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ON THE METHODOLOGY OF COMPLEX GEOECOLOGICAL STUDIES

Abstract. To study human impact on natural systems different approaches like monitoring, test areas, microcosms, etc. can be used. However, in case of complicated or mosaic geosystems paleogeographical reconstructions may prove much more effective. Using geochemical, paleobotanical and lithological methods for reconstructing the interrelationships between the development of geosystems and external factors, attention was focused on the description of the states of natural systems and environmental conditions at certain reference times. As an example the Kurtna kame field (NE Estonia) was chosen and the interrelationships between the external factors and the state of natural systems were characterized for reference times 8000, 5000, and 3000 B. P. (±500 yr.). Special attention was paid to changes due to the intensive human impact during the last 30 years.

Key words: geosystem, development, human impact, paleogeographical reconstructions, mire and lake deposits, paleoecology, paleomonitoring.

Introduction

In recent decades, constant increase in the human impact on natural systems has stimulated the elaboration of methods and approaches that would enable to estimate the direct consequences of human activities in natural systems and to compile a prognosis of the deviations which may occur in cases of different loads. Considering the multitude of causal relationships and their transformations, it is, at least nowadays, not possible to characterize numerically the dynamics of ecosystems as functional units. However, advances have been made in applying various methods of modelling.

In both cases we deal with an "experiment", where, in order to describe the changes in a natural system (geosystem) under different external influences, the system studied is subjected to the effect of factors in different ways and with different intensities. The most widely used type of analogous modelling is the method of test areas. The main idea here is to study the state of ecosystems, as similar as possible in their natural preconditions and development, in areas subject to different human impacts. Of course, the reliability of the results achieved applying this method is determined by the natural identity of the objects compared and the similarity of their natural conditions. Monitoring data are usually sufficient to carry out analogous modelling and the results may successfully be used in practice on regional and local levels. Preconditions necessary for making more profound scientific conclusions on the level of systems ecology are usually difficult to furnish.

Scientifically more reliable conclusions may be arrived at by numerical modelling based on the study of the dynamics of a system and on ascer-

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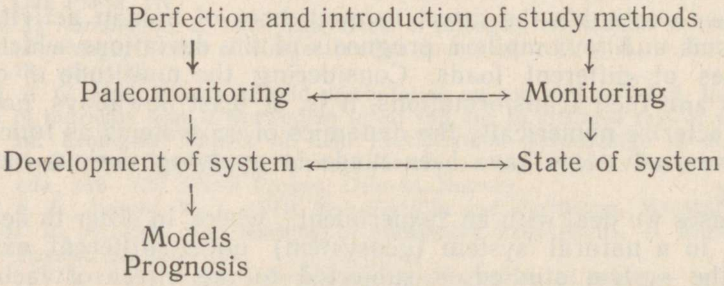
taining the functional causal relationships. To obtain fast results it is necessary to change external factors and to measure the changes of the parameters characterizing the system. Laboratory experiments to assess certain relationships are not sufficient here, as they simplify the composition and structure of a system to the degree which excludes the transition of the results to a natural system. So the possibilities of a direct experiment are rather limited in nature as they neglect the catastrophic consequences of human influence. In the first approximation it is possible to study the dynamics of ecosystems by the so-called method of microcosms, where a certain part of the system is isolated from the whole and attempts are made to influence it in certain ways. It must be mentioned that this approach is rather promising in studying the influence of the changes in matter cycle and energy flow on the physiological state of organisms and also on processes in relatively homogeneous (water) environment. The method of microcosms is probably not applicable in investigating the dynamics of more complicated or mosaic geosystems. In this case one of the few serviceable methods is that of paleoecological reconstructions. It is based on determining changes in the state of an ecosystem under the influence of varying external conditions. Choosing for reconstructions time intervals of greatly differing natural conditions (temperature, precipitation and hydrological regime, atmospheric transfer processes, etc.), connections may be found between the external factors and the state of the system. This, in turn, serves as a basis for creating models predicting development. However, comparing the present state of a system with that in a period with analogous environmental conditions, we can give a rather objective estimation of human impact on the state of one or another system or landscape component. These reconstructions can be used to predict the dynamics of environment for different scenarios of natural resources exploitation. The following scheme is used in studying the dynamics of natural systems by numerical modelling:



Methods and Objects

As shown above, a complex of methods is needed to predict the development of geosystems by a paleoecological approach. The methods used must secure reliable paleogeographical reconstructions for certain time intervals, on the one hand, and give sufficiently trustworthy data characterizing the state of the studied system in a definite time interval, on the other hand.

A number of methods have been elaborated for performing paleogeographical reconstructions (Handbook..., 1986; Пуннинг, Раукас, 1983). As all kinds of reconstructions are based on the study of paleogeographical evidence (mire and lake deposits, glacier ice, subfossil faunistic or floristic material, etc.), the first problem is to fix the age of the studied material. There are numerous dating methods, based either on the regularities of radioactive decomposition (^{14}C, ^{210}Pb), the distribution process of chemical elements and their stable isotopes ($\delta^{18}O$, $\delta^{13}C$, Ca/Mg), the biological development process of organisms (dendrochronology, lichenometry, constant peat density), or the regularities in the reaction of communities to the changes of climatic conditions (pollen, carpological and diatom analysis, etc.). As all of these methods have their limits concerning the time scale as well as the peculiarities of objects and natural conditions, it is necessary to use them in complex to obtain reliable results (Пуннинг, 1987).

To reconstruct paleoclimatic conditions, pollen analysis has been widely used. The main problem here is the interpretation of the results, first of all the delimitation of the influence of hierarchic processes (global, regional, local). Here special attention should be paid to the choice of the study object, it also requires knowledge of the main development tendencies of a definite landscape component (Koff, 1990). Analogous problems also crop up when interpreting the results obtained in the isotopic analysis of glacier ice or lake deposits ($\delta^{18}O$, $\delta^{13}C$). The most important external factor among the regional and local factors is the hydrological regime, which can be reconstructed by several paleontological and geomorphological methods. It should be mentioned that in reconstructing the hydrological regime complex regional studies are of special importance, as mechanical transfer of data from neighbouring areas may lead to serious errors. This concerns especially the border areas of the Fennoscandian shield, where the hydrological regime in the Holocene was mainly conditioned by the Scandinavian glacier shield, on the dynamics of which both the regional water regime and the parameters of glacioisostatic uplift depended.

