Approaches to the plane landscapes altitudinal organization study

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Abstract. Terrain elevation variations (absolute and relative) play a special role in the organization of plain landscapes. They are most clearly observed in the form of zonal landscape vertical differentiation. Vertical relief transformation leads to formation of altitudinal landscape systems, which are dynamically and morphologically united groups of landscapes. They have a common altitudinal position and genesis under the influence of horizontal and vertical physiographic processes. We have analyzed the influence of relative and absolute altitudes on morphometric parameters of the land surface as well as indicators of landscape-forming processes and textural terrain indicators, and so identified altitudinal landscape systems of different dimensions. A well-studied region in terms of landscape science, the Central Black Earth region, was the case study area. As a result of the study, we revealed spatial patterns in (i) the indicators of horizontal and vertical terrain ruggedness in relation to the absolute terrain altitudes at the level of landscape, and (ii) the morphometric indicators of terrain, landscape-forming processes and landscape shapes at the local level.

1. Introduction

The problem of landscape organization as a complex parodynamic system have being actively discussed in the scientific literature, so numerous works had been devoted to this topic. At the same time the term of landscape organization is understood rather broadly by different authors: from landscape arrangement of a specific territory to processes which form a landscape as a system. This leads to some confusion in landscape science, as “landscape organization” may refer to an inner structure, a spatial organization, a dynamic process, and some other landscape attributes. In our opinion, the landscape organization should be considered as a process of multiple mechanisms, which action may form some certain landscape structures.

The study of landscape organization mechanisms is still in its early stages, which is caused on the one hand by the complexity of landscape structure, and on the other hand, by the lack of data on the processes taking place in geosystems. However, in recent years, the improvement of research methods and technologies (geographical information systems, mathematical modeling approaches, remote sensing data analytics, and the instrumentation progress) lets researchers gradually move from the descriptive models of landscape structure to quantitative analyses of the mechanisms of landscape formation. A number of successful studies of inter-component and inter-landscape relationships may be highlighted as an example of this [1-6].

Factors that influence landscape-forming processes and structures play a special role in landscape organization. Among them, changes in absolute and relative heights of terrain are of great importance. In mountains, they contribute to formation of altitudinal belts and tiering of mountain countries. In the
plains they are manifested in the form of zonal landscape vertical differentiation \[7\], slope microzonality \[8\], forming of landscape-geochemical units \[9\], landscape storey \[10\], landscape layers \[11\], and so on.

2. Materials and methods

The general methodology of the study based on the following premises: i) vertical differentiation of plain landscapes is the universal property of qualitative change of geosystems depending on their absolute and relative heights and some other features of relief. Despite zonality of this property it is quite clearly reflected in the structure and dynamics of geosystems and thus acts as an indicator of transformation of zonal landscapes \[13\]; ii) vertical differentiation of landscapes is the result of changes in the intensity of vertical flows of the landscape sphere, which are primarily caused by gravity; iii) the height of terrain significantly predetermines the invariant properties of landscapes, the rate of material and energy flows, and direction of landscape forming process and, as a consequence, different landscape patterns are formed at different altitude sections \[15\]; iv) vertical differentiation of landscapes is a multiscale phenomenon, inherent in geosystems of different taxonomic rank (across the Central Black Soil Region, it is observed in landscapes from local unit levels to the landscape provinces); v) the process of vertical relief transformation forms altitudinal landscape systems, which are dynamically and morphologically unified groups of landscapes of different taxonomic rank with common altitude position and formed due to the common genesis under the influence of horizontal and vertical physiographic process.

We use the Central Black Soil Region (it includes Belgorod Oblast, Voronezh Oblast, Kursk Oblast, Lipetsk Oblast, and Tambov Oblast of Russia) as a case study area, because it is well-studied in terms of landscape science. The region is almost completely allocated in the Steppe-Forest zone of the East European Plane, particularly in the Central Russian Upland, the Volga Upland, and the Oka-Done Lowland landscape provinces (just a small part of the South of Voronezh Oblast places in the Steppe zone, according to zone delineation made by F.N. Milkov). Orographic differences among these provinces predetermined the plane landscapes altitudinal differentiation in the study area.

