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Changes of plant cover and land use types (1950's to 1980's) in three mire reserves and their neighbourhood in Estonia

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Abstract

The dynamics of plant cover and land use types in three study areas – Keava (1192.05 ha), Meenikonna (15 13.35 ha) and Natsi-Vdlla (888.61 ha) mire landscapes, each divided into natural (N) and anthropogenous (A) subareas, was investigated by repeated aerial photo (black-and-white panchromatic, 1:10,000) interpretation. Nineteen plant cover and land use (PC&LU) types were differentiated and three contour maps were drawn for each study area (corresponding to 1950's, 1960's and 1980's).

The dynamics of mire landscapes were modelled by transition matrices $P = [p_{ij}]$, which contain the transition probabilities between i-th and j-th PC&LU types during the time interval between the aerial photographs. A total of 12 transition matrices were constructed.

In A-subareas peat milling was started in the middle of the 60's whereas N-subareas acquired mire reserve status in 1981, which is manifested in a different development. 93% of N-subarea and 69% of the A-subarea remained unchanged from the 50's to the 80's. The increase of anthropogenous land use types in A-subareas of Keava, Meenikonna and Nätsi-Võlla were respectively 0.84%, 0.32% and 1.17% per year.

Two different matrices (I and II period) were used to predict the future state of the study areas. The applicability of the transition matrix model has been discussed by comparing matrices of different base periods. Errors arising from photointerpretation, contour input, (transition) area measurement, matrix reduction etc. are evaluated.

1. Introduction

Estonia is rich in mires – they cover about 22% of its territory (45,216 km^2) and serve as an important ecological stabilizing factor of our landscapes. The natural succession of Estonian mire plant communities on a 'centuries' scale has been investigated by using stratigraphical data and modelled by the transition matrix approach (Aaviksoo *et al.* 1984). Under current conditions, when human influence brings about big changes in natural ecosystems, it is necessary to follow the main trends over shorter time periods.

This paper focuses on the anthropogenous changes in mire landscapes, based on clearly distinguishable spatial and temporal units. The availability of aerial photos determined the time span of investigation – the oldest photos date back to 1947. This time limitation allows one to register predominantly man-generated changes.

The selection of the study areas proceeded from the following provisions: 1) the availability of *three* sets of successive aerial photographs, and 2) they had to embrace two approximately equal parts –

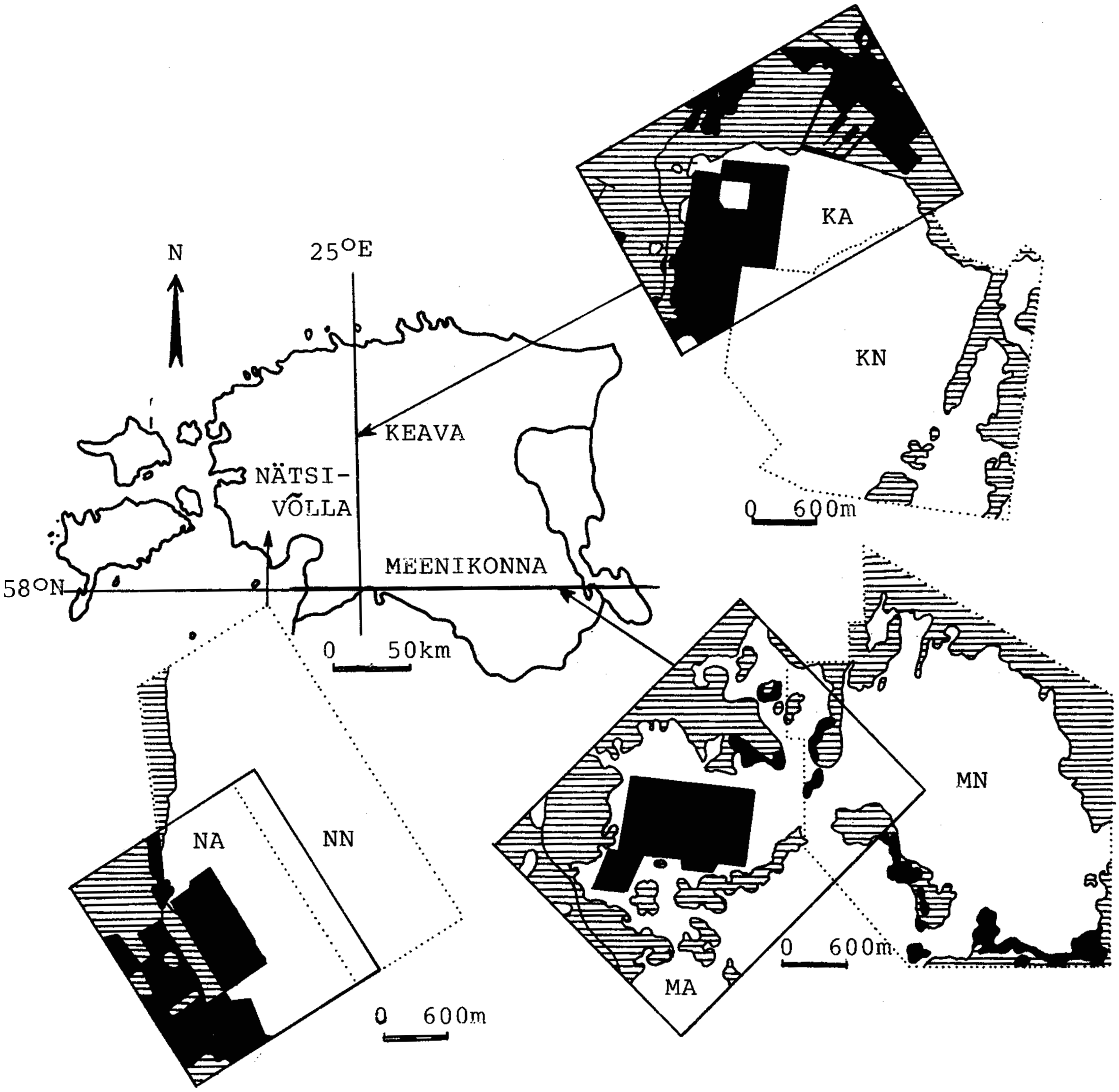

Fig. 1. Location map of the study areas: Keava, Meenikonna and Natsi-Vdlla mire landscapes. Borders: .....natural (N) and —— anthropogenous **(A)** parts (80's). Cover types: ☐ natural, ▤ semi-natural, ■ anthropogenous.

natural (N) and anthropogenous **(A).** Hence, the study areas dominated by mires consisted of two interdependent subsystems, and were termed *mire landscapes – i.e. territories, where genetic mire types in all their stages* ***of*** *development and utilization (including mire islets and* ***pools)*** *are represented together with surrounding areas contiguous to mire and largely influenced by mire.* The underlying interrelations are mainly induced by natural and anthropogenous changes in the hydrological regime and may be followed by a unifying quantitative model.