Where matter cycle processes and energy flows are concerned it is necessary also to reconstruct the changes in landscape structure. Here use is made of complex profiles, geomorphological and paleobotanical studies of mires and lakes, which enable to reconstruct the spatial and temporal development of certain landscape elements, as well as to estimate the openness of a landscape in certain time intervals (Ilomets, 1990; Ilomets et al., 1989; Punning, 1989).

Having established the main parameters of external factors and the tendencies of their changes at different hierarchical (global, regional and local) levels, reference times must be selected that would characterize certain crucial points in the development of landscapes. We used for detailed studies the reference times 8000, 5000 and 3500 B. P. (±500 yr.). We proceeded from the following considerations.

8000±500 B. P.: by the end of the Boreal climatic period the glaciogeneous relief had been formed in its main features, the primary invasion of the tree species had come to an end. The reference time 5000±500 B. P. is characterized by the hydrothermic conditions corresponding to the so-called climatic optimum, when the mosaic vegetation and the versatility of ecological conditions reached the culmination. In 3500±500 B. P. the natural conditions were in many respects rather similar to the present ones. Pollen spectra and influx can be compared with the current ones in quantity as well as quality, the water-level of lakes and the spatial and temporal dynamics of mires were close to those of today. So this time interval is a suitable standard in determining background conditions.

Mire and lake deposits are the main source of information in estimating the state of ecosystems in these time intervals. Complex studies were performed on lakes of different nutrient status as well as mires of different development stages. The research methods used can be divided into three big groups — geochemical, paleontological and lithological.

The aim of geochemical studies is, on the one hand, to investigate the relationships between the changes of external conditions and the kinetics of the matter cycle process, to reconstruct the physico-chemical parameters of the system (Eh and pH), to study the possibilities of the appearance of geochemical and biochemical barriers depending on landscape development. On the other hand, the geochemical method enables to reconstruct also the dynamics of landscape development, the peculiarities of atmospheric and hydrospheric transfer processes (Punning, 1989, 1990a). Among the main research methods the most suitable are the destructive methods of analysis (neutron activation analysis), as well as such methods as atom absorption analysis, ion chromatography and spectrometry for determining biogenic elements (N, P, H, C) (Punning, 1989; Punning et al., 1989).

A number of micro- and macropaleontological methods can be used to characterize the biotic component of systems. Here belong pollen analysis, diatom analysis, carpological analysis, macrofossil analysis, etc. These methods make it possible to characterize the biota, which develops and reaches equilibrium in definite geographical and physico-chemical conditions; to find relationships and correlations between communities, their components, and environmental conditions; to estimate the inertia of ecosystems, their survival limits, and the most suitable ecological niches for components of communities.

Lithological methods enable to characterize the peculiarities of the sedimentation process under definite conditions. This process gives a good survey of the productive ability of a system, its destruction and accumulation. The study of sedimentation dynamics and the composition of sediments is especially important in lakes as these processes determine directly the most important parameter in the development of lakes — eutrophication (Rajamäe, Varvas, 1989).

At the final stage of the studies simulation models are created and scenarios of the development of natural systems under different nature exploitation are compiled. As the systems are extremely complicated, models of different levels are needed. For example, while the eutrophication of a lake may be described with the help of the generation or transformation of biogenes using a comparatively simple mathematical model, then the mathematical model of a mosaic geosystem is difficult to compile as well as to use. Instead, models of the development of separate elements or various descriptive schemes are applied.

Below the results obtained in complex paleoecological studies in the Kurtna State Landscape Reserve are presented.

The Development of Ecosystems in the Kurtna State Landscape Reserve Area

As an example, we are going to view the development of ecosystems in the Holocene in the 15-km² (7 km long, 0.5—3.5 km wide) Kurtna kame field situated in the 2—3 km wide meridionally running Vasavere buried valley in NE Estonia (Fig. 1).

In the west the kame field is separated from the undulating morainic plain by the ca 2 km wide paludified Kurtna valley. To the east the field is surrounded by the Puhatu mire system. The buried valley is filled with up to 50 m thick limno- and fluvioglacial deposits represented by medium- and fine-grained sands with a high quartz content and poor carbonates content. As these deposits are characterized by good filtration properties, the kames were not subjected to surface flushing in the Holocene. In the water balance of the kame field, comprising 40 lakes, the transit ground water flow from the morainic plain and surface infiltration participate equally. The kame field is surrounded by mires where the thickness of peat reaches 6—7 m, thus the water level of the lakes situated here has been determined by the increasing mire level (peat accumulation). Most of the lakes are located in the glaciokarstic depressions of the kame field, the others in the paludified Kurtna valley. The shores of almost all the lakes are either partially or totally paludified. The thickness of lake sediments is up to 13 m.

