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FEATURES OF ECOLOGICAL GEOMORPHOMETRY AS A PROSPECTIVE FIELD OF STUDY, ITS MAIN CONCEPTS AND METHODS

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Abstract. The main concepts and methods of ecological geomorphometry as a research field aimed at studying relationships between terrain morphometric characteristics and ecological factors and processes are reviewed in the paper. The progress in this research field has been conditioned by the propagation of high-resolution digital elevation models in free access and of methods of their digital analysis, namely: the calculation of derivative quantitative characteristics (attributes and indices) of terrain and the statistical models of analyzing the relationships between the latter and the ecological properties and factors (those relevant for a certain ecological subject). A peculiar feature of ecological approach to regarding terrain (its morphology) is subjectcentrism (that is, regarding it from a point of view of a certain subject). The subject of ecological relationships can be living entities (populations, species, communities) as well as a human, social entities, economy and its branches.

Three main concepts of ecological geomorphometry are put forward: terrain attributes (relatively simple quantitative characteristics of terrain form that characterize its geometry and some elementary physical processes); topographic indices (quantitative surrogates for some complex physical or biophysical processes of ecological significance); morphotops (spatial units that are distinguished by terrain morphology, using criteria of ecological homogeneity relevant from a viewpoint of a certain ecological subject).

Morphotops can be distinguished with different level of detail (and, as a result, with different characteristic dimensions), relative to the study aim, to the geographic features of the area, and to the available data and the methods of their analysis. While morphotops are distinguished with strictly defined quantitative morphometric parameters (terrain attributes, topographic indices), this enables using formalized methods with their advantages of reproducibility and possibility of automatizing. In our studies aimed at morphotop mapping for a small area in the hilly terrain of Davydiv range near Lviv and for a larger area in the central part of Ukrainian Carpathians, morphotops delineation was based on topographic indices that characterize insolation level (solar radiation incidence on terrain elements of different aspect and slope values), lateral redistribution of water on slopes and redistribution of solid matter by washout on slopes. Morphotops were distinguished with cluster analysis method, which allows to distinguish natural groupings of data in the attribute space. Presetting different number of clusters to be distinguished, morphotopes can be distinguished with different levels of detail, larger number of clusters corresponding to more homogenous morphotops with smaller characteristic sizes.

Key words: ecological geomorphology, ecological geomorphometry, morphotops, terrain attributes, topographic indices.

ОСОБЛИВОСТІ ЕКОЛОГІЧНОЇ ГЕОМОРФОМЕТРІЇ ЯК ПЕРСПЕКТИВНОГО НАПРЯМКУ ДОСЛІДЖЕНЬ, ЇЇ ОСНОВНІ ПОНЯТТЯ ТА МЕТОДИ

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Анотація. В статті розглянуто головні поняття і методи екологічної геоморфометрії – наукового напрямку, який вивчає залежності між морфометричними характеристиками рельєфу та екологічними факторами і процесами. Розвиток цього напрямку зумовлений поширенням цифрових моделей рельєфу високої роздільної здатності у вільному доступі, а також методів їх цифрового комп'ютерного аналізу: обчислення похідних кількісних характеристик (атрибутів та індексів) рельєфу та статистичних методів аналізу залежностей між останніми та екологічними властивостями і чинниками (такими, що мають значення для деякого екологічного суб'єкту). Специфікою екологічного підходу до розгляду рельєфу (його морфометрії) пропонується вважати суб'єктоцентризм. Суб'єктом екологічних відношень при цьому можуть бути як живі організми (види, популяції, угруповання), так і людина, соціальні утворення, господарство та його окремі галузі.

В якості основних понять екологічної геоморфометрії запропоновано використовувати поняття атрибутів рельєфу (відносно прості кількісні характеристики форми земної поверхні, що характеризують її геометрію та деякі елементарні фізичні процеси), топографічних індексів (складені показники, які характеризують складніші екологічно значимі процеси), морфотопів (територіальні одиниці, які виділяються за ознаками морфометрії земної поверхні, виходячи з критеріїв екологічної однорідності з-погляду певного суб'єкту).

Морфотопи можуть виділятись з різним ступенем детальності (і, відповідно, мати різні характерні розміри), виходячи з цілей дослідження, географічних особливостей території, наявних даних і методів їх аналізу. Оскільки при їхньому виділенні використовуються чітко визначені кількісні морфометричні параметри (атрибути рельєфу, топографічні індекси), це дає змогу використовувати формалізовані методи, вагомою перевагою яких є відтворюваність та можливість автоматизації. В наших дослідженнях в основу виділення морфотопів в умовах височинного рельєфу Давидівського пасма в околицях Львова та гірського рельєфу Українських Карпат було покладено топографічні індекси, які характеризують рівень освітленості (надходження сонячної радіації на поверхні різної крутизни та експозиції), латеральний перерозподіл вологи на схилах та перерозподіл твердого матеріалу під дією схилових потоків. Виділення морфотопів здійснювалось методом кластерного аналізу, який дозволяє виділяти природні поєднання даних у просторі атрибутів. Задаючи різну кількість кластерів, можна виділяти морфотопи з різним ступенем детальності (більшій кількості кластерів відповідають більш гомогенні морфотопи з меншими характерними розмірами).

