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UNCERTAINTY OF RELATIONS BETWEEN LANDSCAPE COMPONENTS – A TOOL FOR MODELLING EVOLUTION OF SPATIAL PATTERN

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Abstract

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Dynamics of landscape spatial pattern is a topic of great concern in landscape ecology. Most publication on the problem focus on short-term dynamics. We argue that long-term trends in spatial pattern can be revealed using analysis of interrelations between landscape components. Abiotic components (landforms, deposits) determine to some extent behaviour of mobile components (soils, vegetation cover) and gradually force them to adapt. We identify several reasons for discrepancy between properties of abiotic and biotic components, namely: different stages of recovery process, anthropogenic impact and self-development of landscape independent on lithogenic controls. The purpose of the research is to evaluate contribution of self-development to evolution of landscape spatial patterns and to reveal driving forces of self-development as well as to determine spatial scales for intercomponents relations. We test the hypothesis that lateral transfer and radial flows of substance are the important controls over mobile components that can induce self-development of landscape. On the example of the study area in boreal forests in the Northern Russia we propose to evaluate uncertainty measure for intercomponents relations to separate patterns with different degree of determinism between abiotic and biotic components, to identify diverging and converging landscape units and to evaluate degree of internal equilibrium in landscape.

Key words: evolution, self development, spatial pattern, equilibrium, scale, boreal landscape, component, relations, uncertainty, long-term dynamics, divergence, convergence

Introduction

Dynamics of landscape spatial pattern is a topic of great concern in landscape ecology and geography. Research on the problem combines both spatial and temporal approaches which is essential for modern natural science. Great advance in remote sensing and GIS technologies enables to get insight into evolution of spatial pattern for relatively short periods of time like decades. Most publications on the problem focus on short-term dynamics induced by human impact, like timber harvesting, agriculture (Mladenoff et al., 1993; Pan et al., 2001; Ojala, Louekari, 2002; Saunders, Briggs, 2002). Natural disasters - windfalls, pest outbreaks, mudflows, erosion etc. – can also promote rapid changes of spatial patterns easily observed using series of aerial and space images (Tang et al., 1997; Keane et al., 2002). Long-term dynamics of spatial patterns is difficult of access for direct observation. The lack of publications on this topic, especially dealing with self-development of spatial patterns, is emphasized by Phillips (2001), Turner et al. (2001). Indirect indicator of long-term spatial trends are in great demand. We believe that equilibrium measures for intercomponents relations in landscape are useful in solving this problem.

Landscape spatial pattern can be interpreted as a result of two types of natural phenomena inducing two corresponding types of spatial variability of components like vegetation cover and soils. On the one hand, certain proportion of vegetation cover and soil properties is strictly determined by geological and geomorphological features of the territory. Russian landscape science school has rich traditions in research of abiotic constraints imposed on mobile components (Isachenko, 1973). Conventional landscape mapping is based on few fundamental principles having roots in deterministic approach: a) mobile components reflect properties of lithogenic base on landscape, b) landscape boundaries and boundaries of geological and geomorphological units are in one-to-one correspondence, c) each hierarchical level of landscape organization is controlled by specific principal factor of differentiation (Vidina, 1962).

On the other hand, every researcher is aware of great number of examples in nature that similar types of soils and plant cover can evolve despite the fact that landforms and deposits differ in the area of interest. And vice versa mobile components can have diverse properties despite homogeneous deposits covering homogeneous landform. Proportion for mobile components properties explained by abiotic environment usually turn out to be not too high; for instance, Pan et al. (2001) evaluated the figure for coniferous forests landscape in North America as 13%. Our research in similar landscape shows higher proportion (see below) but it is still less than 50% of total variability of soils and plant cover. Thus, larger proportion of mobile components variability seems not to depend on abiotic environment. It can be evaluated as residual values from regression model explaining deterministic relations between abiotic components and mobile components. We identify three most frequently occurring explanations for the discrepancy between abiotic and mobile components. First and the simplest explanation is mosaic land use. Second, spatial mosaic is quite often a result of different stages of landscape evolution under the influence of the same principal factor. The obvious examples are mosaic of landscape strips on glacial deposits in front of retreating glacier or different stages of waterlogging around a mire. This sort of "pseudo"-heterogeneity is not surprising since landscape components have different time scale of evolution and need centuries to adapt to each other before they reach common climax state of equilibrium in relation to deposits and climatic conditions. The third and the most exciting variant of discrepancy in relations of landscape components, is emergence of new landscape units as a result of self-development being independent on abiotic conditions. We define *self-development of landscape unit as changes of mobile compo-*

