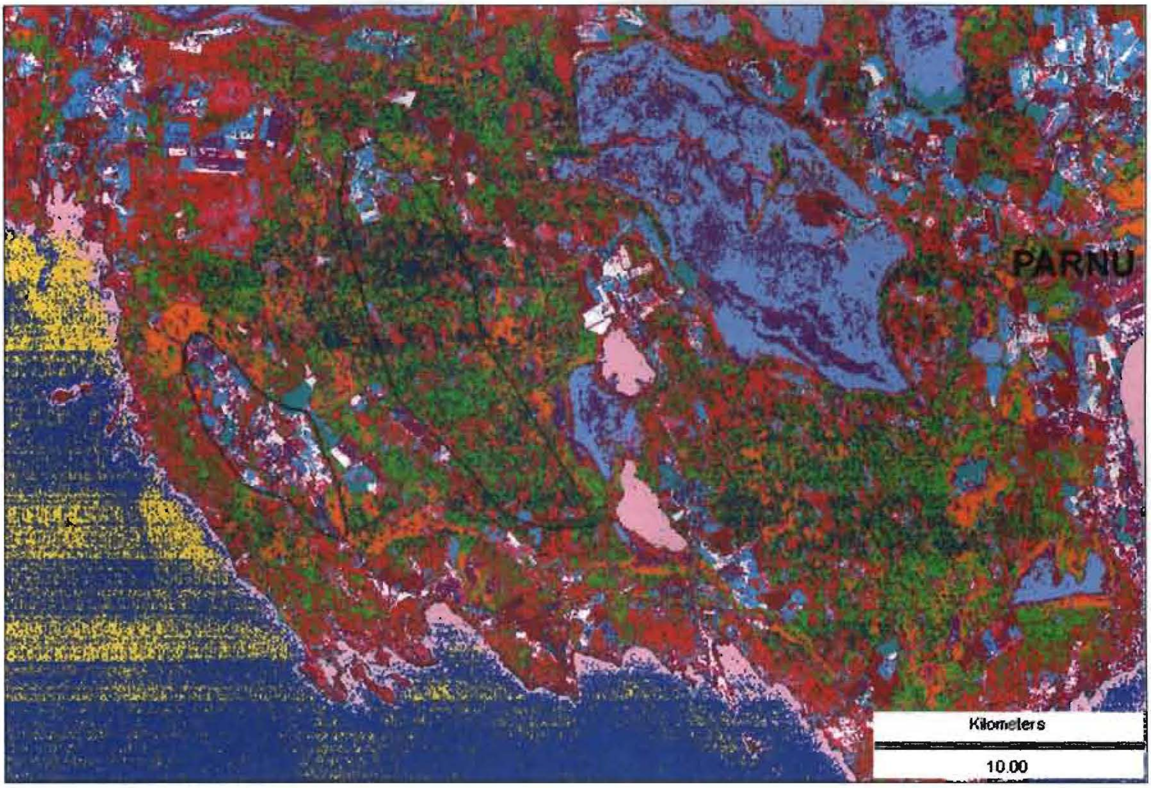

Fig. 62. Window from isocluster image of the Estonian, unsupervised classification. Composite scene 345 as background image, and bands 1, 2, 3, 4, 5, and 7. Scene 86/07/28, Landsat 5. The drumlins are highlighted by black line. The drumlin located in the western part of the scene is highlighted by distinctive borders of land-use pattern. The drumlin is cover by rectangular cropfields, which are surrounded by forest.

Eskers

In the system of fractures that developed within the ice during the final stage of deglaciation, different types of glaciofluvial sediments have originated. Marginal eskers are usually connected with bedrock depressions. Radial eskers occur in different topographic conditions often in ancient valleys. Eskers often occur in zones of glacial erosion (Raukas and Teedumae 1997). On the analyzed scene marginal eskers are impossible to be separated from end moraines and were analyzed together. The best-preserved geomorphic forms of radial eskers are located on the islands Saaremaa and Vormsi (figs. 63, 64). On Saaremaa eskers are difficult to be recognized. As an area blanketed by fluvioglacial sediments, eskers are used for the agriculture type of land use. The vicinity of the eskers is covered by forest, which grows on sandy and loamy soils. On the Vormsi island an esker is composed of sandy fluvioglacial sediment. This esker is probably the best preserved one on the entire scene. It has characteristic elongated shape and is covered as the most of the island's area by forest.