Ключові слова: екологічна геоморфологія; екологічна геоморфометрія; морфотопи; атрибути рельєфу; топографічні індекси.

Introduction. Nowadays ecology is widely considered not only a natural scientific discipline, a subdivision of biology, but also a point of view and perspective into the problems derived from the interrelationships between human society and its natural environment. Spatial ecology grew in importance recently as a subdiscipline that focuses specifically on the study and modeling of the roles of space on ecological processes that in turn affects ecological patterns (Fletcher & Fortin, 2018). The development and maturation of the subdiscipline of spatial ecology in the last few decades was conditioned by the growing availability of spatial data, constantly increased computing capacities, as well as the advances in spatial modeling techniques.

A notion of ecological factor (ecological gradient) is one of the central concepts in ecology as it relates the requirements of the ecological subject (e.g. a species) with observable and measurable parameters of its environment. There are several types of ecological gradients. For instance, in plant ecology resource gradients relate to matter and energy used by plants for growth (light, water, nutrients, carbon dioxide, oxygen), direct gradients include those having direct physiological impact but not consumed by plants (temperature, pH), while indirect gradients have no direct physiological influence on plant growth and act indirectly by influencing resource and direct gradients (Austin & Smith, 1989). Among the latter group, terrain attributes like slope and aspect play a prominent part as they redistribute solar energy, water, and solid particles, together with dissolved nutrients and suspended matter.

In "classical" landscape science the relief together with closely interrelated local geology and the spatial distribution of parent rocks are considered to be the "strongest" component of the natural landscape that deterministically controls other components including soils, natural plant cover, and local fauna (Kruhlov, 2016; Miller, Petlin & Melnyk, 2002). Discrete forms of relief readily discerned on contour topographic maps, stereoscopic aerial photos and by visual observations in situ are the spatial basis for the delineation of the landscape units of different ranks. Characteristics of soils and biotope are then spatially bound to these units, as well as the characteristic of potential vegetation (the one assumed to eventually establish there under the assumption of the cessation of any anthropogenic disturbances and the constancy of present climatic conditions for the time long enough for the climax vegetation and ecosystems to settle down).

Terrain attributes are often used in species distribution modeling as proxies to the characteristics of energy and water regime that influence the distribution of plant and animal species. As noted in (Strahler, Logan & Bryant, 1978), "Many ecological and sylvicultural studies have shown the importance of the topographic parameters of slope angle, aspect, and relative elevation in determining vegetation composition". J. Franklin in her paper on predictive vegetation mapping as based on the modeling of relations of biospatial patterns to environmental gradients has attempted to classify terrain attributes (topographically derived variables) by the concrete mechanisms of their effects on spatial distribution of direct and resource gradients (Franklin, 1995). Thereby four kinds of topographically derived variables have been distinguished by their effect on spatial distribution of direct and resource gradients: 1) elevation affecting temperature and precipitation; 2) slope angle and aspect affecting radiation regime, and therefore moisture demand; 3) slope angle and hillslope and drainage basin position, influencing soil moisture and development (hence, moisture-holding capacity and also nutrient availability); 4) wind exposure affecting temperature and moisture (Franklin, 1995). In fact, ecological mechanisms are thus classified rather than variables themselves as some terrain attributes appear in more than one group.

Some studies use terrain attributes as auxiliary variables that allow to increase the accuracy of vegetation classification and mapping results obtained with remote sensing data (Strahler, Logan & Bryant, 1978). A. Strahler presented a method for estimating the conditional probabilities of a vegetation type's occurrence based on topographic variables, and using those priors to modify a maximum likelihood decision rule applied to remotely sensed data, and, as a result, the estimated accuracy of his vegetation map increased from 58% to 77% (Strahler, 1980).

The utility of spatial ecological models based on terrain attributes has significantly increased in recent decades due to the advance of accessible high-quality digital elevation models (DEMs) and technologies of their processing and analysis. Several choices are already available for the free of charge DEMs with near-global coverage and spatial resolution fine enough for the purposes of the detailed analysis of land surface processes (Kovalchuk, Luk`yanchuk & Bohdanets, 2019). For instance, newly versions of SRTM DEM and ALOS DEM have horizontal resolution of 1 arcsecond which is roughly equivalent to 30 m in projected units (Jarvis et al., 2008; Takaku, Tadono & Tsutsui, 2014). As to processing and analysis of DEM, a number of software options are available, from popular proprietary GIS like ArcMap (a component of ArcGIS suite of geospatial processing programs) to open source SAGA GIS with a graphical user interface to a large suite of terrain analysis tools and methods (Conrad et al., 2015; Svidzinska, 2014), to *raster* package of R language and environment for statistical computing (R Core Team, 2017) that, along with in-built *terrain* function that computes a set of basic terrain attributes and indices, allows users to construct their own rather complicated models of spatial interactions.