nents properties, intercomponents relations and spatial pattern not determined by geological and geomorphological conditions. Self-development is usually induced by occasional (sometimes catastrophic) short-term events like windfalls, beavers activity, fire etc. which force mobile components to evolve following positive feedback loop loosing perfect adaptation to abiotic environment. Self-development of spatial units can result in multiple stable states of landscape given that abiotic conditions are the same (so called divergence of spatial units) or in reduction of spatial diversity (convergence). Multiplicity of stable states is a reflection of non-linear relations between components. This sort of relations is becoming central point in present-day research of nature (Naveh, 2000). Anthropogenic pressure can induce multiple stable states of adaptation of landscape structure (Khoroshev, 1998).

The purpose of our research is to evaluate contribution of self-development to evolution of landscape spatial patterns and to reveal driving forces of self-development as well as to determine spatial scales for intercomponents relations. We test the hypothesis that lateral transfer and radial flows of substance are the important controls over mobile components that can induce self-development of landscape. The starting point is dependence of radial flows on texture of soil-forming deposits and dependence of lateral transfer intensity on degree of dissection of relief.

Material and methods

Study area is located in middle taiga region in North European Russia (the Vaga river basin, 60°53' N 43°20' E). The research has been performed since 1994 (Dyakonov et al., 2000; Khoroshev 2000, 2001). Interrelations among landscape components are studied in fine scale on transect 8050 m long with landscape properties being recorded over interval 25 m as well as in coarser scale with 500 sample plots being regularly dispersed over the area 200 km^2. Landscape is typical for plains with morainic loams covered by surface sandy deposits being transformed by lake dammed by retreating Würm glacier. In Holocene landforms were shaped by erosion following networks of neotectonic joints. Lithogenic diversity is determined by different thickness of limnoglacial sands and Riss morainic carbonate loams lying over Permian marlstone as well as by exposures of marlstone on river valleys slopes. Emergence of alkaline groundwater on slopes and joints zones is essential for geochemical diversity: typical acid Podzolic soils are in close neighborhood with neutral Umbric Albeluvisols and Umbrisols. Plant cover consists of primary spruce forests (*Picea obovata*) alternating with secondary pine (*Pinus sylvestris*) forests on sandy soils and birch (*Betula pendula*) and aspen (*Populus tremula*) forests on clayey soils. Recovery succession after clearcuttiing or plowing includes stages of pine and birch dominance and ends with spruce forest. Low shrubs layer is typical with dominance of *Vaccinium myrtillus, Vaccinium vitis-idaea, Rubus saxatilis*. Moss layer composition varies in concordance with water supply: sequence of communities with dominance of *Sphagnum sp., Polytrichum commune* and *Pleurozium schreberli* is common for the series of landscape units as soil moisture content increases. Central sections of watershed areas poorly dissected are occupied by oligotrophic mires tending to expand since 6850 years ago (Dyakonov et al., 2000). Arable lands are located in the area with the most dense system of joints manifested in network of deep and wide river valleys with exposures of marlstone on steep slopes. Fertile Umbrisols on slopes and watershed areas enable intensive agricultural activity gradually declining during last decade. Abandonment of arable lands results in increase of meadows and rapid recovery of forests.

Field material includes description of plant cover (species composition, abundance of species, canopy density, coverage for each layer), soils (thickness of horizons, color according to Munsell charts, texture, depth of carbonate horizon), landforms (genesis, shape, slope angle, aspect). Texture of deposits measured up to the depth of 150 cm with record over the interval 5 cm is used as the control over intensity of radial flows in soils. Landsat 7 space images as well as map of quartenary deposits and digital elevation model DEM (scale 1:50 000) were used to identify landscape units. ArcView 3.2a software was applied as a tool to calculate characteristics of relief dissection, namely: total length of valleys around each sample plot, variance of elevations, diversity of aspects, distance to the closest stream, slope angle. These indices are believed to characterize intensity of lateral transfer at the site and general drainage conditions.