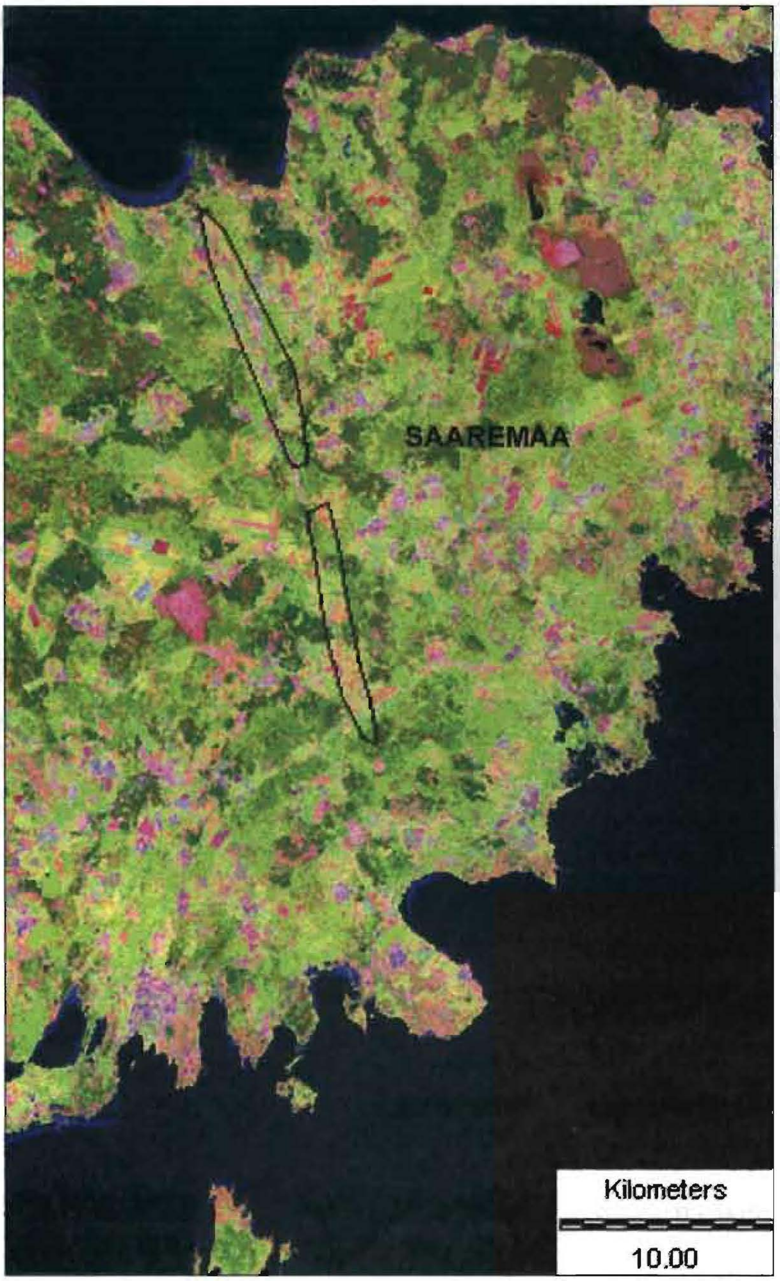

Fig. 63. Window from false-color composite scene 345 image of southwestern Estonia, 86/07/28, Landsat 5. Bands 3, 4, 5 - blue, green, red. Eskers are highlighted as black lines. The eskers on the scene are difficult to recognize. On the scene, eskers are used as agricultural type of land use , which is adjacent in many places to the forest.