Several papers have investigated landscapes dynamics on the basis of repetitive aerial photographs or satellite imagery: 1) wetlands (Wynn and Kiefer 1978; Petersen 1980; Larson *et al.* 1980; Vinogradov and Konstantinov 1981; Larson and Golet 1982; Frayer *et al.* 1983; Vinogradov *et al.* 1984) 2) other types of landscapes involving different LU categories (Svensson 1972; Vinogradov 1979, 1984;

Vinogradov *et al.* 1986, 1987; Darbandi 1982; Barsch and Kaden 1986; Haase and Neumeister 1986; Iverson and Risser 1987; Iverson 1988). Most of them describe the observed changes in a qualitative manner with the emphasis on the mechanisms of plant succession. In the present paper we do not limit ourselves to the investigation of natural succession. Man-generated processes prevail almost everywhere – nearly 80% of the Earth's surface is considered modified (Vinogradov 1981) – and we have tried to develop a uniform approach to follow the changes in hybrid landscape systems where plant cover and land use (PC&LU) types are simultaneously present.

A succession has been defined by F.E. Clements (1916) as 'a sequence of plant communities marked by the change from lower to higher lifeforms'. Changes that take place in natural plant communities as a consequence of human activities and which lead to the formation of new communities, characteristic of given region, can be called *anthropogenous successions* (Mirkin 1984). Man's influence on the vegetation and landscape, *e.g.* through clearings and small fields, can be looked at as a succession of catastrophies, bringing plant successions back to earlier stages (Malmer and Regnell 1986). The vegetation types altered by man in this way are often designated as seminatural.

When changes occur among PC&LU types as a result of direct human interference into an existing landscape pattern by creating permanent LU types (roads, buildings etc.), we call these changes *replacements*.

Given the typological maps, numerical models (Markov chain models) have been developed in a number of papers (Debussche *et al.* 1977, 1987; Feoli and Scoppola 1980; Larson *et al.* 1980; Larson and Golet 1982; Frayer *et al.* 1983; Vinogradov 1984; Vinogradov *et al.* 1984, 1986, 1987; van Dorp *et al.* 1985; van der Maarel *et al.* 1984, 1985; Miles 1987; Aaviksoo 1986, 1988; Aaviksoo and Kadarik, 1989). A great advantage of this approach is that the probabilities of all possible transitions between the types, given as a matrix, permit a direct and unambiguous prediction of the future development of the study area (Debussche *et al.* 1977; Aaviksoo *et al.* 1984; Vinogradov *et al.* 1984; Aaviksoo 1988).

2. Study areas

The abundance of mires in Estonia (mean annual temperature 5°C, precipitation 500–700 mm/yr (Climatic Atlas of the Estonian SSR'' (1969)) is determined by the postglacial development of the territory (relatively flat relief with watertight sediments) and the surplus of moisture – nearly 45% of the territory belongs to the areas where precipitation exceeds the amount of evaporation. The location of the three study areas is given in Fig. 1.

The natural (N) subareas, which embrace oligotrophic mires (65%) with mesotrophic (13%) and eutrophic (6%) mire types in the peripheral areas, together with unchanged surrounding territories on mineral ground **(16%)**, constitute a part of the mire reserves, created in Estonia in 1981 (Ranniku 1981). The anthropogenous (A) subareas are situated in the immediate vicinity of the latter, protected territories, and are to a considerable extent influenced by human activities.

The three mire landscapes cover 3,594.01 ha in total. Meenikonna (M) forms 42% (MN – 757.04 ha and MA – 756.31 ha), Keava (K) 33% (KN – 592.05 ha and KA – 600.00 ha) and Natsi-Vblla (N) 25% (NN – 445.10 and NA – 443.51 ha) of the whole. The size of each study area was determined by the size of the peat-milling area, which forms about 12% of each the anthropogenous parts under investigation.

The KEAVA mire is situated on the North-Estonian Plateau, Lower Estonia, flooded once by the Baltic Glacial Lake and the Baltic Sea, and lying on Lower-Silurian limestone bedrock covered by glacial, glaciofluvial and glaciolimnic deposits. Dystric and eutric histosols, gleysols and podzols are common. Oligotrophic mires with a bare centre and widespread hummock ridge complexes prevail. Stunted pines occur in wooded mires. Mesotropic and eutrophic mire types are represented by sedge communities and their wooded relatives (swamps) with birches. Eskers and kames which surround the mire are covered by birch, alder and pine forests. Geobotanically, the Keava mire landscape belongs to the region of boggy forests and raised bogs, open woodlands and grasslands (Laasimer 1965). In **KA** the moraine plains have been used for agriculture

Table 1. Overview of the aerial photomaterial used in the present study.

Study area	Field work time	Time and scale of the aerial photographs		
		I (50's)	II (60's)	III (80's)
Keava (K)	1984,1985,1986	1951,1:17000	1966,1:10000 1968,1:10000	1982,1:10000
Meenikonna (M)	1984,1985	1947,1:8000	1968,1:10000	1980,1:10000
Nätsi-Võlla (N)	1984,1985	1950,1:17000	1966,1:10000	1973,1:10000

(mainly after land improvement) and cattle-breeding. These areas are exploited for timber as well as peat mining (87.5 ha in 1966) and gravel excavation.