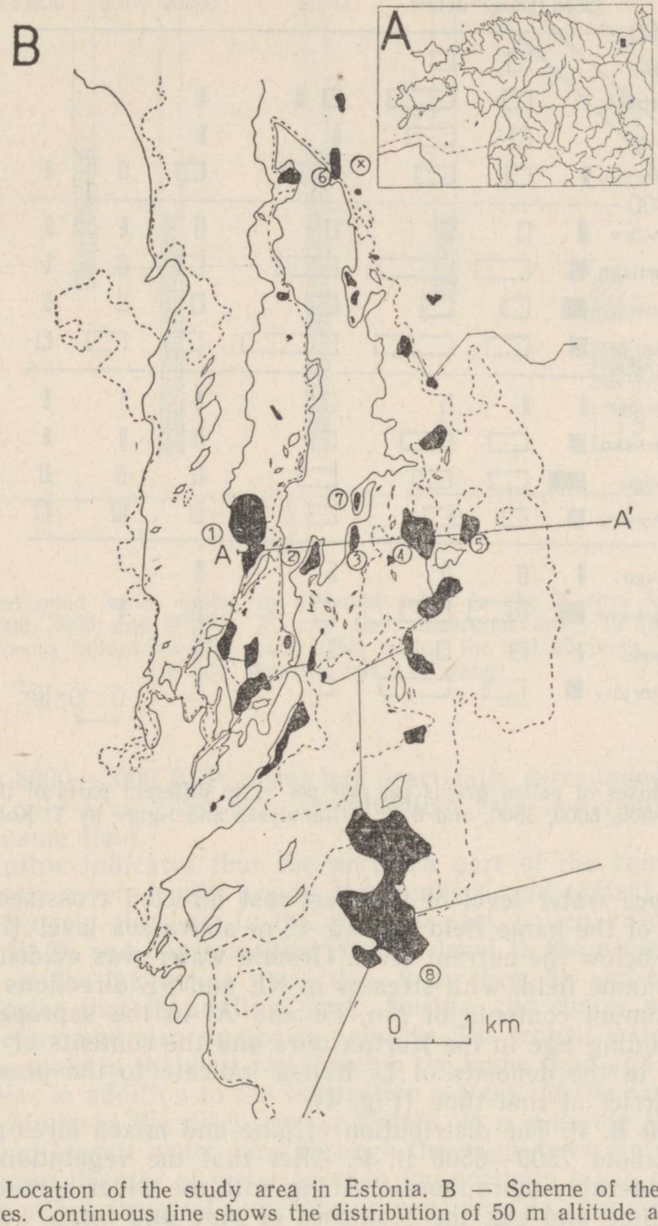


Fig. 1. A — Location of the study area in Estonia. B — Scheme of the Kurtna kame field with lakes. Continuous line shows the distribution of 50 m altitude above sea level, dashed line indicates the distribution limits of mires around the kame field. A—A′ is the transect for studying water table changes (see Fig. 3). x — location of sampling points for elements content in Fig. 4. Lakes: 1 — Kurtna, 2 — Ahnejärv, 3 — Martiska, 4 — Jaala, 5 — Valgejärv, 6 — Liivjärv, 7 — Kuradi, 8 — Konsu.

8000±500 B. P. It is quite probable that by that time the kame field had been formed completely. Although tree species succeeded in spreading and developing in that area, two of them — pine and birch — dominated (Fig. 2). However, the forests were rather scattered and perhaps the uppermost parts of kames were without tree canopy. If in the northern part the influx of *Betula* and *Pinus* pollen appears to have been rather equal, then in the southern and especially the central part, *Betula* predominated. In the present-day paludified depressions, mixed birch-pine forests were spreading.

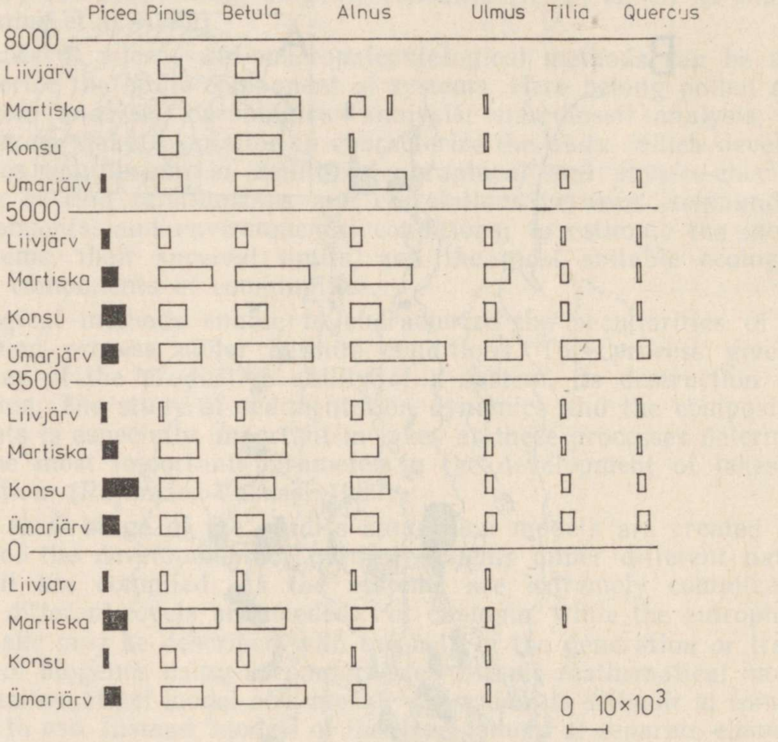


Fig. 2. The influxes of pollen grains per cm² per yr in different parts of the study area for 8000, 5000, 3500, and 0 B. P. (analyses and figure by T. Koff).

The surface water level of the west-east directed cross-section in the central part of the kame field was ca 42 m above sea level (Fig. 3), i. e. up to 5.5 m below the current level. Ground water was evidently flowing through the kame field, with streams in NE and SE directions prevailing.

The maximum contents of Mn, Fe and Al in the sapropel layers of the corresponding age in the Kurtna mire and the contents of Mn, Fe, Ti, Mg and Br in the deposits of L. Konsu indicate to the presence of an oxidizing barrier at that time (Fig. 4).

5000±500 B. P. The distribution of pine and mixed birch-pine forests culminated about 7500—6500 B. P. After that the vegetation started to become considerably more mosaic. Along with the wider spread of spruce, alder, elm, lime and oak the econiches of pine and birch were reduced. The rather quickly formed mosaic vegetation remained stable in the course of several thousands of years, and retrogressive development of these mosaic forests started ca 5000 B. P.