The widely recognized utility of terrain data for spatial ecology, a set of usable data and methods available, and a large number of studies already undertaken on the relationships between terrain characteristics and ecological properties and processes warrants the notion of the distinctive study field named “ecological geomorphometry”. Ecological geomorphometry can be regarded as a subdivision of ecological geomorphology – the scientific and applied field concerned with the significance of relief in the functioning of different components of environment under the intensive human economic activities (Stetsiuk, 1998), and that regards relief as an indirect ecological factor that indirectly influences the vital activities of living organisms, the progress of ecological processes, the formation of ecological situation (Kovalchuk, 1997). While geomorphology is concerned with such properties of relief as its genesis, age, and history, the properties of relief that bear the most on the ecological factors and processes are mostly connected with the geometric properties of terrain. The latter are the subject of geomorphometry – the science of quantitative land-surface analysis (Hengl & Reuter, 2008). It is a part of geomorphology concerned with quantitative characteristics of relief elements, forms, and types. These characteristics direct, interfere and moderate the flows of energy, water, solid particles and nutrients in landscape, thereby influencing resource and direct ecological gradients. As stated in (Chervanev, 1991), ecological geomorphology should consider the part of relief as a modifier, differencing agent, concentrator, and disperser of matter and energy flows, from high-scale natural zonality up to elements of micro- and nanorelief.

It is considered relevant to use the term “ecological geomorphomerty” for such a research area, concerned with the action of the actual terrain, while ecological geomorphology can be regarded as a more general and vaguely defined discipline which engages itself in multifarious aspects of the influence the relief exerts on ecological subjects.

The aim of the study is to review the methodological basis of ecological geomorphometry, to suggest a set of the main concepts of ecological geomorphometry and to clarify their meaning, to illustrate the application of the concepts and methods of ecological geomorphometry for concrete regional studies.

Material and methods. In the present time, the researches in geomorphometry for the most part rely on DEMs as the principal source of information on terrain morphometry. A number of textbooks still mention TIN (triangular irregular network) as an alternative data model, but this for the most part could be regarded as obsolete, as DEM in the form of regular matrix of elevations provides considerable benefits as concerns the possibilities of its analysis and derivation of terrain attributes and indices.

In the cases of academic studies, especially with absent or limited funding, downloadable DEMs available free of charge are of high importance. Several options of such are available at the present time. One is SRTM DEM, obtained in February 2000 with Shuttle space mission applying a radar interferometry technique (Jarvis et al., 2008). The coverage spans a global area from 56°S to 60°N. The data with an initial resolution of 1 arcsecond (~ 30 m) were finally released in 2014.

ALOS (Advanced Land Observing Satellite) DEM, obtained with PRISM panchromatic radiometer installed on a Japanese Earth-observation satellite operating from 2006 till 2011, has the same spatial resolution of 1 arcsecond (~ 30 m) and spans a global area from 82°S to 83°N (Takaku et al., 2014). Yet another product is ASTER GDEM with 30-meter spatial resolution, covering land surface between 83°N and 83°S. However, its accuracy is regarded as somewhat inferior, comparing with aforementioned SRTM and ALOS DEMs (Kovalchuk et al., 2019).

While mentioned products are being distributed in the format ready for use without preprocessing from a user part, the techniques used for their acquisition presuppose some inaccuracies and artifacts. One case is the canopy effect: in the areas of dense tree canopy land elevation values in DEM can be overestimated due to part of the signal being reflected from tree canopy rather than from the ground surface underneath (Rabus et al., 2003). This requires additional preprocessing for DEM to more correctly reflect real ground surface elevation.

More fine-resolution DEMs can be accessed on paid conditions. They can also be produced by manually or automatically digitizing the data on topographic maps (contour lines, elevation points, thalwegs), and interpolating these with certain algorithms. This method however is labor-consuming (especially if DEM for a large area is being created) and error-prone.

Methods in ecological geomorphometry include those required to derive ecologically meaningful quantitative parameters of terrain – terrain attributes and terrain indices – and those used for the analysis of relationships between the latter and the distribution of species, communities, ecosystems, and their characteristics. Terrain parameters are calculated by certain algorithms applied to DEM data; many of them are realized by corresponding tools and functions of appropriate GIS software packages. Some terrain attributes can be calculated by several alternative algorithms producing slightly different results with a same input data.