The MEENIKONNA study area is situated in the most elevated part of Estonia. It lies on Devonian sandstones, which are covered by Quaternary (sandy clay moraine) and peat deposits, where dystric histosols, gleyic planosols and podzols prevail. Geobotanically this area belongs to the region of pine forests on sandy soils (Laasimer 1965). Bog hollow complexes in oligotrophic and cottongrass complexes in mesotrophic mire types prevail. Wooded mire sites are represented by pine (bog complexes) or pine and birch (mesotrophic mire). On mineral ground pine forests are common, although some patches of the other tree species (birch, fir and alder) occur also. The main economic activity has been forest improvement and silviculture. Since 1969 peat has been mined on 94.6 ha.

The NÄTSI-VÕLLA mire lies in Lower Estonia. Glaciolimnic watertight sediments (among them varved clays) on Devonian sandstone are common and serve as the main reason for paludification. Dystric, eutric histosols, gleysols on Holocene (aqueous) deposits, rendzic leptosols, cambisols and luvisols are represented there. The plant cover of the (N) area – hummock ridge and cotton-grass communities in oligotrophic and mesotrophic mire types respectively and wooded mire types with pine and pine-birch stands – is unaltered and the vegetation types develop undisturbed towards the climax communities. The Nätsi-Võlla mire landscape belongs to the region of meadows, paludified and broadleaved forests (birch, aspen, alder) and open woodlands rich in species (Laasimer 1965). Croplands have replaced earlier fir stands, and peat mining on 48.23 ha has taken place since 1966.

3. Material and methods

3.1. *Material*

The present study uses black-and-white repetitive aerial photographs from three different time periods, which reflect the state of the study areas at the given time and the dates of field work (see Table 1).

In order to increase the reliability of photointerpretation, field data – nearly 200 descriptions of plant cover – were obtained from 4m^2 study plots. Additional materials such as 1) photomaps (as the basis for topographical ones), 1:10,000; 2) published literature, such as general and/or detailed geographical descriptions of the study areas, reports on peat layer borings etc.; 3) soil maps, 1:10,000; 4) forest management maps, 1:10,000 with taxation data; 5) land use maps, 1:10,000; 6) schemes of the mire reserves (1980), 1:25,000; and 7) peat deposit maps, 1:25,000 and 1:100,000, were used to facilitate the interpretation of older photos.

3.2. *Methods*

First, all the photographs were transformed to the same scale (1:10,000). Next, plant cover and land use maps were delineated on the latest (80's) photo overlays. These maps (KN82, KA82, MN80, MA80, NN73 and NA73) were further used as a standard. Other maps (KN51, KA51, KN66, KA66;

Table 2. Legend of the plant cover and land use types.

Class I Natural types	Class II Seminatural types	Class III Anthropogeneous types
A – eutrophic mire	G – grassland and meadow	M – cropland
B – wooded type A	H – shrubland	N – mined peat area
C – mesotrophic mire	I – open woodland	O – abandoned peat mining area
D – wooded type C	J – young forest stand	P – clear-cutting area
E – oligotrophic mire	K – middle-aged forest stand	Q – sand or gravel pit
F – wooded type E	L – mature forest stand	R – farmhouse
		S – road

MN47, MA47, MN68, MA68 and NN50, NA50, NN66, NA66) were derived by a photointerpretation of older photos and using the afore-mentioned auxiliary materials.

Mapping of the PC&LU types was carried out by stereoscopic analysis of the aerial photos. The interpretation key was worked out for natural (virtually unaffected by human influence), semi-natural (slightly or indirectly affected by human activity), and anthropogenous (types featuring strong effects of human activity) transformation classes (see Table 2), proceeding from the field data and aerial photos of the 80's. It was based on the pattern (a combination of tone and texture in the case of natural and semi-natural types), shape and location of the anthropogenous types.

In compiling this legend (Aaviksoo 1988), the classification schemes of several aerial photographic studies (Jeglum and Boissoneau 1975; Zoltai *et al.* 1975; Klemas 1976; Anderson *et al.* 1976; Cowardin *et al.* 1979; Vinogradov 1979; Rafstedt and Andersson 1981; Wastenson 1982; Loelkes *et al.* 1983) were investigated and used as an example as required.

The maps were digitized (0.5 mm step, *i.e.* **5** m field distance) and stored in a computer for data processing.

3.3. The transition matrix (Markov model)

The availability of repetitive maps of LC&LU types allows one to follow the dynamics of the study areas by observing the transitions between the types. Furthermore, a quantitive model, which is known as the transition matrix or Markov model, can be constructed based on these data. This approach has been widely used to follow the dynamics of vegetation (Waggoner and Stephens 1970; Londo 1974; Horn 1976; Debussche *et al.* 1977, 1987; van Hulst 1979; Usher 1979, 1981; Vinogradov *et al.* 1984, 1987; Feoli and Scoppola 1980; Larson and Golet 1982; Heusden 1983; Frayer *et al.* 1983; Tallis 1983; Hobbs and Legg 1984; van Dorp *et al.* 1985; van der Maarel *et al.* 1985; Miles *et al.* 1985; Aaviksoo *et al.* 1984; Aaviksoo 1986, 1988).

The transition matrix model assumes that changes depend only on the initial state and not on the previous (historical) states (first order Markov model which prevails in ecological treatment (Usher 1987)). In order to construct the transition matrix, we need to calculate the total area of these regions where a change of type i into type j is observed. The set of all possible transitions $i \rightarrow j$, divided by the total area of type i in the initial state, constitutes the probability p_{ij} of the changing type i into type j over the time period separating the two maps. The area set of the PC&LU types at a given moment gives one the corresponding state vector.

A stationary Markov chain is completely determined when 1) the finite number of states (PC&LU types), 2) the matrix $P = [p_{ij}]$ as a stationary one-step transition probability matrix between the types and 3) the initial state vector have been given (Turner 1976). In other words, if these three presumptions have been given we can determine the future development of the system simply by multiplying the state vector at a given moment by the transition matrix $[p_{ij}]$, which yields the new state vector.