The approach proposed to identify self-developing landscape units and to interpret driving forces includes following steps.

1. Principal components analysis is performed for sets of data characterizing soils, plant cover, relief and deposits. Factor values obtained are used at the following steps.
2. Classification of sample plots by abiotic conditions. Two types of classification were performed using k-means method in Cluster analysis module (Statistica 5.5 software). Classification by texture of deposits affecting soil formation up to the depth of 150 cm characterizes conditions for radial flows. Classification by topographic variables, namely a set of variables characterizing drainage conditions.
3. Discriminant analysis is performed in order to assess proportion of patches that differ by soil and plant cover in perfect concordance with classes of topography or deposits identified before. Posterior probabilities are computed for each sample plots.
4. Shannon formula is applied to assess uncertainty measure for each sample plot:
   $H = SP_i\log(P_i)$, where H – uncertainty measure, P_i – probability that plant cover and soils correspond to a certain class of topography or deposits.

Uncertainty measure shows degree of concordance in relations between mobile components and abiotic conditions. Understanding these relations is critical for assessment of landscape stability (Huba, 1998). Some patches have soils and plant cover that can correspond to two or three classes of physical environment with equal probabilities. For example, some species (e.g. *Agrostis tenuis*) prefer sands, other one prefer loams (e.g. *Trifolium pratensis*), but at the moment they co-exist – so uncertainty of plant cover is high. These patches are most likely in unequilibrium state in relation to topography or/and deposits for the given scale. They can be relatively easily forced to follow this or that pathway. Patches with low uncertainty of intercomponents relatioships are quite stable. Components are adapted to each other like pine forests with Podzols on sandy terraces which can be hardly replaced by any other community.

5. Interpretation of uncertainty measures is performed using regression models:
   $H = b0 + b1*v1 + b2*v2 + b3*v1*v2 + b4*v1\^{}2 + b5*v2\^{}2 + \ldots$,

where v1, v2 - factor values characterizing landscape properties.

The question solved is: which factor is responsible for equilibrium/unequilibrium in intercomponents relations.

6. Interpolation of uncertainty measures over the study area enables us to identify areas with perfect adaptation of components and areas with continual transitions between contrast equilibrium units. Forecast of future development and landscape planning can be based on these maps. The approach to mapping landscape patterns is in compliance with notions of absolute and relative space which differ by method of units identification. Absolute space is strictly determined structure described by Euclidean geometry, while properties of relative space are determined by structural and functional relations between objects (Marceau, 1999; Meentemeyer, 1989). We identify patterns based on relations between components.
7. Estimation of space scale relevant for analysis of intercomponents relationship. To solve this question we compared uncertainty measures calculated in relation to topography with 1000 (H1) and 2000 m (H2) as radius around each sample plot. If uncertainty in intercomponents relations decreases as larger environment is taken for description of topography ($H1 - H2 > 0$), it means that broad space scale is more relevant. In case of increase of uncertainty measure for broader scale ($H1 - H2 < 0$), we conclude that the properties of the certain sample plot needs smaller environment in order to be explained by topography.

Results

Proportion of variance of mobile components properties explained by abiotic environment differs much. Diversity of moss and low shrubs layers is constrained by properties of deposits and topography to a greatest extent in comparison with bush layer and tree layer. For