The main objectives of our research were:
- to study the influence of relative and absolute altitudes on morphometric parameters of the terrain as well as indicators of landscape-forming processes and textural terrain indicators;
- to reveal patterns in the interrelations of the abovementioned indicators in the context of different spatial scale levels;
- to identify altitudinal landscape systems of different dimensions and to develop their classification.

As a first stage of the research, we made a digital elevation model (DEM) of Voronezh Oblast with the spatial resolution of 10 m per pixel using Saga GIS. And for the Central Black Soil Region we used the hydrologically correct DEM of 30 m resolution released by D. Yamazaki \[14\]. Using these both DEMs we computed derived morphometry indexes such as the Aspect, Slope, Curvature (general, plan, profile, cross-sectional) indexes, Topographic Position Index (TPI), Topographic Raggedness Index (TRI); and measures such as valley depth, vertical distance to channel network, watershed areas, closed depressions depth, which are may be related to factors of the landscape-forming process intensity. And to quantify these processes we computed the following indexes: Length-Steepness Factor (LSF), Stream Power Index (SPI), Mass-Balance Index (MBI), Topography Wetness Index (TWI), Photosynthetically Active Radiation (PAR), flows overland and their mechanic work.

The second stage dealt with the fishnet analysis. We covered the prepared raster maps of all the DEMs and derived indexes with fishnets of different cell size (25*25 km and 10*10 km for the Black Soil Region, and 5*5 km and 1*1 km for Voronezh Oblast). Then we aggregated the statistics from the raster maps to the fishnet cells as the minimum, maximum, mean, standard deviation (SD), and range of the raster values per cell. Thus we created a geodatabase of the regular squares with descriptive statistic variables on underlying terrain. Using multiple regressions based on these variables let us reveal interrelations of the computed indexes and changes of the study terrain altitude.
In order to identify textural patterns of landscapes we used the landscape map of the mestnost types of the Black Soil Region (scale 1:500,000) and landscape map of Voronezh Oblast (scale 1:200,000). As an indicator of landscape texture we used a complexity measure based on entropy [15]. Finally, we applied cluster analysis of the indicators which showed statistical significance for altitudinal differentiation of landscape and used the results to identify taxa and devise a classification of altitudinal landscape systems of different dimensions.

3. Results and discussion
The altitudinal landscape differentiation forming is a global phenomenon due to multidimensional flows of matter and energy, which can be simplified to upward, downward and lateral flows. F.N. Milkov has written that such flows «caring out different functions in the cycles of matter and energy, and so play different but equally important roles in landscape forming» [7]. Upward or antigravity flows have special place among all others, because they initiate a start point for geographical cycles. Changes in intensity and direction of the vertical flows are the premise of the altitudinal differentiation of landscapes and formation of the altitudinal landscape systems. Their main energy sources are the solar irradiance, the Earth’s inner energy and it’s gravity.

Solar irradiance determines intensity of the upward flows in the atmosphere, which in its turn forms altitudinal differences of the climatic conditions and the top border of the natural zones. That was clearly shown by G.E. Grishankov (1972) during proving of the three-dimensionality of geographic zoning. Thus in subequatorial zones, which powerful upward air flows are well known, the top border of the zone is in about 800-1000 m of height, while in the temperate zones it is in 350-400 m of height, and in the polar zones is only 200-250 m [12]. That is the reason why even high upland plains in the equatorial Africa is allocated in the same natural zone and have common vertical differentiation of landscapes, while e.g. lower uplands in the Kola peninsula may have up to four natural zones. The heights of the East European Plane do not reach the top border of its natural zone, so there is only zonal vertical differentiation everywhere except the Volino-Podolsk Upland, the Codrii in the Republic of Moldova, and partly the Donetsk ridge, where the initial altitudinal zonality can be observed.

The inner energy of the Earth determines direction and speed of vertical crust movements, which impact on the altitudinal differentiation of the relief. There are significant transformation of climatic conditions going along with deep changes in zonal landscapes and altitudinal zones on the height uplands (at least 1000 m above sea level). Additionally, the formed altitude gradients intensify the downward flows of matter and energy caused by gravity.