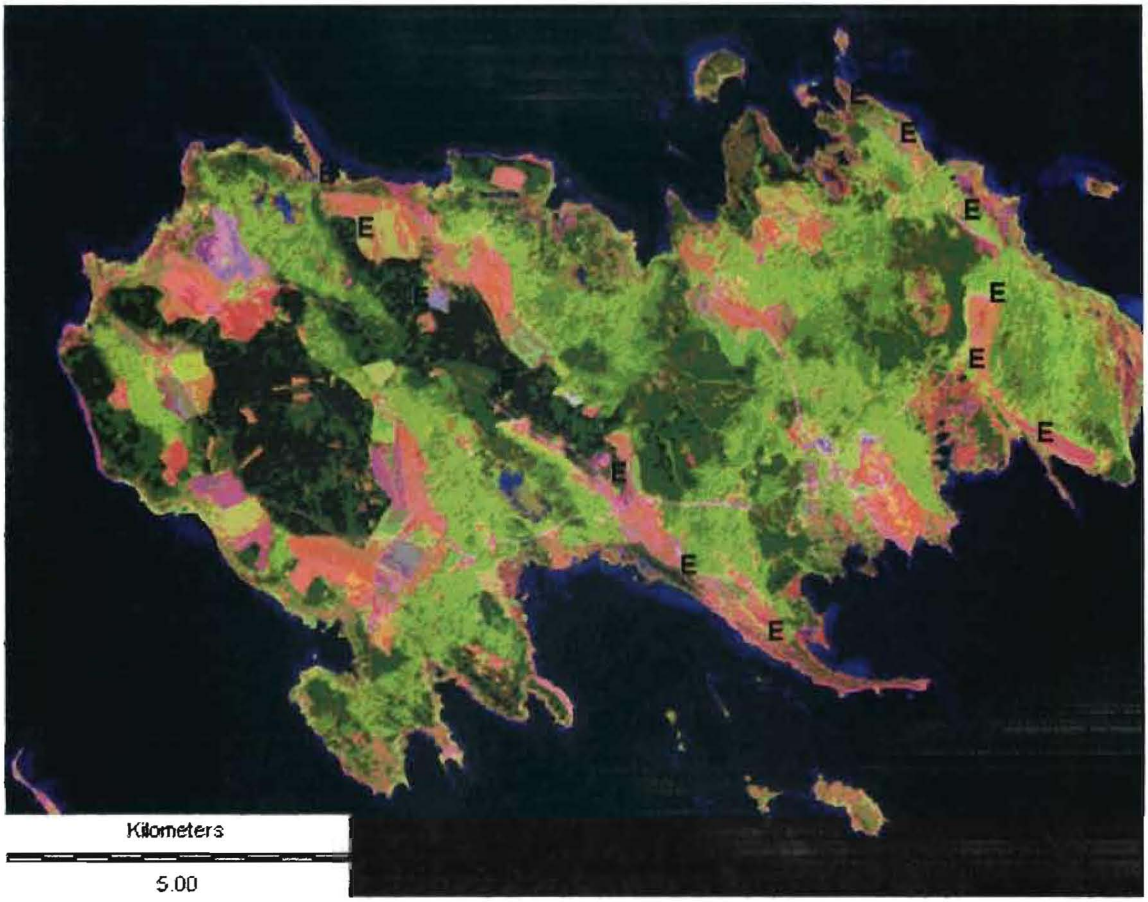

Fig. 64. Window from false color composite scene 345 image of the southwestern Estonia, 86/07/28, Landsat 5. Bands 3, 4, 5 - blue, green, red. Vormsi Island. Two eskers are highlighted by "E" letters. The eskers on the scene have typical linear shape very they prominent in the morphology of the island. Both ends of the western eskers create small peninsulas. On the scene, the eskers are used mainly for forestry (brown and green colors). Eskers on Vormsi Island are covered by coastal/beach sediment.

Dunes

The distribution of sand dunes is restricted to the coastal areas (figs. 65, 67, 69). In many places dunes form several stripes, parallel to the coast, reflecting the isostatic uplift of the coast (figs. 67, 69). In many places dunes are located on old beach ridges. During the analysis of dunes, supervised and unsupervised methods of feature classification were utilized (fig. 66). Dunes are covered by specific type of vegetation, pine forest, which is able to grow on sandy sediment. A majority of the dunes, on the analyzed scene, was created as a result of the prevailing southwestern winds (figs. 65, 67). Therefore in the southwestern coastal zone dunes are bigger and more common comparing to the northeastern coast of Estonia. The separation of the dunes is usually easy as a result of the characteristic arcuate shapes. Dunes are characteristic zones of land use covered with pine forest, which preserved its original character, not changed by humans. Dunes usually are zones dividing different types of land use. Unsupervised isocluster classification does not always give satisfactory results. Therefore, in this situation supervised classification may provide good results in the separation of dunes from the background. Since dunes are blanketed by poor soils, on the NDVI scene they are covered by vegetation having lower NDVI values (fig. 68).