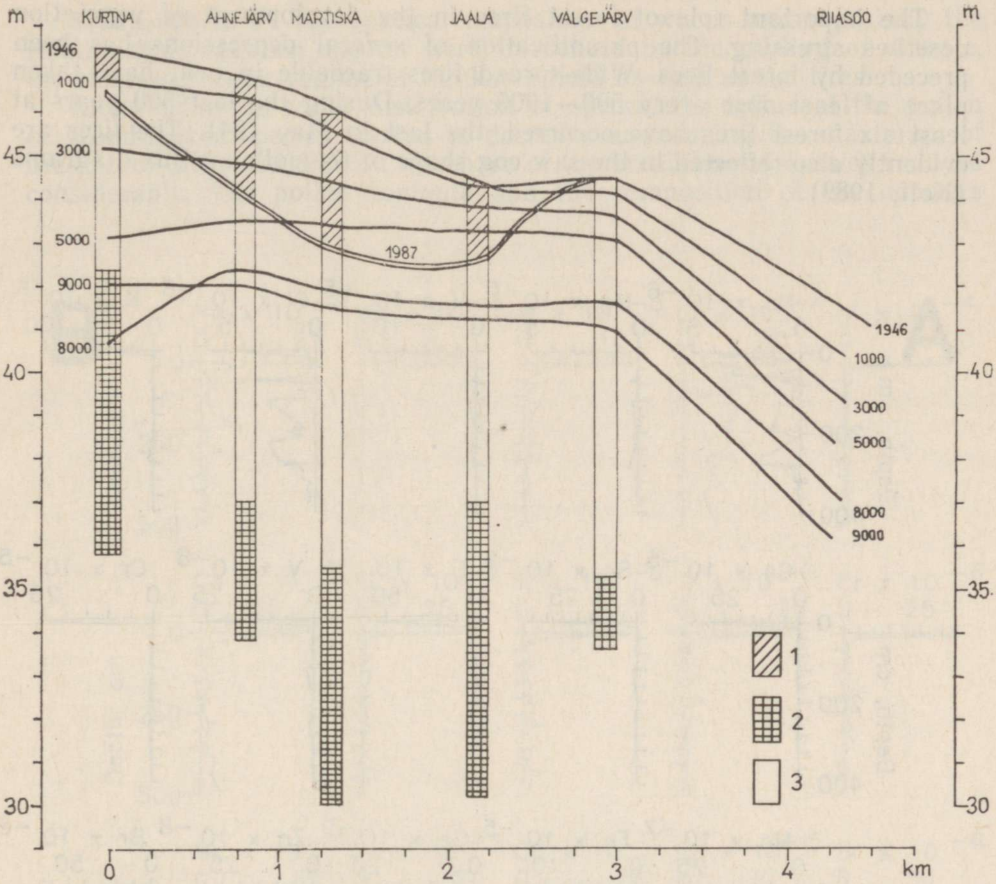


Fig. 3. Reconstructed water tables in different lakes in the Kurtna kame field for 9000, 8000, 5000, 3000, and 1000 B. P. and their measured levels in 1946 and 1987. 1 — technogeneous falldown of the water table during the last 25 years, 2 — thickness of lake deposits, and 3 — water.

Between 8000—5000 B. P. mires had practically surrounded the Kurtna kame field, only a ca 2-km wide unpaludified area had remained in the NE to the kame field.

Pollen influx indicates that the northern part of the kame field was rather sparsely covered with woods, the southern and central parts somewhat more densely (Fig. 2). In the northern part, pollen influx decreased about 5500 B. P. and has remained on that level to the present day. The water level in the lakes rose more than 2 m (Fig. 3) and the observed profile indicates that in addition to L. Kurtna, the shores of L. Kuradi and L. Ahnejärv had also started to paludify. The transit water flow from the morainic plain in the west ran through the kame field and fed the surrounding mire in addition to the infiltration waters. At the same time, the mires have hindered the discharge of waters. It is possible that then the NE-directional transit water flow through the kame field started to dominate, furthering the rise of water level in the northern lakes (Fig. 5).

In the input of chemical elements no considerable changes took place at that time (Fig. 4). The short-time variations of concentrations may have been connected with the development of the mires and lakes themselves.

The important role of forest fires in the development of vegetation deserves stressing. The paludification of several depressions has been preceded by forest fires. Wide-spread fires traceable in peat have taken place at least once every 500—1000 years. During the last 500 years at least six forest fires have occurred, the last in May 1941. The fires are evidently also reflected in the saw cog shape of the pollen influx diagrams (Koff, 1989).