Relationships between terrain parameters and ecosystem properties can be analyzed by a number of statistical techniques, the choice of which is conditioned on a type of data and on a supposed output. When we are interested in the impact of one or several quantitative terrain parameters on quantitative output (e.g., biomass, primary and secondary production, etc.), simple or multiple regression can be applied. In case the output is nominal (e.g., we are interested in the distribution of the types of ecosystems), discriminant analysis is appropriate. In case we are interested in whether two or more types of ecosystems (communities) differ with regard of a certain parameter, analysis of variance can be used. When a number of variables (e.g., terrain attributes) are interrelated, factor analysis can be used to detect structure in the relationships between them and to combine strongly related variables into a smaller set of integrative factors. When both input and output variables are nominal or ordinal (e.g. types of terrain and types of ecosystems), correspondence analysis can be used to analyze relationships between them. When we want to analyze the relationships between two different sets of quantitative variables (e.g., terrain attributes and ecosystem quantitative characteristics), canonical correlation analysis is appropriate. Methods of cluster analysis are applied to identify the natural groupings based on the values of variables. Recently, methods of machine learning are becoming popular for the analysis of different types of data (e.g., different architectures of neural networks, random forests, support vector machines, boosted regression trees, etc.), which are considered more flexible, less demanding regarding the quality of data, and often producing more accurate predictions comparing to traditional statistical techniques.

Results and discussion. Ecological geomorphometry can be regarded as an integrative scientific field between ecology and geomorphometry. The question still remains as to what should "ecological" part mean in this term. Two equally disputable approaches are commonly taken in scientific usage of this adjective: to narrowly limit it to a branch of biology concerned with the interaction of plant and animal species with their environment, including other species, and to extend its meaning to the broadest set of usages concerning environmental problems, nature management and conservation, and even sociocultural and psychological phenomena.

It looks appropriate to instead regard "ecology" and "ecological" as a peculiar point of view, the certain mode of analysis of the phenomena involving different forms of causality (inert/mechanistic, living, and human/social). Ecological approach thus looks at complex systems as composed of active subject, being either living organisms (populations, species, communities) or human communities, that interacts with (relatively) passive environment. This approach is a kind of simplification, because it mostly ignores complex processes taking place in environment it regards as "stable". However, this approach is common and quite effective in many applied studies when it is practical to regard an environment as a relatively stable set of conditions that influence the suitability of environment for either a certain biological entity (populations, species, communities), or some aspect of human activity.

As an environment comprises a large (potentially infinite) number of elements and properties, ecological approach guide in selecting a subset of these that are relevant to a certain subject, serving as an information filter. As one of the founders of landscape ecology Lev Ramensky puts it, "ecology is a common yardstick for the heterogeneous factors and indices; geobotanical, soil, climatic, and other characteristics should be generalized, systematized and expressed in ecologically meaningful and comparable values" (Ramensky, 1938). And, further, "ecology is a uniform language in our field, that is the only one which allows obtaining a genuinely complex coverage of its subject in its multiformity and unity" (Ramensky, 1938).

Relief is a rather complex phenomenon by itself, and can be regarded and analyzed from different viewpoints (as is done with different subdisciplines of geomorphology). Here, the ecological perspective is considered, that is the one being centered towards a certain subject. An issue of subject then requires some clarification. An ecological subject here is understood as a living entity in the widest sense, including biological communities as well as an human seen either as a biological organism or as a subject of social relations and economic activities. Characteristic of a subject of ecological relations is that it should bear a degree of independence from influencing ecological factors, being able to adapt to them as well as to change them to a certain degree. This relative independence manifests itself as an ecological plasticity of living organisms and as the ability of humans to adapt differently to different environments and transform them by technical means.

Ecological studies of living organisms interacting with their environment, and applied studies that assess the suitability of land for a certain land utilization type were generally carried out by researches from essentially different scientific disciplines. Nonetheless, the methodology of these two types of studies is very similar in its core. In both cases, a set of environmental factors that influence the given subject are analyzed, that often relate to local climate, terrain, soil properties (in case of natural plant species and crop production), as well as location relative to man-made entities (roads, settlements, etc.) The principle of limited factor is valid in either case, saying that in case some single factor makes a site unsuitable for some species or land utilization type, it usually cannot be compensated for by other factors, however suitable they might be.

As relief is commonly regarded as a relatively stable component of natural environment, its properties (mainly morphometric ones) can easily be connected to ecological factors in the realization of ecological approach. Next, the main concepts of ecological geomorphometry are considered.

The concept of "**terrain attributes**" can be regarded as a basic one, and is defined as "quantitative descriptors, or measures, of land-surface form" (Hengl & Reuter, 2008; Wilson & Gallant, 2000). Synonymous terms are "land-surface parameters" (the term preferred in (Hengl & Reuter, 2008)), "topographic variables", "land surface variables", "terrain variables"; the term "terrain attributes" though has been preferred by the largest number of active visitors of geomorphometry.org web portal (http://geomorphometry.org/content/your-preferred-term).