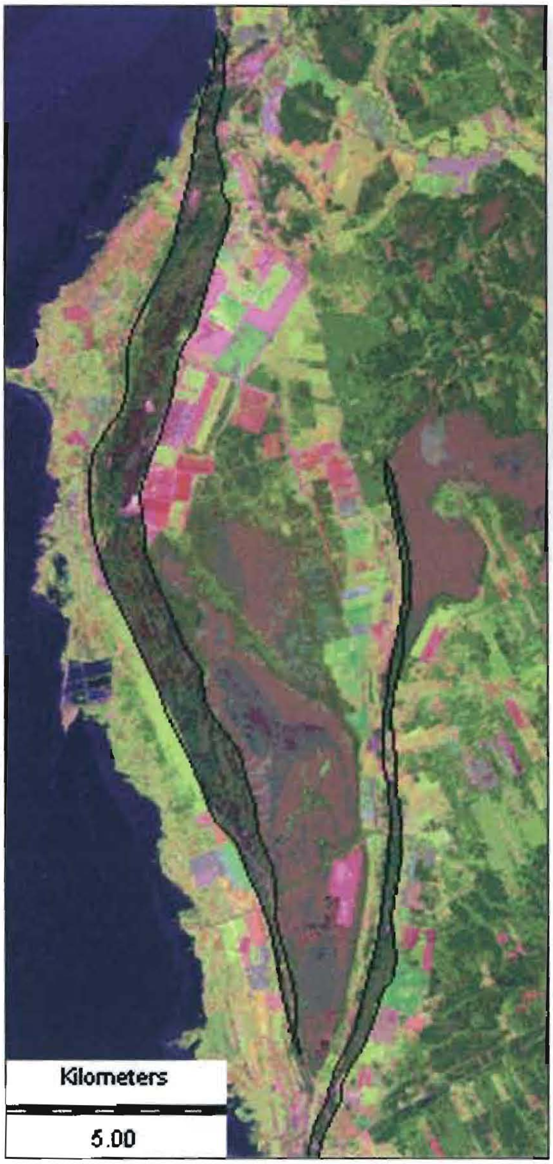

Fig. 65. Window from false color composite scene 345 image of southwestern Estonia, 86/07/28, Landsat 5. Bands 3, 4, 5- blue, green, red. Dunes are highlighted as a black line. Both Dunes have a typical arc shape. The spectral signatures of the vegetation covering dunes are significantly different comparing to the surrounding areas. The western dune from inland side is covered by pine forest, which is dark green and reddish brown, The coastal part is probably covered by grass. The eastern dune is covered by pine forest. Agricultural land is light green.