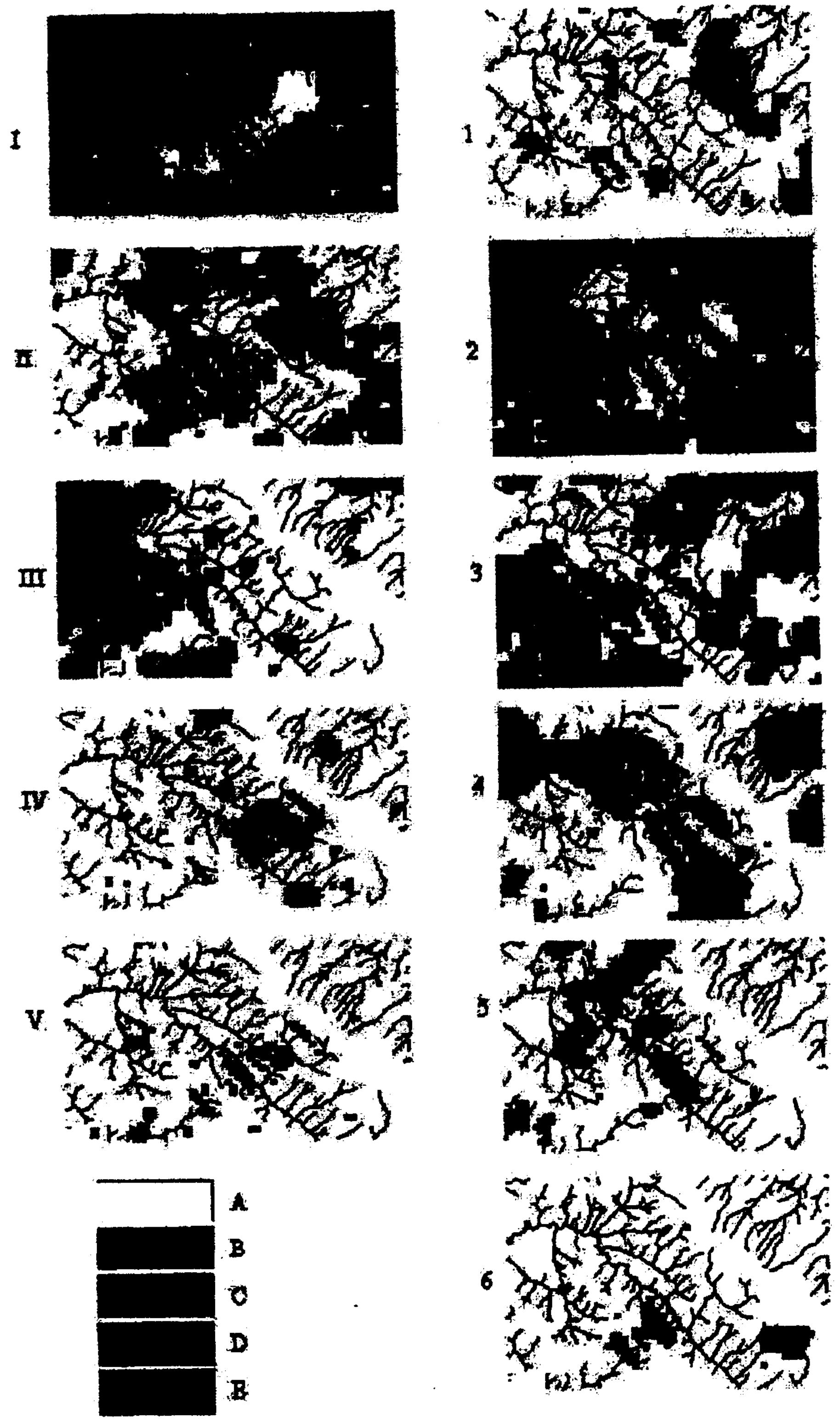

Fig. 1. Posterior probabilities that soils and plant cover correspond to classes of deposits (I–V) and classes of topography (1–6). Probability values: A – 0.0–0.2, B – 0.2–0.4, C – 0.4–0.6, D – 0.6–0.8, E – 0.8–1.0.

the moss and low shrubs layer 50–60% of sample plots are perfectly discriminated among classes of abiotic environment while for trees and bush layers the figure is 40–45% and for soils – 35–45%. Total variance of mobile components properties that can be explained by diversity of abiotic environment is about 50%. Thus half of sample plots is subject to factors that do not depend on topography and deposits directly. Plotting posterior probabilities for each class of abiotic environment enables us to present continuous picture of landscape patterns (Fig.1). It depicts probability that soils and plant cover correspond to the certain class of physical environment: the darkest areas correspond to the most perfect adaptation of mobile components to abiotic environment. Uncertainty measure is derived from posterior probability values for each pixel.