Gravity affects the intensity of majority exogenous landscape-forming processes, which are responsible for relief morphostuctures and patterns of landscapes. It compensates the upward flows and determines strength of the relations among geosystems by regulating flow volumes of water, air and solid mater. So V.N. Solncev was precise to write, that gravity is one of the two equally important factors of landscape forming and functioning [3; 16].

The forming mechanism of altitude zonal landscape differentiation and altitudinal system genesis is presented with the following steps: 1) changes in the intensity of the Earth’s crust movements (tectonic upwelling) increase the altitude range between peaks and base surfaces of erosion; 2) the potential energy of surface flows and slopes between head watersheds and valley bottoms increase; 3) the speed of water flows increases, their kinetic energy and work increases as well; 4) the depth and density of terrain ruggedness grow, the kinetic energy and work of surface flow keep increasing; 5) the aspect differentiation of the slope surfaces and the landscape patterns are forming in general; 6) the local solar irradiation of surfaces and the corresponding microclimatic regime are changing along with slope and aspect variations; 7) the altitudinal landscape systems of similar morphology and dynamic are forming.

The backward process would be observed in case of tectonic lowering: sedimentary rocks accumulate, the terrain gets flatter, the potential and kinetic energy of surface flow decreases, and the differences in aspect, insolation and microclimatic conditions start to disappear.
Thus, to study the influence of the absolute and relative heights on the relief morphometry, the landscape forming processes, and features of the landscape patterns is the main objective of the altitudinal landscape analysis.

First of all, it is necessary to identify relations between absolute heights and the terrain ruggedness. The terrain ruggedness is the key factor of altitudinal landscape systems forming. We estimated the terrain ruggedness by computing altitude range within the regular square plots on several scale levels. It was expected that such terrain ruggedness estimates would depend on absolute heights at all studied scale levels. Although our regression analysis results show that coefficient of determination \( R^2 \) increases for the models based on larger sampling plots: \( R^2=0.76 \) when the sampling cell size was 25*25 km, \( R^2=0.59 \) when it was 10*10 km, \( R^2=0.46 \) when it was 5*5 km, and \( R^2=0.28 \) when it was 1*1 km. So the role of absolute altitudes in the terrain ruggedness forming is lowering with zooming in the research scale.

The situation is different with relations among the relief morphometry indexes and relative altitudes. Thus the calculations showed that correlation between the terrain ruggedness and maximum degree of slope per cell is increasing along with zooming out the study scale. So \( R^2 \) increases from 0.23 to 0.76 when the size of sampling plots changes from 25*25 km to 1*1 km. We found out similar correlations of the terrain ruggedness with some other indexes and textural patterns of the landscapes as well.

We are providing generalized results of calculations here in this article as we obtained measures of 350 correlations per each study scale level. All the responses of three groups of indexes (the factors, the processes, and the textures) to relative and absolute altitude changes could be divided into five types: 1) the indexes which are dependent on altitude variations and their correlations get stronger with smaller sampling plots (e.g. most of the relief morphometry indexes and the landscape forming processes); 2) the indexes which are dependent on altitude variations and their correlations get stronger with greater sampling plots (e.g. most of the indexes based on the relative altitudes variation); 3) the indexes which are dependent on altitude variations with no matter which size of sampling plots used (e.g. indexes of pretty same phenomenon such as deep of valleys, heights of watersheds above the local base of erosion, potential energy of surface flow and so on); 4) the indexes which are not dependent on altitude variations with no matter which study scale used (e.g. most of the mean values of the solar insolation indexes); 5) the indexes which are dependent on altitude variations just at some scales (there are a few of them, e.g. the daylight index which is significantly correlated \( R^2=0.77 \) with terrain ruggedness at the scale level of 1*1 km sampling plots and shows non correlations at other study scales).