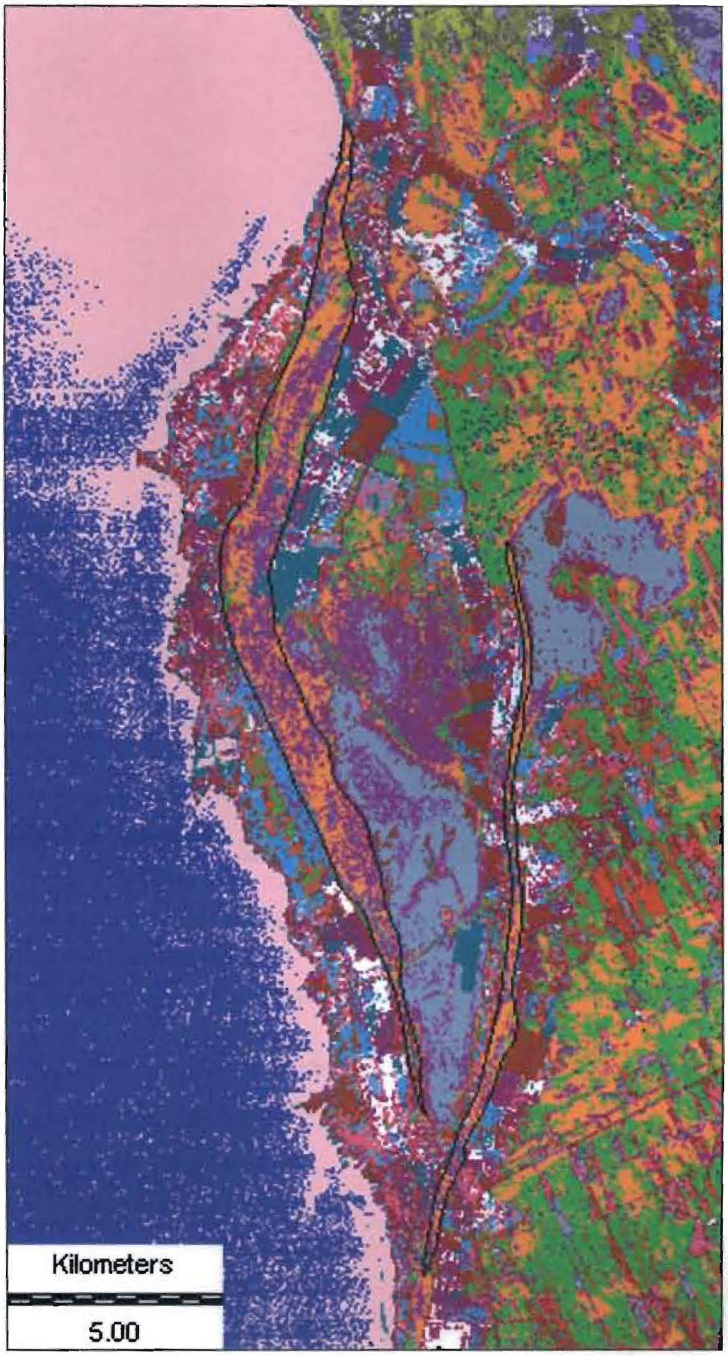

Fig. 66. Window from isocluster image of the Estonia, unsupervised classification. Composite scene 345 as background image, and bands 1, 2, 3, 4, 5, and 7. Scene 86/07/28, Landsat 5. The dunes are highlighted by black lines. Isocluster scene shows that dunes are the border zones of different types of landuse. Behind the dunes are located peat bogs (pale blue).