Table 3. Transition matrix of the anthropogenous part of the Keava study area (KA6682; state vector V_{66} and V_{82} components are in ha, transition probabilities in %, italics is used to denote transition probabilities introduced deliberately to predict future development).

	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	66	82
C	87	13																25	23
D	8	89		1						2								23	24
E			58	1								37	4					134	85
F				20	78								2					32	30
G					27	3		2			66					2		54	18
H					1	38	1	7	**8**	4	39			2				14	10
I					8	2	3	7	62	5	13							27	1
J						2		55	34	4	4			1				55	59
K						2		3	41	42	3			2		1		85	83
L								26	4	53				16	1			63	73
M							2				94				4			13	62
N												91	9					31	78
O				13									87					24	30
P						1		56	23					20				13	15
Q								***40***							60			–	1
R											31					69		2	3
S																	100	5	5

3.4. Construction of the probability matrix

As mentioned above, a maximum of 19 PC&LU types were differentiated on maps. The areal sums of each type constitute the corresponding state vector: KN51, KN66, KN82, KA51 etc. To follow the changes between subsequent maps, the maps were overlaid and two matrices – from the 50's to the 60's (I period) and from the 60's to the 80's (II period) were constructed. For example, the overlaid maps of 1966 and 1982 of the KA study area give us the transition matrix KA6682 (see Table *3)* which reflect changes during the second period of investigation.

The computation of the state vectors and transition matrix elements was automatized. That is, all typological maps were digitized by using a graphic tablet with a 0.5 mm step and stored in a computer. Programs to handle the bit-map information and calculate the corresponding areas were compiled. By super-imposing two consecutive maps in the computer and calculating the areas of all transitions between PC&LU types the corresponding transition matrices were compiled together with the state vectors (Aaviksoo 1986).

Altogether the following 12 transition matrices evolved: KN5166, KA5166, KN6682, KA6682 (Keava), MN4768, MA4768, MN6880, MA6880 (Meenikonna), NN5066, NA5066, NN6673, NA6673 (Nätsi-Võlla), where the digits indicate the times of the corresponding initial and final states. In order to compare the photointerpretation accuracy and check the applicability of the first order Markov model, three additional transition matrices were compiled: KN5168, KN5182 and KA5182.

4. Extrapolations of the development and discussion

4.1. General changes of the study area

The general trends of mire landscape (including both subareas) – changes are depicted in Fig. 2, where the areas under different PC&LU types are summarized.

Three common trends are evident:

1) in natural types A ... F (Class **I**, abbreviations see Table 2) a decrease of treeless types and an increase of wooded types (A – B, C – D and **E** – F) took place;

2) seminatural types G ... L underwent the greatest changes: afforestation and cultivation, mainly on account of types G, H and especially I,

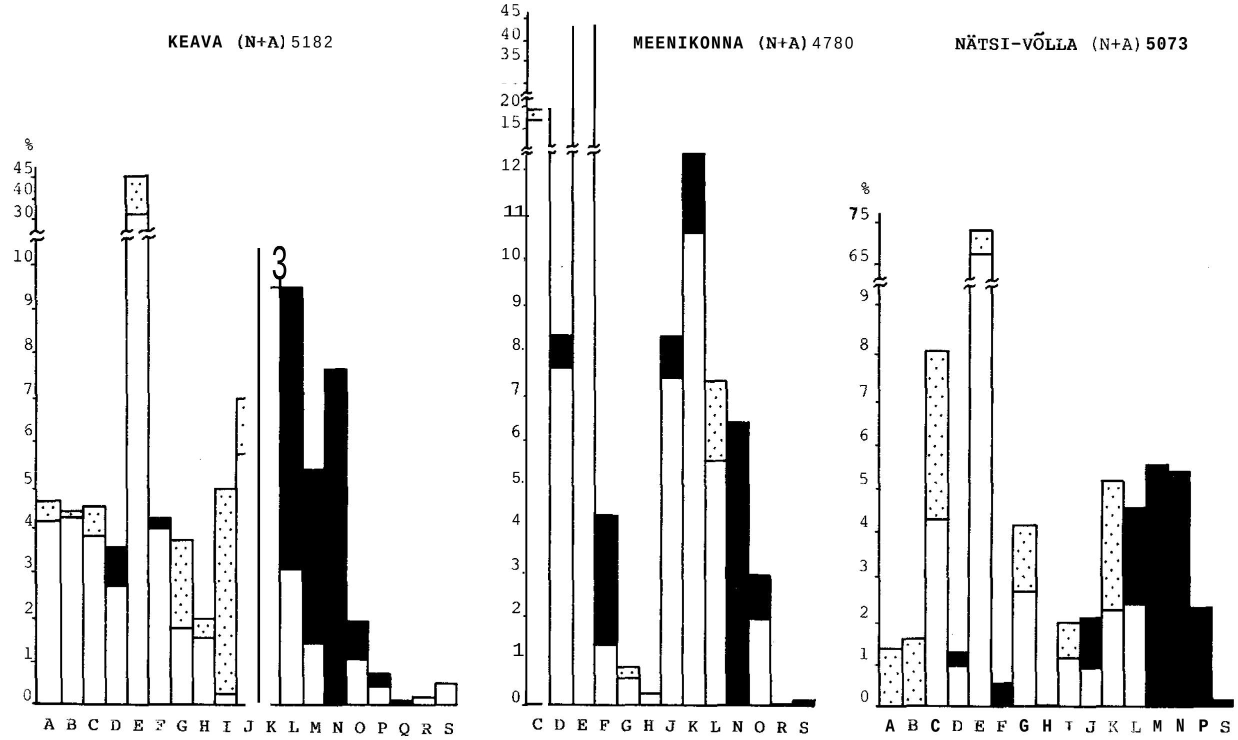

Fig. **2.** Percentage of different PC & LU types in the study areas, from the **50's** to the 80's. 1 – unchanged, **2** – decreasing, and **3** – increasing types. Cover types as in Fig. 1.

dominate. The forest types evolve consistently in a cycle J – K – L – P – J;

3) anthropogenous types M ... S have a tendency to expand, especially types M, N and P.