Few possible explanations for high uncertainty in relations between soils, plants and abiotic conditions are shown on Fig. 2. It turned out that landscape patch evolves less and less dependent on topography under the influence of rich mineral nutrition due to emergence of alkaline groundwater (Fig. 2A). Uncertainty increases since

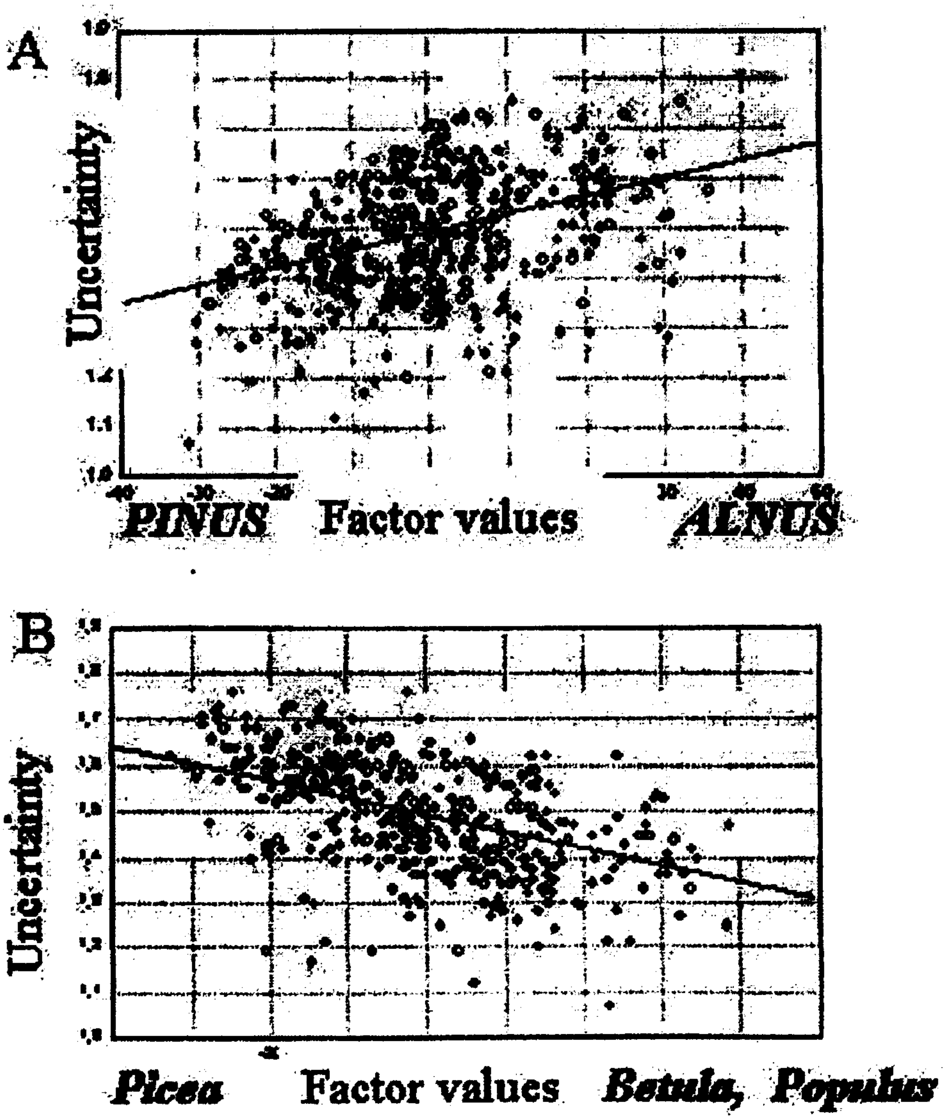

Fig. 2. Interpretation of uncertainty measures for trees and bush layers in relation to topography: A – factor of mineral nutrients supply, B – factor of recovery succession stage.

boreal and broad-leaved forests species are mixed and soil have properties of both podzolic process and humus accumulation. Abundance of *Alnus incana* and other species with the same ecological demands is typical for sites with rich mineral nutrition in any landform while *Pinus sylvestris, Juniperus communis, Agrostis tenuis* etc. dominate in oligotrophic habitats. Fig. 2B suggests other explanation for high uncertainty in relation to topography. While recovering from cutting landscape pattern becomes more uniform. At the first stages of succession secondary forests with *Betula pendula* and *Populus tremula* prevail being highly sensitive to abiotic conditions. Gradual recovery of spruce forests makes landscape pattern more uniform and less dependent of deposits and topography. Spruce litter forces soils to evolve under strong influence of organic acids resulting in evolution of uniform Podzols cover despite diversity of landforms. Accumulation of clay in soil profile over the contact of sandy and loamy horizons changes drainage conditions. In certain period of time clay accumulation can cause development of gley process and gradual waterlogging of the site. This phenomena follows non-linear pattern. The better illuviation process is manifested the less uncertainty is for soils in relation to parent rocks. Thus, emergence of alkaline groundwater, illuviation of soils profile, recovery of forest climax state can be considered driving forces of self-development of the landscape.