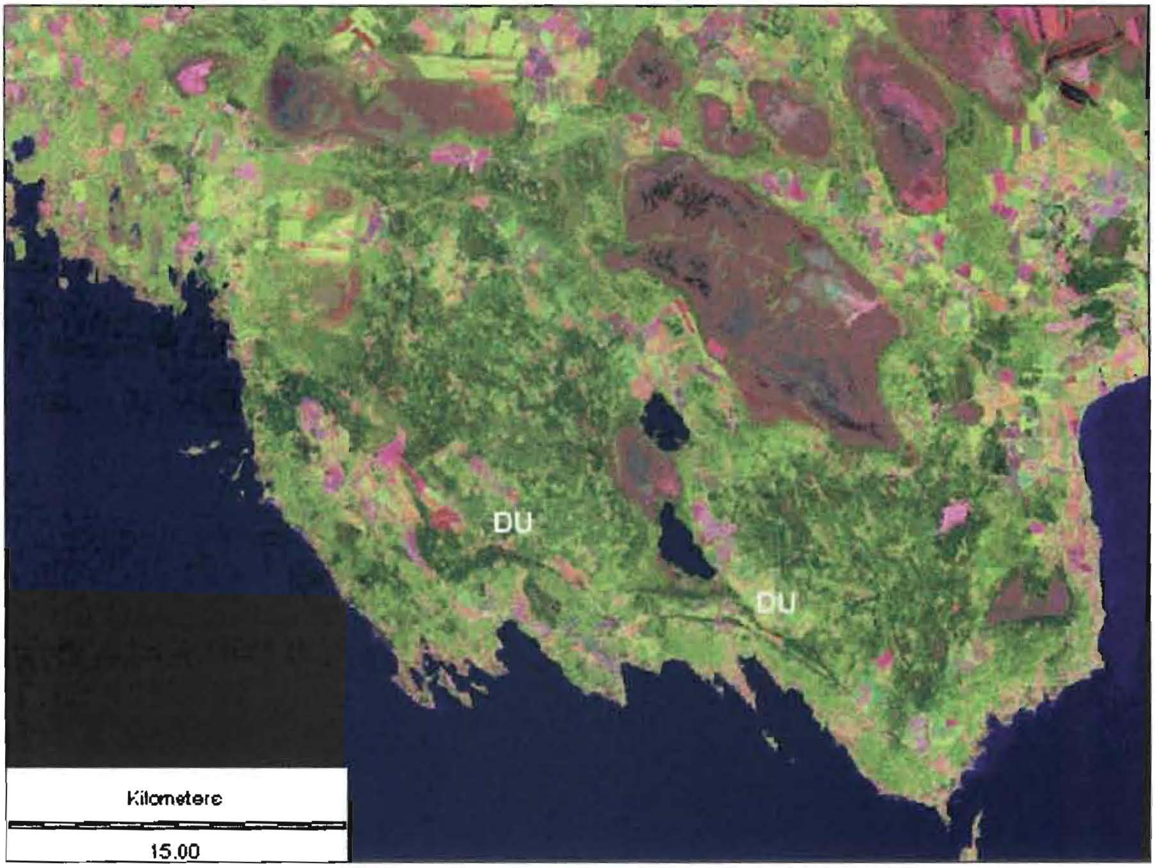

Fig. 67. Window from false color composite scene 345 image of southwestern Estonia, 86/07/28, Landsat 5. Bands 3, 4, 5 - blue, green, red. Dunes are highlighted as "DU". On the scene are visible two dune ridges having characteristic arcuate shape. Dunes are covered by pine forest (dark brown).

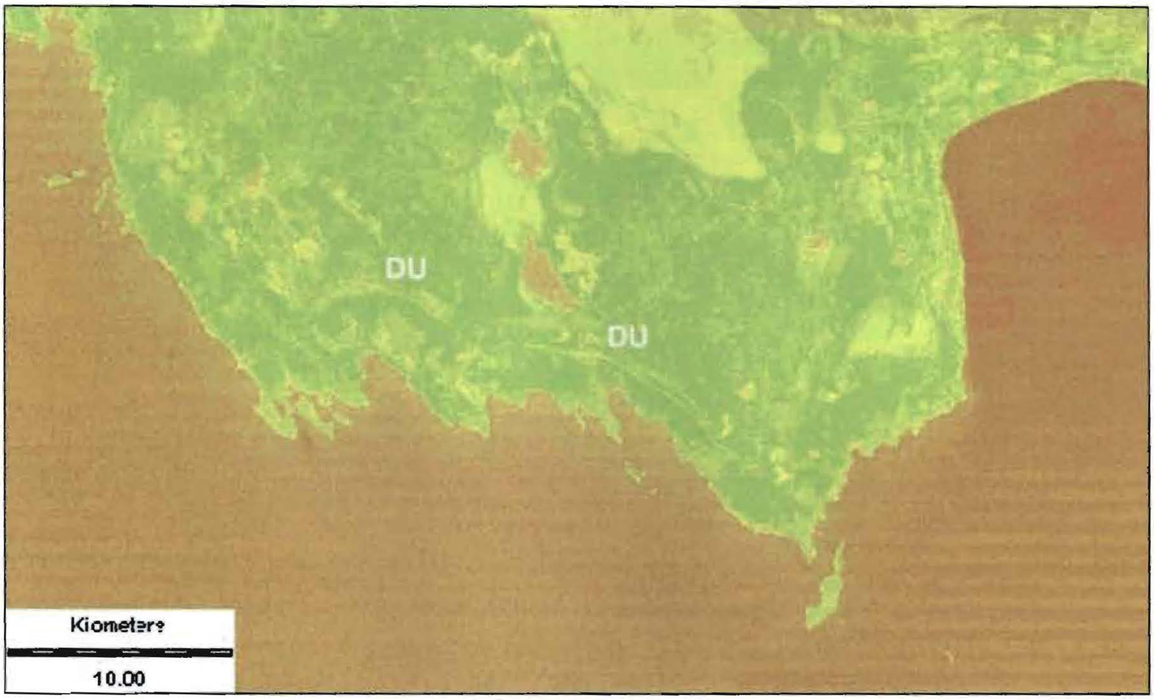

Fig. 68. Window from NDVI image. Scene 86/07/28, Landsat 5. NDVI 256 palette. The NDVI window shows that dunes have different NDVI values (lower) than the background vegetation. Dunes are highlighted as "DU".