In general, the effect of the absolute altitudes on the relief morphometry, the landscape processes and its textures is mostly observed at a coarse resolution sampling matrix (25*25 km and 10*10 km), while the effect of the altitude range is mostly noticeable at the fine resolution matrix (1*1 km). That let us to group the sampling cells by values of the absolute and relative altitudes to identify similar territories in terms of the morphometry, dynamic and texture of the altitudinal landscape systems. We used the Natural Break (Jenks) method to identify border values between groups. So there have been three main groups of the cells (25*25 km) identified in the Black Soil Region, which corresponds to the three altitudinal landscape systems of the regional level: the top step with moderate terrain ruggedness, the middle step with strong terrain ruggedness, and the low step with light terrain ruggedness. That happened to be close to what F.N. Milkov had described in his works [7].

For each of the three altitudinal steps we applied the same approach to subdivide them. Grouping cells of 10*10 km size within the altitudinal steps let us identify altitudinal systems of the landscape subregional level. Their inner structures were revealed by clustering the cells of 5*5 km size. So we found two altitudinal landscape systems in valleys and three such systems in the watersheds. Clustering of the cells of 1*1 km size let us delineate altitudinal systems of the mestnost level.

Classification of the altitudinal landscape systems was the logical completion of our research. So we devised a taxonomy of the altitudinal landscape systems based on their geomorphological and lithological differences, dynamical interrelations, genesis and direction of evolution. It includes the following taxa: divisions, classes, subclass, types, subtypes, families, genera, species, and subspecies. Divisions are identified by the type of contact between contrast spheres (the lithosphere - the atmosphere, the
lithosphere - the hydrosphere) which forms vertical differentiation of landscapes and differentiation of underwater geosystems by deep. Classes are delineated by the relief morphostructures of the first order (mountains - flats) and are presented by the vertical differentiation of flats and altitudinal zonality of mountains. Subclasses are identified by the insolation differences and let vertically subdivide the flat landscapes of the polar, moderate, subtropical and tropical zones. Types are allocated by the steps in relief of lowlands, uplands and height flats. Subtypes separates one of each other on the basis of the main landscape forming processes (accumulation and denudation), so they imply valley-watershed dichotomy of geosystems. Families are identified based on the zonal position of geosystems and bioclimatic features of altitudinal differentiation of plain landscapes. Genus are delineated on the basis of the watersheds tops changes which define local altitude ranges and let to identify low, moderate low, height, and moderate height areas. Species is defined by characteristics of the hydrological and geochemical regimes, the erosion and accumulation balance (there are autonomous watershed geosystems, slope trans-eluvial geosystems, terrace trans-accumulative geosystems and accumulative floodplain geosystems). And it is possible to identify landscape subspecies using relative altitudes, morphology, and dynamic processes of the local geosystems (e.g. landscape subspecies of central, sub-peaks, and sub-edges parts of watersheds; subspecies of low, moderate, and high floodplains; subspecies of top, middle, and bottom parts of slopes). Such classification system superiors the ones previously proposed by F.N. Milkov (1981), A.G. Isachenko (1995), D.L. Armand (1975), V.A. Nikolaev (1979) et al. in distinction of the zonal and vertical terrestrial landscape units of low ranks, as it takes to account the criteria which are significant for the altitudinal landscape transformation process.

4. Conclusions
In sum, the research results could be stated as following: i) The terrain altitudes significantly affect the landscape organization mechanisms. The altitudes define changes of the upward flows intensity and the processes initiated by the Earth’s gravity. ii) Correlations of the absolute terrain altitudes with the indexes of the terrain ruggedness, the altitude ranges, and the valley deepness were clearly identified at the sampling matrix with a cell size of 25*25 km and 10*10 km, and were not significant at the finer spatial study scales. That pattern corresponds to a spatial level of landscape. iii) Correlations among the indexes of the relief morphometry, the landscape forming processes, and the landscape patterns were clearly identified at the sampling matrix with a cell size of 1*1 km and 5*5 km, and were not significant at the coarser spatial study scales. That pattern corresponds to a spatial level of landscape low rank units like mestnost. iv) The result of the altitudinal differentiation of the geosystems structures is the identified altitudinal landscape systems, which are dynamically and morphologically unified groups of landscapes of different taxonomic rank with common altitude position and formed due to the common genesis under the influence of horizontal and vertical physiographic process. v) The taxonomy of the altitudinal landscape systems may have the following hierarchy: divisions, classes, subclass, types, subtypes, families, genera, species, and subspecies.

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