4.2. *The dynamics of natural parts*

In the natural areas six natural, six seminatural, and two anthropogenous (croplands, clear-cutting areas) PC&LU types appear. In the following we take into account these types, whose area is more than 1% of the total and transition probability is greater than 10% (Table 4 and Fig. 3) (the graphic presentation follows van Dorp *et al.* (1985)).

The stability of the Keava mire reserve, expressed by the weighted probability of autotransformation (static stability S_s, determined by the percentage of unchanged area), was 87% in I and **94%** in II period, which results from the great share of mire types (88%). In seminatural types, maturing of the forest stand is the main change. Open woodlands disappear and turn into forest types.

In the Meenikonna mire reserve the share of mire types is smaller – 76%, likewise the values of S_s – 89% (I) and 88% (II period). The characteristic trend here is widening of forest types (K) on account of drained transitional mire forests D and young forest stands J. Forest develops in the cycle J – K – L – P – J. The widening of clear-cutting areas on account of L and K can be observed.

The most stable is the Nätsi-Võlla mire reserve, where the share of natural (94%) and seminatural types ***(6%)*** has not changed during 23 years (S_s = 99%) and the observed transitions reflect natural changes.

The stability of all the types in natural parts (mire reserves) is rather high. Oligotrophic mires and wooded oligotrophic mires proved to be the most stable (99%) types. Nevertheless, some transitions with frequencies higher than 50% took place:

Table 4. Area (in ha) of the 14 PC & LU types (for legend see Table 1) in the natural parts of the study areas.

Type	50's			60's			80's		
	KN51	MN47	NN50	KN66	MN68	NN66	KN82	MN80	NN73
A	53.77	–	–	51.41	–	–	49.33	–	–
B	51.21	–	–	52.90	–	–	52.77	–	–
C	25.49	181.6	–	20.86	177.2	–	23.28	167.8	–
D	10.22	27.09	–	16.16	25.05	–	16.14	32.83	–
E	361.3	358.6	417.2	361.6	353.9	416.2	356.5	341.8	415.4
F	17.59	12.14	.20	17.92	16.87	1.14	21.76	28.96	1.97
	519.6	579.5	417.4	520.9	573.0	417.4	519.8	571.4	417.4
G	3.84	5.67	–	1.04	3.16	–	.55	3.16	–
H	3.47	–	–	2.16	.94	–	.01	.94	–
I	5.67	–	–	6.41	–	–	–	–	–
J	25.23	48.34	4.08	3.93	21.01	2.95	7.35	27.82	2.95
K	33.03	64.07	8.69	30.95	82.16	6.12	25.37	72.79	5.23
L	–	58.50	14.92	26.62	64.50	18.62	37.83	49.38	19.51
	71.24	176.5	27.69	71.11	171.7	27.69	72.19	154.0	27.69
M	1.19	–	–	–	–	–	–	–	–
P	–	.95	–	–	12.25	–	–	31.51	–
	1.19	.95	–	–	12.25	–	–	31.51	–

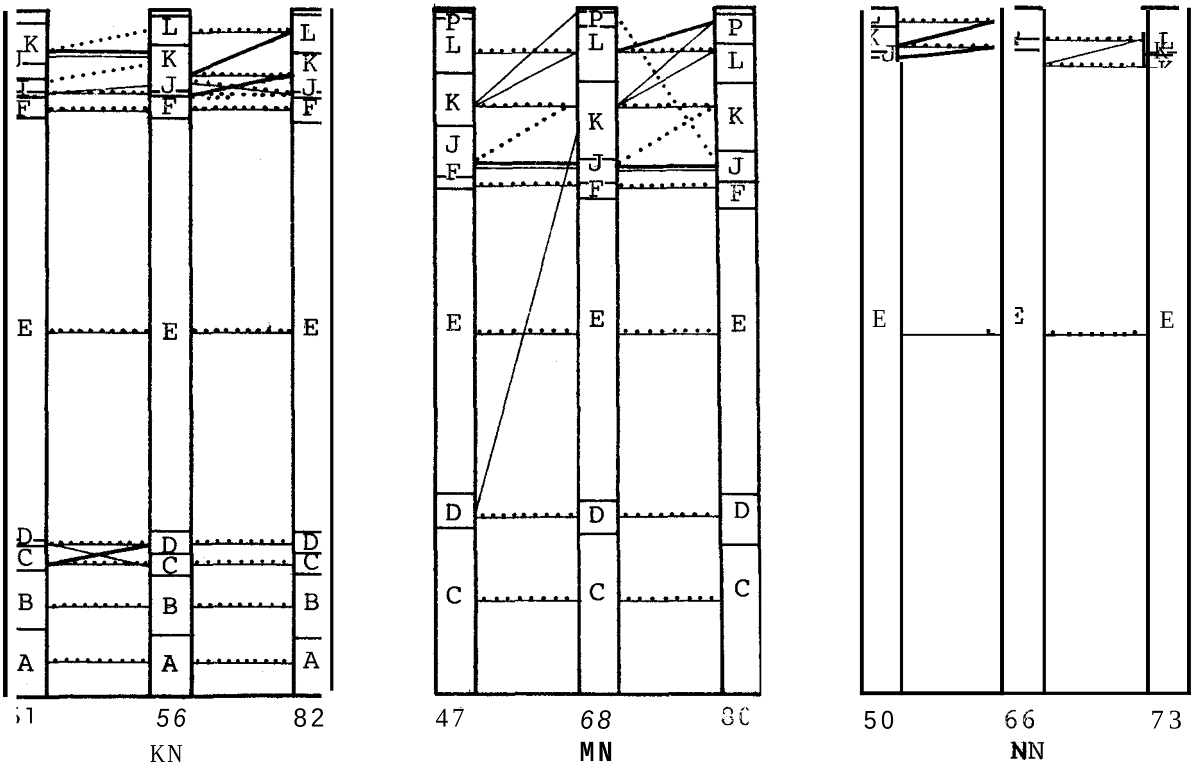

Fig. 3. The transitions between PC & **LU** types in natural parts of the mire landscapes – KN, MN, and NN. Thin lines – 10–24% frequency, solid lines – 25–50%, dotted lines > 50%. Double lines mark 'auto-transformations'.