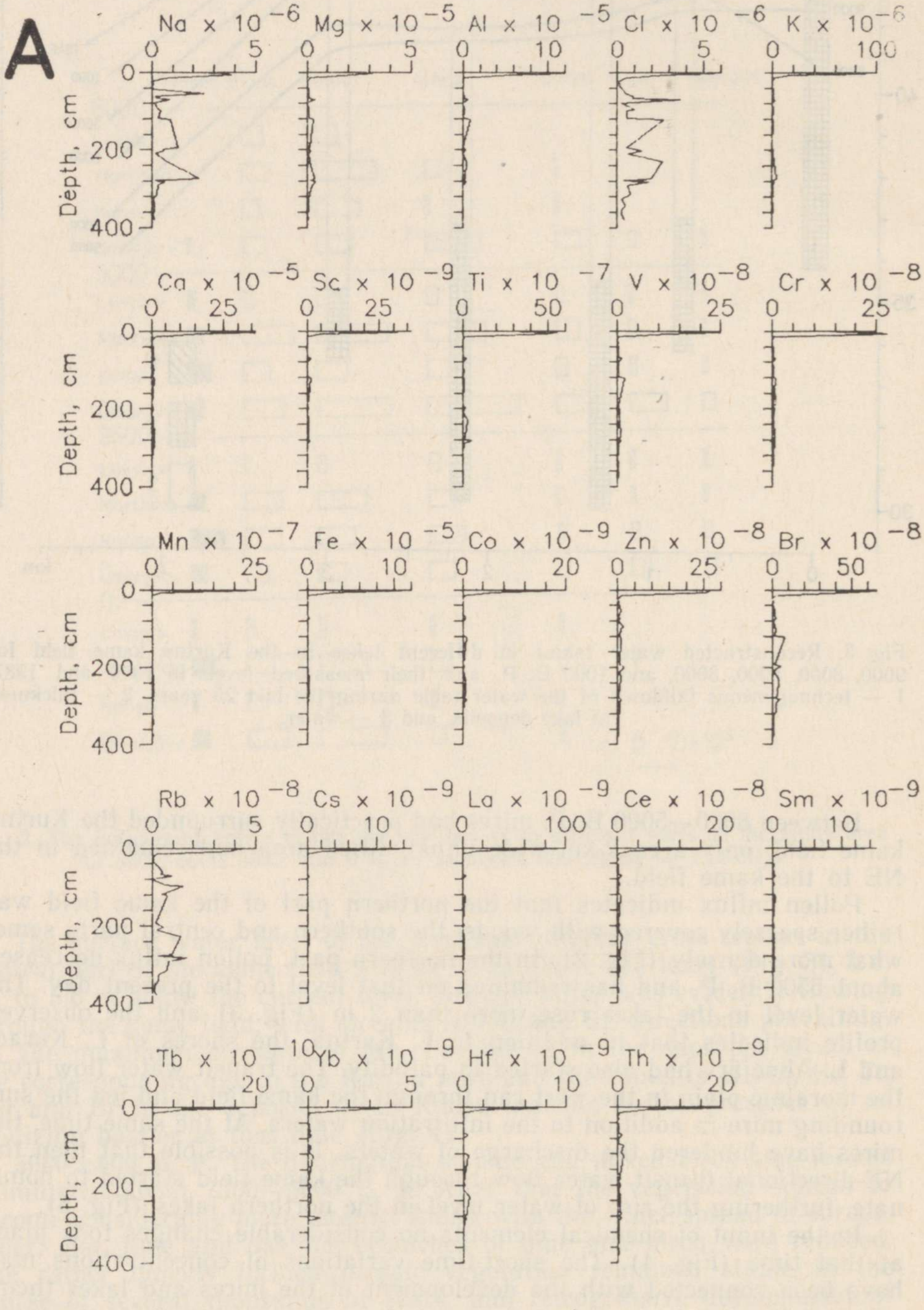


Fig. 4 A. The accumulation of elements $(\mathrm{g} \cdot \mathrm{g}^{-1})$ in the Liivjärve bog.

3500±500 B. P. The species composition of woods and especially the relationships between species were influenced by the cooling of climate, the changing water regime of the kame field as well as the fires.

Along with the wider distribution of spruce, the influx of the pollen of broad-leaved species started to decrease and during the maximum of the spruce 3500—3000 B. P. the share of the broad-leaved species reduced considerably. The pollen contents and the composition of the deposits

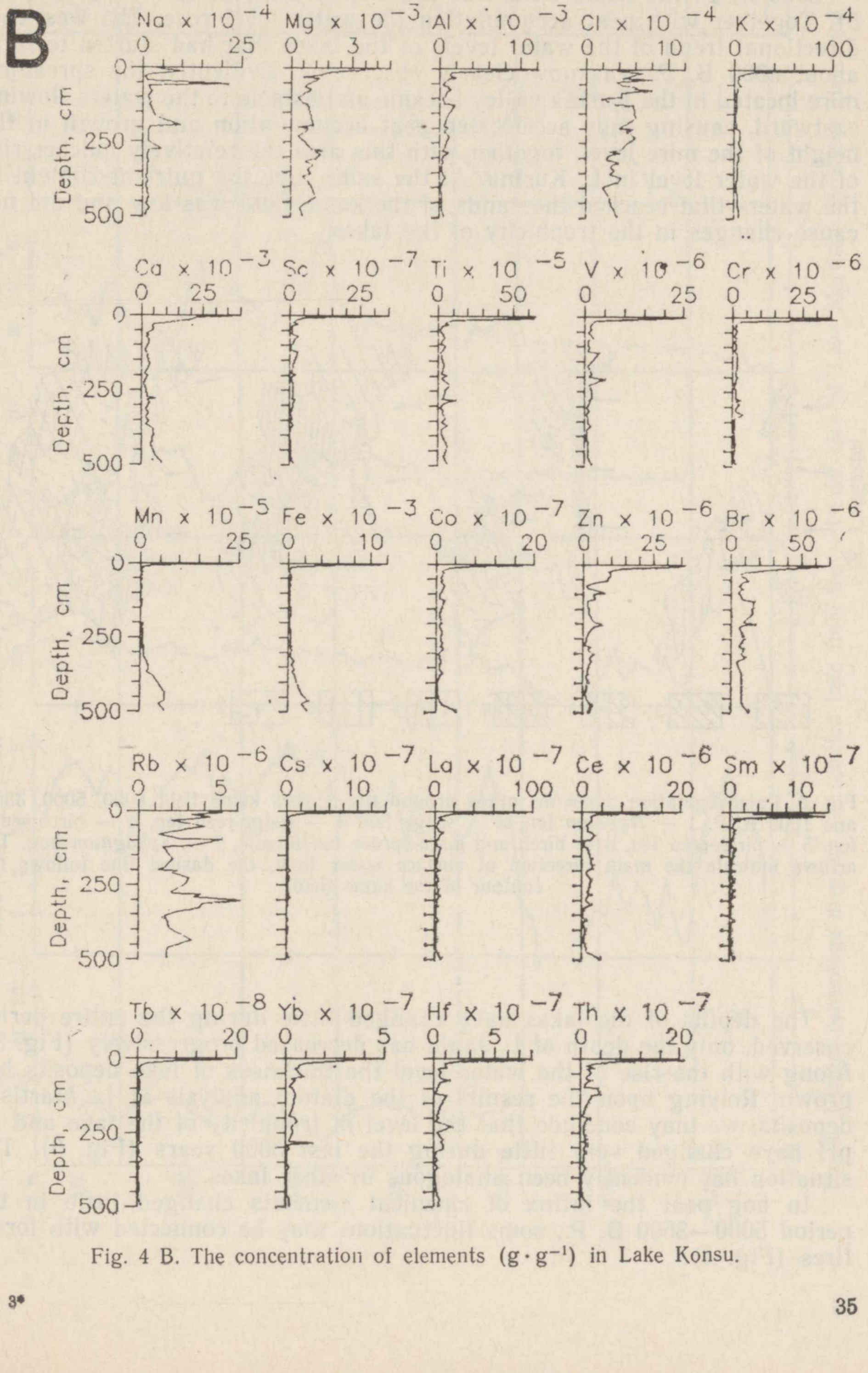


Fig. 4 B. The concentration of elements $(g \cdot g^{-1})$ in Lake Konsu.