The number of terrain attributes is large (potentially infinite) and many of them characterize or influence some land surface processes. As noted above, ecological approach provides criteria of significance, that among the host of possible terrain attributes allows to select those that either directly influence some processes of ecological significance (e.g., energy or water balance), or serve as an indicator of some ecological conditions (e.g., soil depth, soil water content, etc.)

All terrain attributes in geomorphometry are subdivided by formal criterion into local ones, that are computed within a definite small vicinity of a place (e.g., slope and aspect, that are usually computed within 3×3 window), and regional, that require to consider other parts of the DEM, even quite remote from the exact point where they are to be calculated (e.g., flow accumulation, that is calculated based on number of cells upstream from a given place, the distance of which depends on the area and shape of the local watershed and can be arbitrarily large). There are a number of classification schemes of terrain attributes which will not be considered here.

Another important concept in ecological geomorphometry is "***terrain (topographic) indices***". Like terrain attributes they are quantitative spatially distributed measures derived from DEM by some numerical algorithm. The difference between two concepts is that, while terrain attributes are relatively simple measures of terrain geometry or some elementary abstract (theoretically simplified) processes, terrain (or, as often called, topographic) indices characterize some complex process of ecological significance, or, as put by I. Moore et al., can be used as surrogates for complex physical or biophysical processes (Moore, Grayson & Ladson, 1991). Three main groups of topographic indices can be distinguished: 1) those characterizing the redistribution of solar energy on inclined surfaces of different slope and aspect; 2) those characterizing the redistribution of soil water under the gravity; 3) those characterizing the redistribution of solid matter under the gravity (Mkrtchian, 2010) (see below in more detail). Some other types of topographic indices can also be relevant under the specific circumstances, e.g. those describing the heading of surfaces towards the prevailing wind directions or those characterizing the flow and accumulation of cold air on still nights in terrain depressions leading to the prevalence of night frosts.

Another concept considered here has been proposed by the author in earlier work as a generalization and reflection on methodological approach commonly utilized in applied spatial ecology. The concept of "***morphotops***" relates to spatial units that are distinguished by terrain morphology, using criteria relevant by a viewpoint of a certain ecological subject (Mkrtchian, 2004). The delineation of morphotops is based on the spatial homogeneity of ecological (environmental) conditions. This spatial homogeneity, however, is relative and its required level is conditioned by ecological properties of the particular subject as well as by research purposes, the geographic characteristics of study area, the available data, etc. Thus it is not restricted to the small spatial units at the level of morphoform elements or microforms.

The concept of morphotop is related to "biotop" defined in ecology as an area with homogenous ecological conditions regarding some plant and animal species, or occupied by a certain biological community (biocoenosis). As biotop encompasses an whole set of abiotic conditions, partial "topes" are sometimes defined (mainly – in German schools of landscape ecology), e.g. climatop refers to climatic conditions, lithotop – to properties of surface geology, pedotop – to soils conditions. Morphotops can be regarded as an another kind of "partial" biotop, with a difference that criteria for their delineation are more pragmatic: while climatic, lithological and soil characteristics are usually not directly observable (perceivable) on land surface, the terrain morphology can easily be seen, measured and spatially analyzed. In fact, detailed mapping of climate, surface lithology, and soils characteristics highly rely on terrain morphology as a strong indicator (factor) for which detailed spatially distributed data are available.

As noted above, only those characteristics of relief relevant for a certain ecological subject are employed in delineating morphotops and used in their descriptions. Thus, maps of morphotops can differ substantially from common maps of land surface forms, their elements and their complexes, created by geomorphologists. E.g., some forms that are differentiated on geomorphologic maps because of differences in age (e.g., different-aged river terraces) could be united into a single morphotop if they possess common surface lithology, similar water regime and soil-forming conditions. Morphotops, however, can be internally heterogeneous regarding ecological conditions in case of some factors acting independently of land surface forms, especially the factors of biologic and socio-anthropogenic genesis (e.g., parts of the same morphotop can have different land-use history that have reflected on the properties of soils and present vegetation).

Now let's consider some examples of morphotop mapping and characterization. First of all, terrain attributes and topographic indices have to be defined that are used as criteria for morphotop delineation. Their selection is conditioned by the aim of the study. If researchers are interested in certain species, the ecological factors that relate to physiology of this species, its nutrition needs, natural enemies, mating behavior, etc. should be taken into account. Likewise, in case of the assessment of the suitability of land for a certain land utilization type, the requirements of the latter regarding a complex of natural conditions have to be accounted for. In some cases a more general approach is taken when morphotops are defined and mapped on the basis of a number of general ecological factors relevant to a wide set of possible ecological subjects. These factors could be the ones related to the aforementioned three main groups of topographic indices: 1) solar energy and its redistribution on the inclined surfaces, influencing the availability of light and thermal regime; 2) water availability and regime dependent on its redistribution under the gravity; 3) availability of soil nutrients and soil chemical regime dependent upon the redistribution of solid matter under the action of the force of gravity (Mkrtchian, 2010). Three topographic indices can be developed based on these, and used subsequently for the purpose of automatic morphotops delineation. The general scheme of this, which has been developed and applied in our works (Mkrtchian, 2008; Mkrtchian, 2010; Mkrtchian, 2013) is shown on Fig. 1.