Table **5.** Area (in ha) of the 19 PC & LU types (for legend see Table 1) in the anthropogenous parts of the study areas.

Type	50's			60's			80's		
	KA51	MA47	NA50	KA66	MA68	NA66	KA82	MA80	NA73
A	–	–	11.33	–	–	–	–	–	–
B	–	–	15.44	–	–	7.84	–	–	–
C	24.87	113.9	71.95	24.68	97.90	39.51	23.06	87.28	37.89
D	24.17	88.36	8.55	22.56	83.12	15.52	24.24	93.44	11.93
E	179.5	300.0	235.0	134.3	200.0	207.6	85.09	180.1	183.7
F	32.44	8.38	.48	32.58	15.30	1.89	29.69	35.22	3.42
	261.0	510.6	342.7	215.4	396.3	272.4	162.0	396.0	237.0
G	38.71	6.29	36.33	54.42	2.94	38.95	18.26	4.59	23.04
H	21.31	–	–	13.60	1.60	1.95	9.99	1.60	4.73
I	54.95	–	17.04	26.70	–	11.06	1.38	–	9.58
J	64.41	63.20	4.19	54.95	55.57	18.26	59.23	98.37	14.91
K	86.81	98.06	36.26	85.39	134.6	28.31	82.69	114.1	14.50
L	36.35	51.29	6.54	63.10	34.28	25.35	73.36	34.46	20.30
	302.5	218.8	100.3	297.0	229.0	123.8	244.9	253.1	87.06
M	12.88	–	.38	13.25	–	.09	61.84	–	49.17
N	–	–	–	31.06	94.60	25.86	77.54	94.60	48.23
O	12.64	–	–	24.43	–	20.05	29.94	–	20.05
P	4.92	26.77	–	12.58	34.64	–	14.96	10.53	–
Q	–	–	–	–	–	–	1.31	–	–
R	1.79	.02	–	1.87	.09	–	2.65	.09	–
S	4.17	–	–	4.50	1.56	1.19	4.77	1.85	2.00
	36.40	26.79	.38	87.51	130.8	47.19	193.0	107.0	119.4

J → K, K → L, and I → K (I period); J → K and P → J (II period).

4.3. The dynamics of anthropogenous parts

All 19 PC&LU types are represented on these territories. The areas (state vectors) are given in Table *5* and the major transitions in Fig. 4.

The analysis of the 6 transition matrixes shows that 3/4 of the transitions are opposite to the natural changes. This is largely due to the drainage of areas surrounding the mires. Therefore, during the first period the following characteristic changes took place: 1) grasslands replaced eutrophic mires after drainage (A → G); 2) the area of the forests (J,K,L) expanded after the drainage of wooded mire types (B → J, K, L); 3) peat mining sites (N) appeared in bogs; 4) clear-cutting areas evolved (besides mature stands even middle-aged stands were cut down); *5)* former clear-cutting areas were afforested, and the forest area also expanded on the account of open woodlands, grasslands and shrublands.

The relative widening of the cropland area was the biggest – it increased by a factor of 67 from the initial (50's) to the final (80's) vector. Cropland began to expand in the II period – mainly at the expense of seminatural types – grasslands, shrublands, open woodlands and even unproductive forests. To a lesser extent, they were formed from eutrophic mires if drainage has preceeded. Other changes during the second period were less expressive: the widening of young forest stands at the expense of clear-cutting areas and wooded mesotrophic mires (P → J, D → J) and widening of mined peat areas (E → N).

S_s of A-subareas KA, MA and NA were 62%, 60% and 73% for period I and 57%, 86% and 77% for period II. As we can see from Table 5, the territory under anthropogenous types increased altogether six-fold during the investigation period, especially at the expense of natural types.

The growth rate of anthropogenous types were:

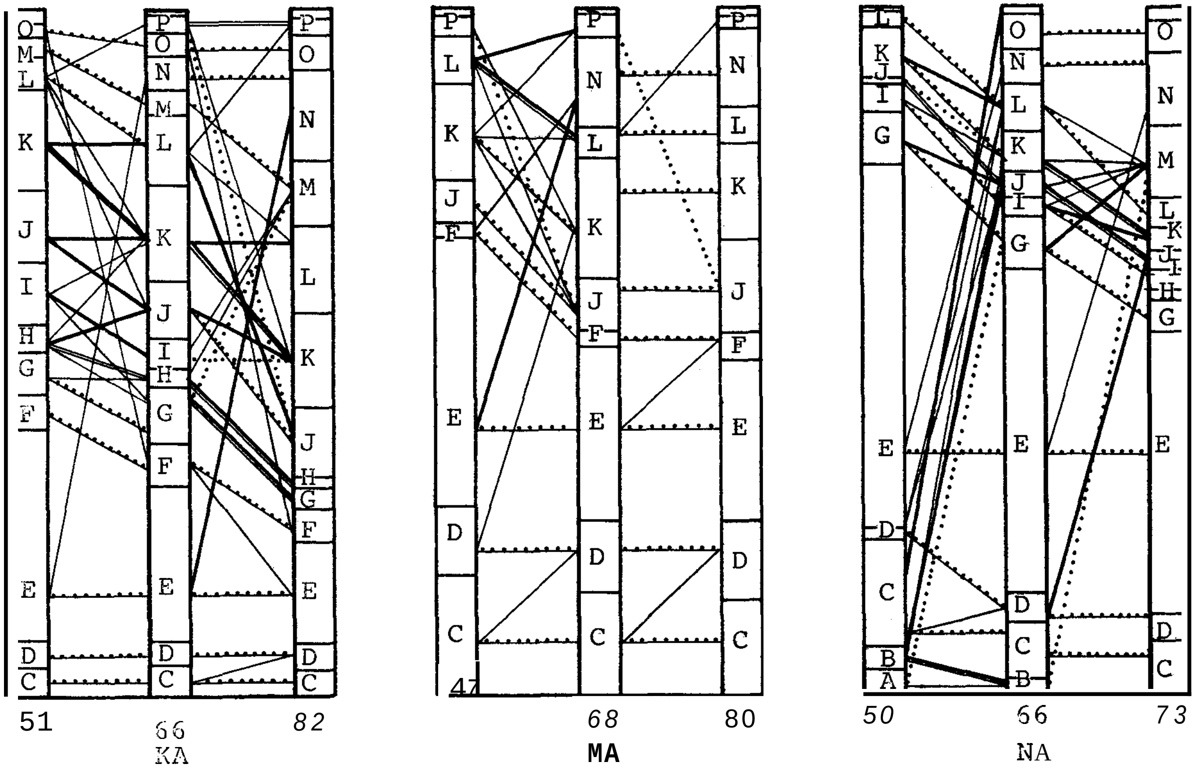

Fig. 4. The transitions between PC & LU in anthropogenous parts of the mire landscapes – **KA, MA** and **NA.** Thin lines – 10–24% frequency, solid lines – 25–50%, dotted lines – > 50%. Double lines mark 'auto-transformations'.

KA – 0.56% per year (I period) and 1.1% per year (II), on the average 0.84% per year; MA – 0.66%, –0.26%, 0.32%; and NA – 0.59%, 2.32% and 1.17% per year. As one can see, the rates differ by a factor of four, that indicates the relative arbitrariness of human activities.

4.4. Predictions

The transition probability matrix can be easily applied to forecast future changes of the system. Its advantage, compared to the linear extrapolation method, lies in the possibility of following all the transitions between the types and in permitting predictions over prolonged periods.

In the following we assume that the I order stationary Markov process is valid, *i.e.*, the changes during the base period will be the same in the future and that they are determined only by the present state of the system. The length of the base period T (the time interval between the initial and final state vectors) was determined by the photomaterials and was, on the average, 15 years.

The matrix model relates the future state vector of the system V_{fut} to the present state vector V_{pres} by multiplying it by the transition matrix M (in matrix notation $V_{fut} = V_{prest+T} = M_T \cdot V_{pres}$). This procedure can be used repeatedly, extending the forecast to distant future states by step T. The most reliable prediction is obtained by the first step while the recommended length of the base period ought to be eight years (Vinogradov, 1984).

In the present paper we made a prediction (separately for N and A parts) to the 90's: V„ = $M_{6682} \cdot V_{82}$ (Keava), $V_{92} = M_{6880} \cdot V_{80}$ (Meenikonna) (in the case of Natsi-Vblla we reached the 90's only after the third step: $V_{94} = M_{6673} \cdot M_{6673} \cdot M_{6673} \cdot V_{73}$). Forecasts were also made for longer intervals (Keava 2014, 2062; Meenikonna – 2016, 2064; Natsi-Vblla – 2015, 2064). We admit, however, that the reliability of these

Table 6. Future development of the anthropogenous study areas. PC & LU types of the state vectors are summarized to the transformation classes and the corresponding percentages are calculated.

Classes	80's			90's			2060's		
	KA	MA	NA	KA	MA	NA	KA	MA	NA
Natural	21	52	53	22	52	56	16	52	53
Average		44			43			40	
Seminatural	41	33	20	37	34	25	33	34	25
Average		31			32			31	
Anthropogenous	32	14	27	41	14	19	51	14	22
Average		24			25			30	

long term predictions may be small – especially for anthropogenous areas – for it is very unprobable that for such a long period 'the law of development and replacement' remains the same. In N-subareas the predictions may, still, rather adequately characterize the development because these areas acquired mire reserve status in 1981, which has prevented economic activity there (we made, accordingly, some correlations in the matrixes before the prediction procedure – such changes as excavation of new ditches, widening of the peat mining areas, etc were inhibited).

In N-subareas the predictions show that natural successions prevail, man-generated trends (mire – wooded mire, wooded mire – forest types on drained ground) will continue and may be interpreted as the result of drainage on adjacent territories. These trends together with putting an end to the clear-cutting will lead to the widening of the total forest area.

In A-subareas the greatest changes occur in Keava (KA). In 80 years (from 80's to 60's of the next century) natural and seminatural types decrease by 11% and 8%, adding 19% to anthropogenous types (see Table 6). Meenikonna (MA) and Nätsi-Võlla (NA) are more stable, indicating that the present PC&LU types are well balanced on the transformation class level.

We estimated the reliability of the predictions (and the transition matrix model in general) by constructing the future states proceeding from different transition matrices and initial states of the same study area. The Keava study area was taken as an example and three different forecasts were made based on: I) the matrix of the 31 year period, KN5182 and KA5182; II) the matrix of the short (16 year) period, KN6682 and KA6682, and III) the averaged matrix, KN5166 + KN6682 and KA5166 + KA6682 (see Table 7). As we can see, the discrepancies between different predictions are on the level of 1% (with respect to the total study area), whereas the changes themselves reach 1.1%. Therefore, we may conclude that the forecast is not sensitive to the actual matrix constructed or its base period T and, in a general case, any of the available matrices may be used.

For a further analysis of the matrix model we have compared the matrix and linear predictions with the real state vector of the Keava N-subarea (see Table 8). The comparison of the data convinces us that the matrix model gives better results (in 9 cases out of 13) than the simple linear extrapolation. Furthermore, the linear description even yields negative results (negative area values).

5. Analysis of the transition matrix model

5.1. Photointerpretation and computing errors

To increase the reliability of the matrix model, we have analysed possible errors arising from 1) the interpretation of aerial photographs; 2) the computerized map processing.

Interpretation errors were estimated by independent interpretation of the photos from 1966 and 1968 of the Keava mire reserve and comparing the corresponding state vectors. Due to the great share of natural and seminatural types we may neglect the changes of these territories during the 2 years. The

Table 7. Forecast of the state of the Keava study area in the year 2013–2014 on the basis of different transition matrices (I, II and III).