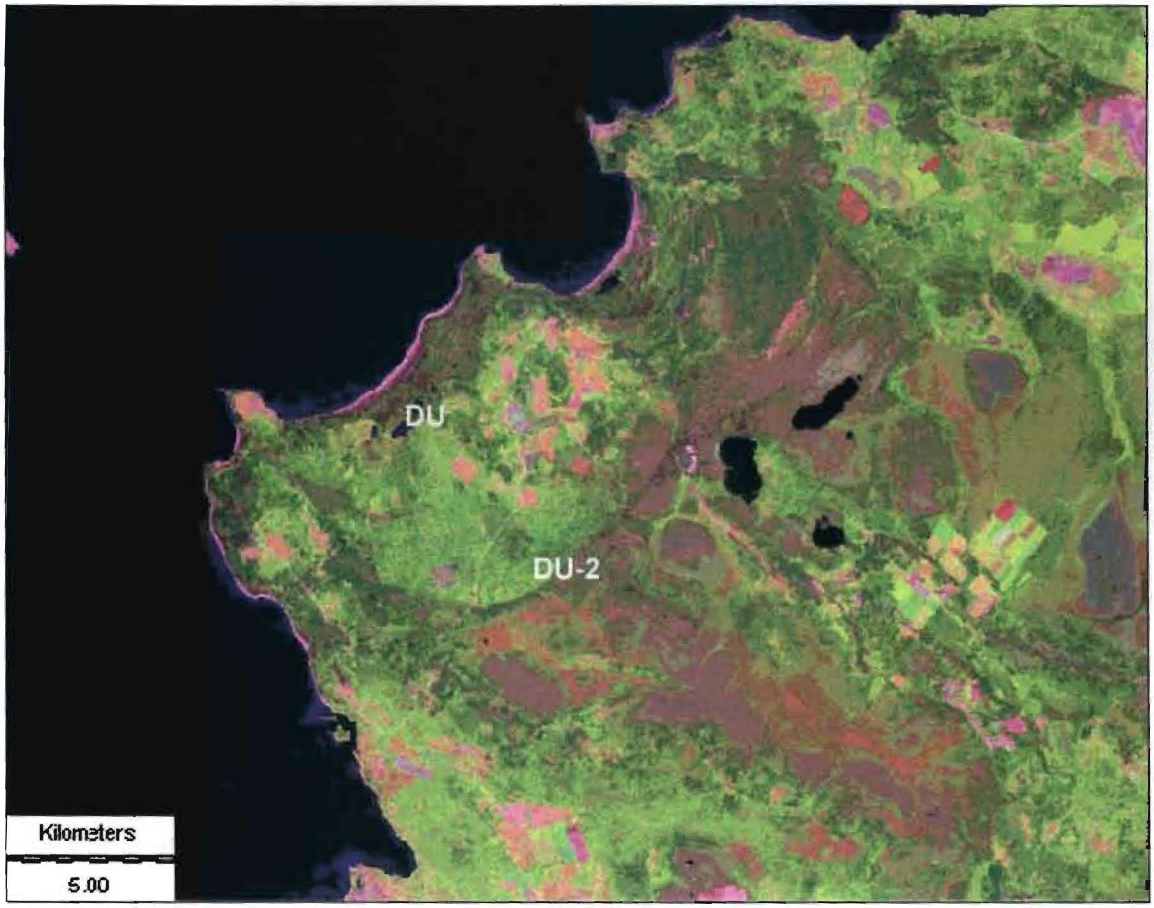

Fig. 69. Window from false color composite scene 345 image of southwestern Estonia, 86/07/28, Landsat 5. Bands 3, 4, 5 - blue, green, red. Dunes are highlighted as "DU" and "DU-2". On the scene are visible two dunes DU- modern dune and DU-2 dune originated when coastline was located farther inland to the south. Dunes have characteristic arcuate shapes originated as a result of northwestern winds. Dunes are covered by pine forest (dark brown).