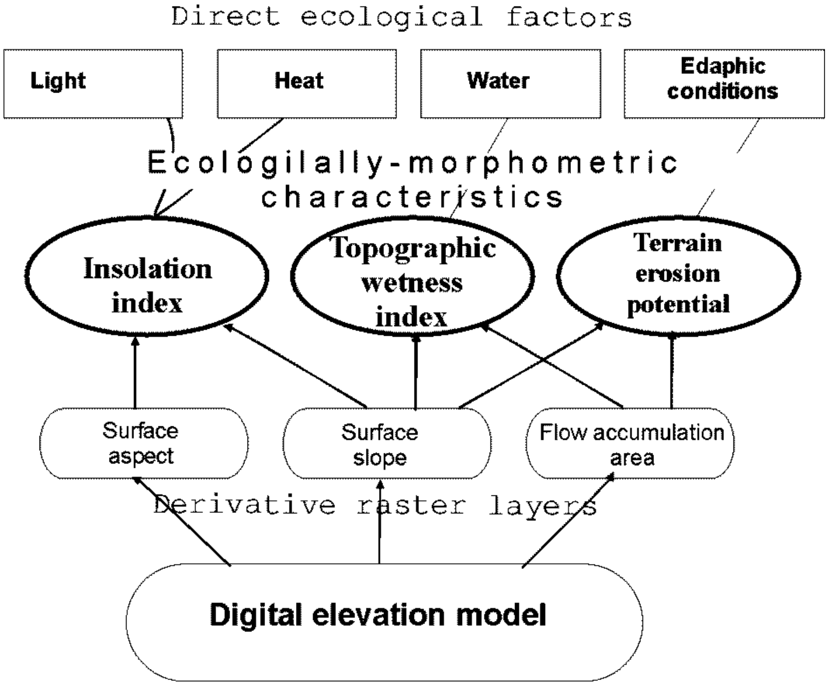

Fig. 1. Topographic indices delineation

As shown, DEM is a basic data source for the derivation of primary terrain attributes (surface slope, aspect, and flow accumulation area) that are used to derive more complex topographic indices that reflect general ecological factors.

Insolation index reflects the relative supply of solar energy on terrain elements of different aspect and slope values, and can be assessed by integrating solar radiation influx values over the period especially sensitive for the plant vegetation and other ecosystem processes (e.g., from April till October). As the modeling of the influx of dispersed solar radiation is a rather complicated task that requires detailed data on atmospheric conditions, this index can be approximately assessed with the modeling of direct solar radiation influx alone, that requires only data on the location latitude, in addition to terrain data provided by DEM (Kumar, Skidmore & Knowles, 1997).

Topographic wetness index (TWI) was introduced by Beven and Kirkby (Beven & Kirkby, 1979) and is defined as $TWI = \ln(A_s / \tan\beta)$, where A_s is a local catchment area and ß – local slope. It reflects on the balance of water accumulation and drainage over a local neighborhood and has been shown to correlate well with a set of soil characteristics (Gessler et al., 1995). As these, together with the water availability and regimen strongly affect habitat characteristics, this index could have a significant value as an ecological indicator. Terrain erosion potential is another index that assesses the potential intensity of sheet-and-rill erosion conditioned by terrain, all other factors being equal, and is calculated with formula: $LS = m(A_s / a_0)^m (\beta / b_0)^n$, where A_s is a local catchment area, ß – local slope, a_0, b_0, m, n – parameters taken from Revised universal soil loss equation (RUSLE) (Mitasova et al., 1996).

The mentioned three topographic indices were calculated for a small area in the forested hilly terrain near Lviv (Ukraine), using 5 m DEM interpolated from a detailed topographic map (Mkrtchian, 2008). The topography of the area is shown on Fig. 2, while the mentioned topographic indices calculated for this area are shown on Fig. 3.

These indices were then used in modeling (delineating) morphotops using iterative cluster analysis method (k-means) (Mkrtchian, 2008). Results of the modeling with 5 pre-given classes are shown in Fig. 4. The obtained classes were analyzed regarding their differences in some observed properties of plant cover, like the distribution of plant species and the tree stand composition (Mkrtchian, 2006; Kovalchuk & Mkrtchian, 2008). ANOVA method revealed the statistically significant differences in some plant species projective cover between morphotops, as well as differences in tree stand composition. For instance, morphotops 1 and 5 (Fig. 4) have got the largest share of beech (*Fagus sylvatica*) among the others, while morphotop 3 have got the largest share of hornbeam (*Carpinus betulus*) (Mkrtchian, 2008; Kovalchuk & Mkrtchian, 2008).