To solve the question how vast is the area of environment that affects landscape unit we compared uncertainty measures in relation to topography with 1000 and 2000 m as diameter. Uncertainty of soils in relation to topography is less for mesoscale (2000 m) in comparison with microscale (1000 m). Set of soil horizons reflects long-term evolution. Microscale processes (within the circle with 1000 m as diameter) affect soil profile much less than flows operating at broader scale (2000 m) because short-term processes fail to be imprinted in depth of horizons borders. Regularity for moss, herbs and low shrubs layers is different. It turned out that characteristic space for these layers differs for units located in valleys and watershed areas. It is critical for units in flat watershed areas what are drainage conditions at least 1000 m around including morphology of adjusting valleys. Uncertainty decreases as larger environment (mesoscale) is considered. Regularity is opposite for sample plots located in valleys and small catchments – remote topography in neighboring watershed areas is much less important for plant cover, so uncertainty increases for mesoscale.

Properties measured in a certain sample plot can be determined by local phenomena occurring in spatial scale finer that DEM is sensitive to. We used remote data to evaluate diversity of environment for the finer scale. Diversity of local flows of matter under the control of microrelief are believed to affect relations between landscape components and landscape heterogeneity as well as a set of mesoforms around. We tested the hypothesis that high uncertainty in intercomponents relations is to some extent determined by poor adaptation of soils and plant cover to diverse local flows of substance and vice versa the more homogeneous is environment the less uncertainty (the higher equilibrium) is in intercomponents relations. Degree of environment heterogeneity was evaluated as entropy measure of space image in a moving window. Quantitative estimation showed that in natural conditions – like primary forests and bog expanses - approximately 40% of uncertainty measure variance is explained by diversity of environment of radius 500 m around the sample plot calculated on space image. Note that uncertainty of intercomponents relations was calculated at landscape level. However, 40% of variance is influenced by local situation. Estimation for anthropogenically changed patches showed no dependence. Thus, anthropogenic influence like clearcuttings seem to destroy links between properties of landscape unit and its surroundings.

Discussion and conclusions

Results obtained show that estimation of uncertainty in landscape intercomponents relations allows forecasting future trends of spatial pattern evolution, given that properties of local environment is taken into consideration. Degree of adaptation of soils and plant cover to abiotic environment, namely topography and deposits is in compliance with landscape stability. We identify the following combinations.

1. Stable unit with low uncertainty in homogeneous environment which belongs to the same class of abiotic environment as the unit itself is evaluated as perfect adaptation of soils and plant cover to abiotic conditions.
2. Patch with low uncertainty in alien environment which belongs to another abiotic class most likely is a relict. Any impact may be harmful, resilience is low.
3. Patch with low uncertainty in heterogeneous environment is most likely in state of divergence. Landscape pattern gradually becomes more and more diverse.
4. High uncertainty of intercomponents relations in homogeneous environment of the same abiotic class indicates start of divergence process or vice versa last stages of adaptation.
5. High uncertainty in homogeneous alien environment most likely indicates disappearing patch or start of divergence.
6. High uncertainty in mosaic heterogeneous environment means instability, state of transition, low resilience.

Results show evidence that landscape heterogeneity is to a great extent induced by various processes relatively independent on abiotic environment. Mobile components have different sensitivity to properties of deposits and topography. Plants with small characteristic space and time scales like mosses, herbs and low shrubs are more perfectly constrained by abiotic conditions than bush and trees. Processes in soils are good indicators and at the same time driving forces for self-development of the patch. Illuviation in soil profile causes substantial changes of plant cover being independent of abiotic environment. New trends of landscape development in boreal forests can also be induced by emergence of groundwater. Gradual recovery of coniferous tree layer after clearcuttings makes landscape spatial pattern more and more uniform and less dependent on abiotic conditions. On initial stages of recovery successions with prevalence of decidous trees abiotic contrasts are especially well manifested in landscape pattern.

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