Chapter 5

Conclusions

Western Estonian geomorphology is a mosaic of glacial and coastal landforms originated during late Pleistocene and Holocene. I have utilized Landsat thematic mapper (TM) datasets to identify, extract, classify, and interpret various landscape elements located within the analyzed region. Different image processing methods including false-color composites, normalized difference vegetation index (NDVI), tasseled-cap transformation and isocluster unsupervised classification were utilized. Geomorphic features were interpreted using the geobotanical approach. Landsat thematic mapper (TM) imagery appeared to be an effective method for identifying different glacial and coastal landforms in the lowlands of western Estonia. During the analysis of the Landsat TM scenes of southwestern Estonian province Pärnu, it appeared that TM images were helpful with the interpretation of certain types of geomorphologic and sedimentologic features. The false color composite images, based on TM bands 3, 4, and 5, appeared to be most useful for classification and interpretation of this data.

Two ways of analyzing features on the scenes were utilized during this research process. The first method of interpreting and selecting the geologic features was supervised classification, where the author selected the pixels, representing a particular sediment type, land use type, or geomorphic form. The second method of interpreting and selecting the geologic features was unsupervised classification. For the purpose of unsupervised classification, with the Idrisi ISOCLUST module appearing to be most useful. The resulting scene of the isocluster classification was composed of 16 categories of pixels. The final classified masks resulting from the isocluster operation were created using a RECLASS module with the supervised selection of the pixels representing the different features on the isocluster image.

Results from this study indicate that using both supervised and unsupervised methods of classification, peat bogs appear to contain the type of sediment which can be easily extracted from the background image and directly mapped using the Landsat TM scenes. The reason why peat bogs are such eminent features on these graphic images is due totheir spectral signatures differing substantially from the surrounding land-use types. Peat bogs have the least vigorous growth compared to surrounding vegetation on the scene, which is indicated by lower NDVI values. Peat mining activity was also possible to be extracted from Tasscap moisture index scenes. The second easiest traced type of sediment appeared to be till. Areas covered by till sediment were extracted using only unsupervised methods of classification. The till sediment coincides with the specific forest-cluster, spruce, which has different spectral signatures compared to surrounding types of forest clusters and other types of land use. The masks of the forest coinciding with the areas covered by till give only an estimation of the spatial distribution of till for each analyzed scene. The use of supervised classification or the use of different composite scenes as background images with isocluster classifications could provide better results yielding an image separating till sediment from the background.

During this research, the author also tried to extract from the background different types of geomorphic forms from the background image. The extracted forms include dunes, end moraines, eskers and drumlins. Dunes, eskers and in some cases drumlins were possible to be extracted from the background using both supervised and unsupervised methods of classification. Drumlins, eskers and dunes are linear features, which have different types of vegetation from surrounding areas, and their spectral signatures are easy to separate from the background in some cases. End moraines are possible to be traced and located on the Landsat TM image as borders between different types of land use. Typically, glaciofluvial and limnoglacial sediments are located in front of end moraines. Behind the end moraines, in the place of the ice sheet stagnation, the area is covered usually by till and in many places by numerous peat bogs. The land-use forms reflect the differences in the sediment. Areas covered by till are used for forestry opposite to areas located in front of end moraine which usually are used for agriculture and other types of landuse.

The results of the research show that Landsat TM images can be successfully used to identify and extract some types of geomorphic landforms and Quaternary sediments in Estonia. Among the most conspicuous glacial and coastal features are peat bogs, moraines, eskers, and sand dunes. Additional data and different techniques of scene classifications would be necessary to provide better techniques of image processing and classification to separate the Quaternary sediment and geomorphic features. To summarize, Landsat thematic mapper (TM) imagery, in combination with existing ground-based observations and geological and peat maps, provides for improved interpretation of regional geomorphology in western Estonia.

Chapter 6

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