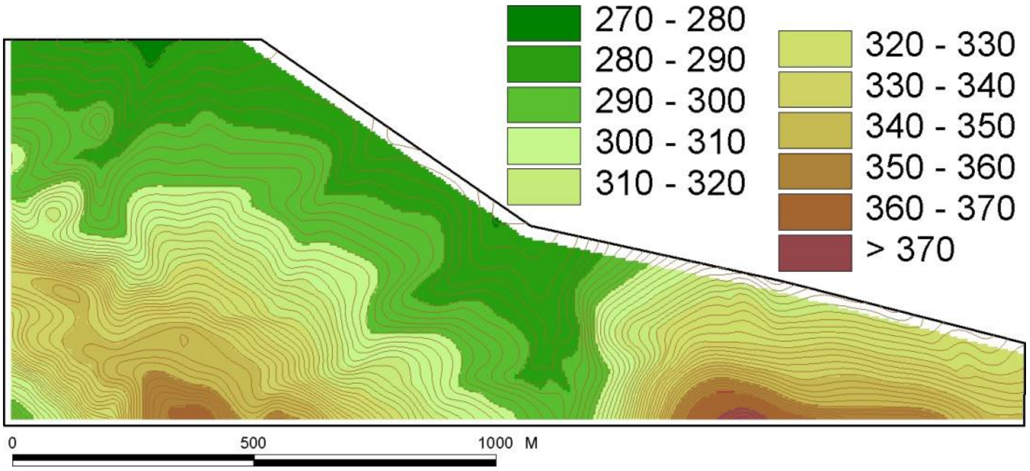

Fig. 2. Elevation data for a study area near Lviv (Ukraine).