formed 3500 B. P. are rather similar to those of the present-day surface layers (Fig. 2). This allows us to use the situation at that time as an analogue of the current natural situation and in this way to compare the technogenic load with the natural background.

The changes in various parts of the kame field were not simultaneous. While in the northern part the pollen influx started to decrease, as mentioned, ca 5—6 thousand years ago evidently due to the intensive expansion of mires, then in the southern part the input fell ca 3500 B. P., and in the central part somewhat later (3000 B. P.).

3500 B. P. the kame field was practically surrounded by mires (Fig. 5). Together with peat accumulation the water level rose. The west-east directional trend of the water levels of the lakes that had started to form about 4000 B. P. was now clearly observable. Evidently, the spreading mire located in the Kurtna valley became an obstacle to the waters flowing eastward, causing thus accelerated peat accumulation and growth in the height of the mire level, together with this also the relatively quicker rise of the water level in L. Kurtna. At the same time the nutrient content of the waters that reached the sands of the kame field was low and did not cause changes in the trophicity of the lakes.

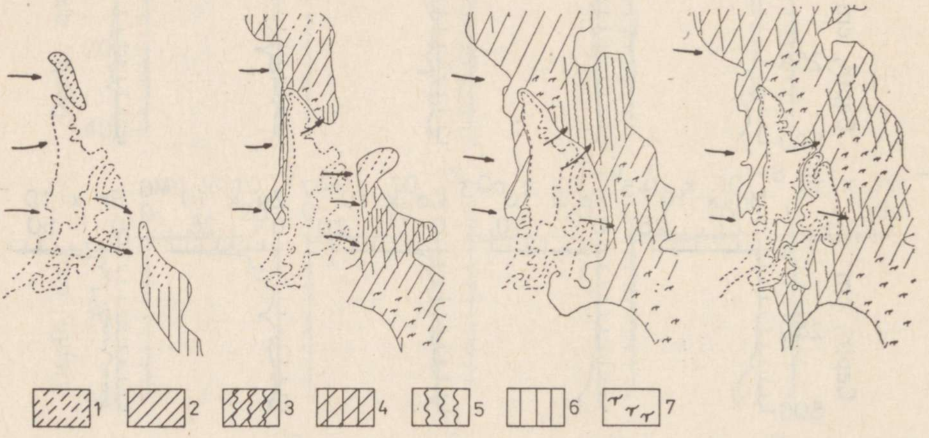


Fig. 5. Paleovegetation maps for mires around the Kurtna kame field 8000, 5000, 3500, and 1000 B. P. 1 — *Hypnum* fen, 2 — sedge fen, 3 — sedge-reed fen, 4 — birch-sedge fen, 5 — birch-reed fen, 6 — birch and birch-spruce fen forests, 7 — *Sphagnum* bog. The arrows indicate the main direction of surface water flow, the dashed line follows the contour of the kame field.

The depths of the lakes have changed little during the entire period observed, only the depth of L. Jaala has decreased progressively (Fig. 3). Along with the rise of the water level the thickness of lake deposits has grown. Relying upon the results of the diatom analysis of L. Martiska deposits, we may conclude that the level of trophicity of the lake and its pH have changed very little during the last 3000 years (Fig. 6). The situation has evidently been analogous in other lakes.

In bog peat the influx of chemical elements changed little in the period 5000—3500 B. P., some fluctuations may be connected with forest fires (Fig. 4).