Types	Natural part			Anthropogenous part		
	I	II	III	I	II	III
A	44,06	45.44	46.87			
B	46.85	52.28	52.12	–	–	–
C	20.60	27.03	22.75	18.65	20.77	22.43
D	23.50	16.55	18.17	25.28	26.40	23.34
E	356.49	346.97	354.44	42.31	38.16	43.59
F	24.17	29.17	23.86	30.26	27.25	29.95
G	–	.15	.21	5.6	3.37	14.41
H	1.89		1.10	11.94	5.65	5.84
I	–	.03	.65	2.36	1.41	2.17
J	.85	4.32	3.26	73.63	67.81	62.17
K	7.72	17.14	17.58	61.39	61.70	67.06
L	64.28	52.66	51.06	68.01	71.09	75.99
M	–	–	–	82.61	87.70	76.28
N				119.72	112.62	100.41
O	–	–	–	31.44	43.52	46.51
P	–	–	–	11.98	17.44	18.22
Q	–	–	–	5.55	5.87	3.03
R		–	–	2.47	2.35	2.57
S	–	–	–	5.08	6.90	6.02

Table 8. Comparison the linear and matrix prognosis and the actual state vector of the Keava study area (natural part).

Types	KN51	KN66	Prognosis for 1981		Actual state
			matrix	linear	**KN82**
A	53.77	50.86	47.87	47.95	49.33
B	51.21	52.90	52.97	51.21	52.77
C	25.49	21.23	18.80	16.97	23.28
D	10.22	15.62	19.05	21.02	16.14
E	361.34	361.8	362.1	362.2	356.5
F	17.59	18.32	19.00	19.05	21.77
G	3.84	1.06	.27	– 1.72	.55
H	3.47	2.16	1.95	.85	.01
I	6.67	6.41	5.06	7.15	1.08
J	25.23	4.02	2.40	– 17.19	7.35
K	33.03	30.74	13.44	28.45	25.37
L	–	26.93	49.14	53.86	37.83
M	1.19		–	– 1.19	–

comparison of the results showed that the interpretation errors were less than 3% (difference divided by the area of the type) in the case of large types (areas > 10 ha). For small types (< 10 ha) the interpretation error reached 80% in case the whole area of the type was formed as a sum of several very small sites which were not interpreted correctly.

The computing errors due to bit-map rounding errors and border line handling were checked by comparing the computed areas in different ways. Differences between areas which were calculated as a sum of several transition areas and areas of state vectors obtained from maps, did not exceed 1 ha or less than 2% of each type.

5.2. The applicability of the matrix model

The existence of three successive sets of photographs enables one to study the applicability of the matrix model. Using the transition matrix of the first period and the intermediate state vector (60's) we predicted the state vector of the 80's, which was then compared with the real value of the state vector. The differences in the base periods I and II could be eliminated by a linear reduction of the transition matrix. This procedure lies in a T_{II}/T_{I} decrease of nondiagonal elements and a corresponding increase of the diagonal ones (the systematic error of this linearized reduction does not exceed 0.1%).

The reliability of the prediction (R) was evaluated by the relative error, given as the ratio of the sum of the differences between the elements predicted and the real state vector elements to the total area of the territory examined using the following formula

$$R = \frac{1}{S} \sum_{i=1}^{N} |a_p(i) - a_r(i)|,$$

where $a_p(i)$ are the elements of the predicted state vector, $a_r(i)$ are the elements of the real state vector, N is the number of types and S is the total area. R was computed for all the three study areas and for both N and A parts.

We conclude that the matrix model satisfactorily describes the dynamics of the mire landscapes and is especially useful in the case of the natural subareas of the territory because the average error in the prediction over 10-15 years was only about 6% (8.4% for KN5166, 11.2% for MN4768 and 0.4% for NN5066). We recall that the latter matrix comprises only natural types.

The relatively large error $e = 28.3\%$ for the anthropogenous parts (28.9% for KA5166, 23.9% for MA4768 and 32.2% for NA5066) indicates great differences in the land management in these periods. These differences are also present in the transition matrixes themselves (not displayed here to save text space). New types of LU such as gravel pits and mined peat areas arose mainly in period II and related contours such as roads and buildings expanded; the field area increased enormously. The nonstationary nature of this development affects the adequacy of the matrix in this case. For these reasons period II, when the extensive land use reached a balanced state, may be a better basis for predicting future development.

This checking shows that a relatively long base period (15 years on the average) may be used to predict the development of the natural territories where autogenic successions predominate. In order to predict anthropogenic changes, one should take shorter periods which follow all the stages of allogenic successions and/or manmade replacements. Using the present data, only a satisfactory prediction may be obtained in the case of anthropogenous territories.

6. Conclusions

The present study may be summarized as follows:

1. The dynamics of mire landscapes classified into 19 plant cover and land use types is followed by using large-scale (1:10,000) repetitive aerial photos available since the 50's.

2. The observed changes may be modelled by the I order Markov model; its applicability is checked by comparing predictions based on this model with real data (facilitated by ***three*** successive photographs of the same study area). The results allow us to state that the Markov model is a good approximation when natural changes prevail (relative errors 1–10%) whereas anthropogenous changes are less predicatable (relative errors up to 30%). We established a clearly better prediction based on Markov approach as compared to linear extrapolation.

3. The analysis of possible error sources in compiling the transition enables us to draw the following conclusions: a) the digitization step of 0.5 mm (5 m in nature) is sufficient and yields a digitization error of less than 1%; b) rounding errors and borderline interpretation ambiguities were less than 2%;

4. A more general classification scheme consisting of three classes (natural, seminatural and anthropogenous) has been used and applied for predicting future development. This approach gave

higher reliability (Markov model applicability) compared to the full model of 19 types.

5. The inclusion of anthropogenous subareas (and corresponding PC&LU types) into the study area formed hybrid systems where ecological succession could be followed. The main trends in this succession are derived from the following influence: drainage, widening of agricultural and sylvicultural lands and peat mining resulting in transitions: mire → meadow and grassland; grassland, shrubland and open woodland (even unproductive forest types) → cropland; wooded mire types → forest types. Forests have their own cycle: young → middle-aged → mature forest stand → clear-cutting → young forest stand.

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