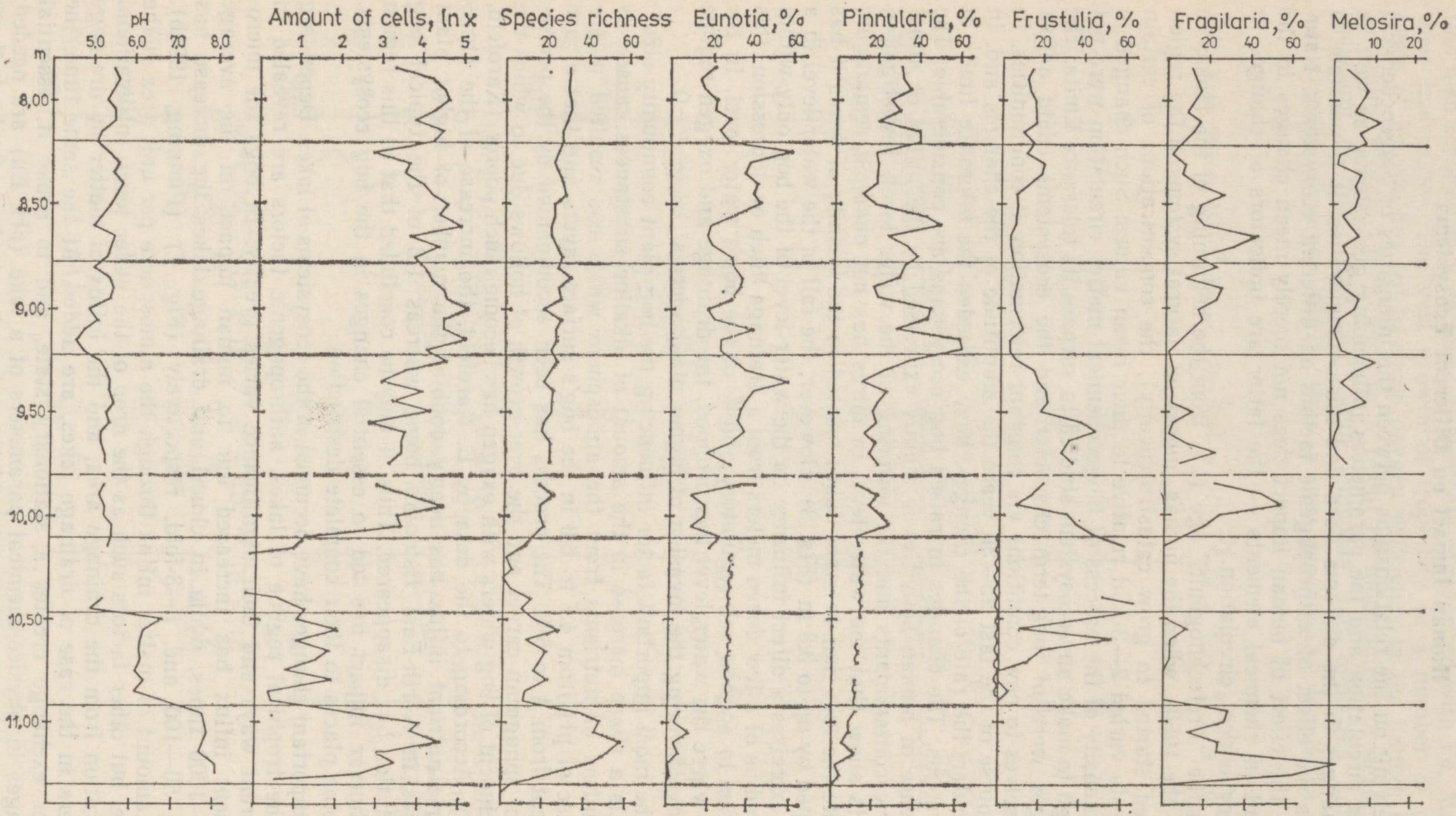


Fig. 6. Diatom percentage diagram for selected taxa from the sediment core of Lake Martiska (analyses made and figure compiled by R. Laugaste).

Human Impact on Different Ecosystems

Relying on the relationships between the intensities of biogeochemical matter circulation and the parameters influencing geosystems, as well as on changes in the diatoms flora and mire communities, it is possible to assess the effect of anthropogenic factors on different ecosystems. Naturally, the effect of human impact does not merely mean changes in the content of chemical elements — the latter are indicators of changes in biogeochemical circulation.

In the "Pretechnogenic" age (i. e. from the beginning of the Holocene up to the 1950s, when the human impact on natural systems of the region studied started to grow catastrophically), the concentrations of certain elements varied 2—3-fold relative to their mean values. Such changes in the intensity of the process of biogeochemical matter circulation were not enough to make any ecosystem studied to surpass its tolerance limits. The changes were of long-term character and the ecosystems could adjust themselves to new conditions via constant reformation of communities. In the course of the last 25—30 years the amplitude of the changes and, in particular, the rate of the changes, have exceeded the tolerance limits of ecosystems. The changes in raised bog ecosystems are considerable. The influence of human activities is mainly expressed by the influx of atmospheric contaminants and the lowering of the water level. Investigation results show that the water level in mires has not changed remarkably despite the fact that in many lakes located in the vicinity of mires it has dropped by up to 3.8 m (Fig. 3). However, the fall of the water level in a lake exercises a direct influence on the water level of the bog only within the radius of a few dozen meters from a drainage ditch or depression; this testifies to a good self-regulatory ability of the bog's water level. In the area where the water level has dropped, the drainage and oxygen regime improve favoring the invasion of higher plant species.

The most important factor influencing the bog plant community structure is a sharp increase in the amount of alkaline substances caused by the influx of nutrients from the atmosphere which has resulted in the icrease of pH from 4.7 to 6.0 in the bog's surface layers and that of ash content from 4 to 6%. The process has been accompanied by the perishing of sphagnum carpet and the over-growth of hollows due to which the enrichment of bog waters with oxygen has become much poorer (Karofeld, 1987). According to the data by E. Karofeld, the increase of the atmospheric nutrient influx has nearly doubled the number of higher plant species in North-East Estonian bogs, whereas 1/3 of the typical bog vegetation has disappeared. Thus, it may be concluded that in this region the human impact has led to essential changes in the bog ecosystems, in some places to their complete destruction.

Important changes have occurred in the ecosystems of lakes. Depending on the trophical regime of lakes, anthropogenic factors are revealed in different ways and their significance varies greatly. In bogs the microelement influx has increased due to human impact on the average 120—1000 times, while in closed and drainage lakes the increase has been 50—100 and 1—3-fold, respectively (Fig. 7) (Punning, 1990b). The amount of matter influx through the atmosphere per unit area is the same, but other factors such as the drop of the water level, infiltrational migration from the drainage area, and the influx of matter by drainage waters in the case of drainage lakes, are added. At the same time, the water exchange creates a stationary state, and to shake it, essential changes in physico-chemical parameters of a lake (pH, Eh) are needed, i. e. the formation of geochemical barriers is required. Such a sharp change took place in many lakes 9000—8000 years ago when pH decreased, this also resulted in a decrease of elements codeposited with Fe, Mn and their hydroxides. The vast growth of trophicity in a number of closed lakes at Kurtna has led to sharp oxygen deficiency in the bottom layers (Punning, Toots, 1987), and, as a result of biochemical processes, the reduction of NO_3^{-1} and SO_4^{-2} into ammonia and hydrogen sulphide has started (Пуннинг, 1987). Thus, a new geochemical barrier is under

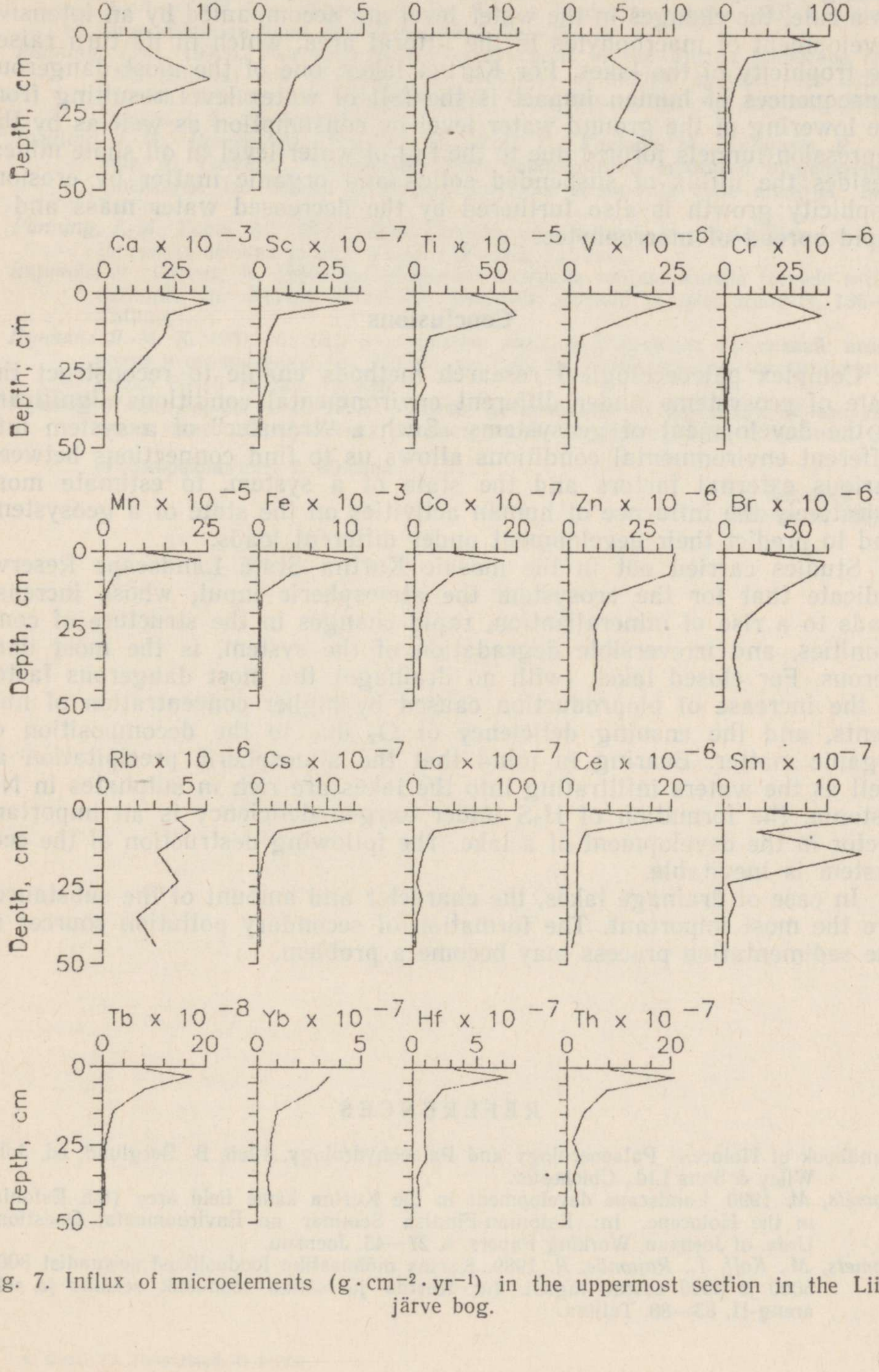


Fig. 7. Influx of microelements ($g \cdot cm^{-2} \cdot yr^{-1}$) in the uppermost section in the Liivjärve bog.

formation which may lead to a strong reformation of the chemical composition of deposits. As the compounds involved (H_2S, NH_3) are extremely toxic, the ecosystems of these lakes are facing total degradation.

Another important factor in the formation of biogeochemical matter flow is the fluctuation of the water level of lakes. Depending on the morphology of the concavity and the feeding regime, the water level alternation may lead to conspicuous changes in the formation of deposits (lacustrine lime — sapropel), which will naturally bring about essential changes in the whole ecosystem. The influx of lithophylic substances, the mixing of deposits, and the influx of allochthonic organic matter occur. As a rule, the changes in the water level are accompanied by an intensive development of macrophytes in the littoral area, which in its turn raises the trophicity of the lakes. For Kurtna lakes, one of the most dangerous consequences of human impact is the fall of water level resulting from the lowering of the ground water level by consumption as well as by the depression funnels formed due to the fall of water level in oil shale mines. Besides the influx of suspended solids and organic matter by erosion, trophicity growth is also furthered by the decreased water mass and a rapid spread of macrophytes.

Conclusions

Complex paleoecological research methods enable to reconstruct the state of ecosystems under different environmental conditions significant in the development of geosystems. Such a "transfer" of a system into different environmental conditions allows us to find connections between various external factors and the state of a system, to estimate more objectively the influence of human activities on the state of a geosystem, and to predict their development under different loads.

Studies carried out in the mosaic Kurtna State Landscape Reserve indicate that for the ecosystem the atmospheric input, whose increase leads to a rise of mineralization, rapid changes in the structure of communities, and irreversible degradation of the system, is the most dangerous. For closed lakes (with no drainage) the most dangerous factor is the increase of bioproduction caused by higher concentration of nutrients, and the ensuing deficiency of O_2 due to the decomposition of organic matter. Bearing in mind that the atmospheric precipitation as well as the waters infiltrating into the lakes are rich in sulphates in NE Estonia, the formation of H_2S under oxygen deficiency is an important factor in the development of a lake. The following destruction of the ecosystem is inevitable.

In case of drainage lakes, the character and amount of the substances are the most important. The formation of secondary pollution sources in the sedimentation process may become a problem.

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