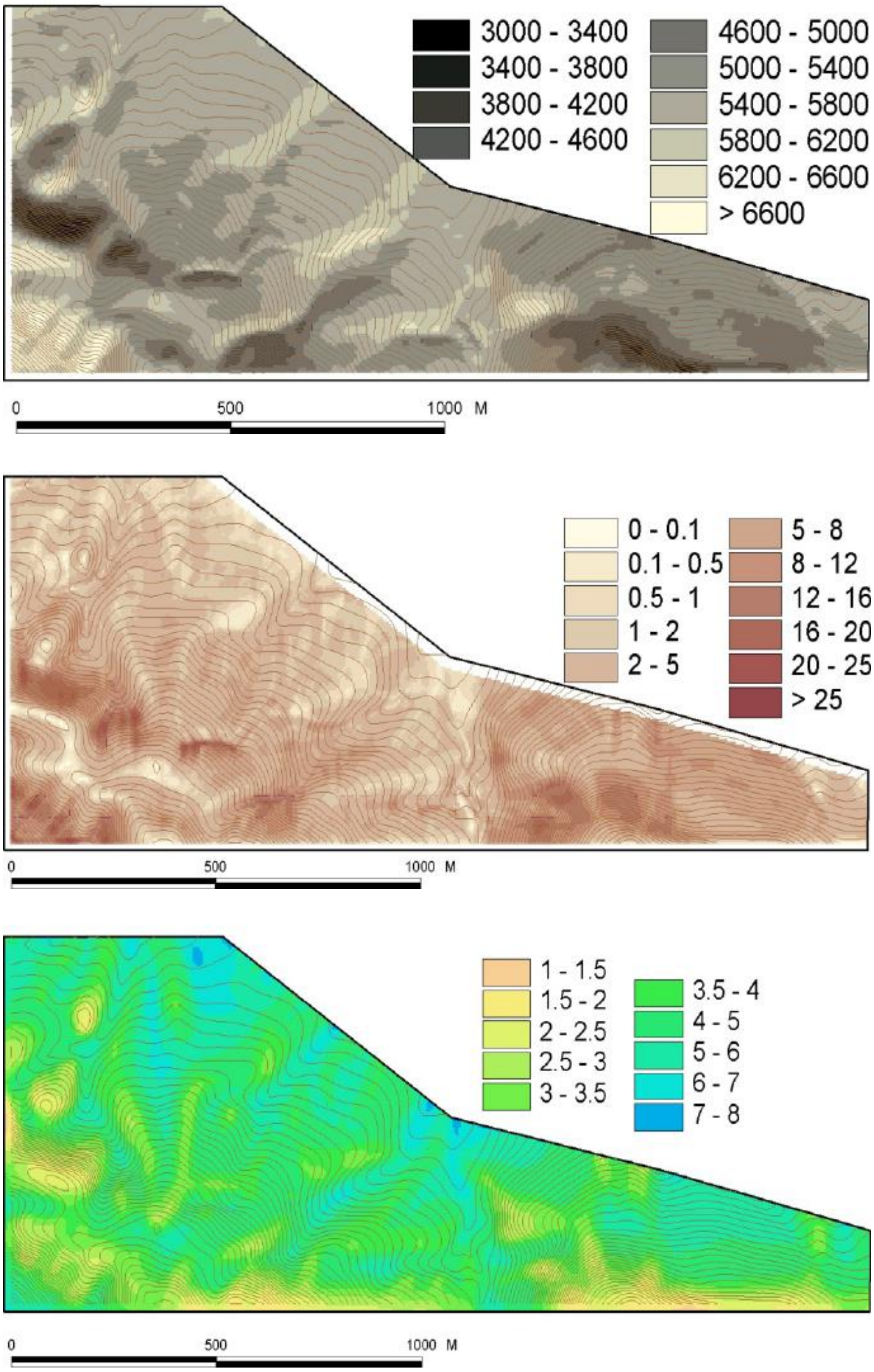

Fig. 3. Topographic indices calculated for study area (Fig. 2): insolation index (top), terrain erosion potential (middle); topographic wetness index (bottom).

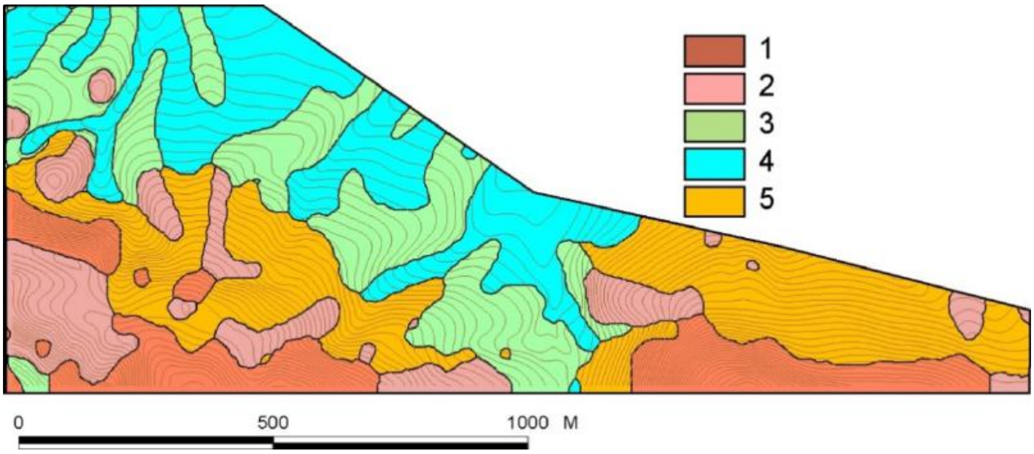

Fig. 4. Morphotops distinguished at the study area (Fig. 2, 3).

In another research, the same method has been used to distinguish morphotops in the 90*70 km area in the central part of Ukrainian Carpathians. Here, the SRTM DEM was used as a data source, with 30 m resolution (Jarvis et al., 2008). Several options with different preset number of clusters have been tried out. The result obtained with only three clusters is shown on Fig. 5. The morphotop cluster 1 here corresponds to foothills and valley bottoms, with elevations approximately up to 500 m a.s.l. Besides the lowest among all the morphotops elevation values, this morphotop is characterized by the lowest erosion potential index and the highest values of topographic wetness index. Morphotop 2 corresponds mostly to steeper north-eastern mountain slopes and is characterized by the highest erosion potential index, the lowest insolation and the relatively low topographic wetness index. Morphotop 3 corresponds to more gentle south-western slopes and mountaintops, and is characterized by the highest elevation values, highest insolation values, moderate erosion potential and relatively low topographic wetness index. When the preset number of clusters is larger, these morphotops become subdivided into smaller ones, which are more homogenous with respect to values of topographic indices. For instance, with 8 total classes, mountaintops have got separated into a separate morphotop with the largest elevation and insolation values, while morphotop 1 (Fig. 5) became subdivided into two smaller morphotops: the one corresponding to river valley bottoms (floodplains, lower terraces and mountain rivers gorges), and the other morphotop corresponding to gentle foothill slopes and upper river terraces.

In another our study, the structure of the relationships between terrain attributes and land surface reflectance values as revealed in LANDSAT ETM+ multispectral image for the mentioned part of the Ukrainian Carpathians has been analyzed using statistical methods of principal component analysis and the canonical correlation analysis (Mkrtchian, 2017). The results of the study prove the existence of rather strong relationships between the land surface morphometry and ecosystem distribution and properties reflected on image bands. The two major morphometric factors of land cover differentiation appeared to correspond to the large-scale distribution of elevation (the distinction between the high and low altitudes, canonical root 1), and to the distinction between the steep shady slopes and sunlit flat areas (canonical root 2) (Mkrtchian 2017).

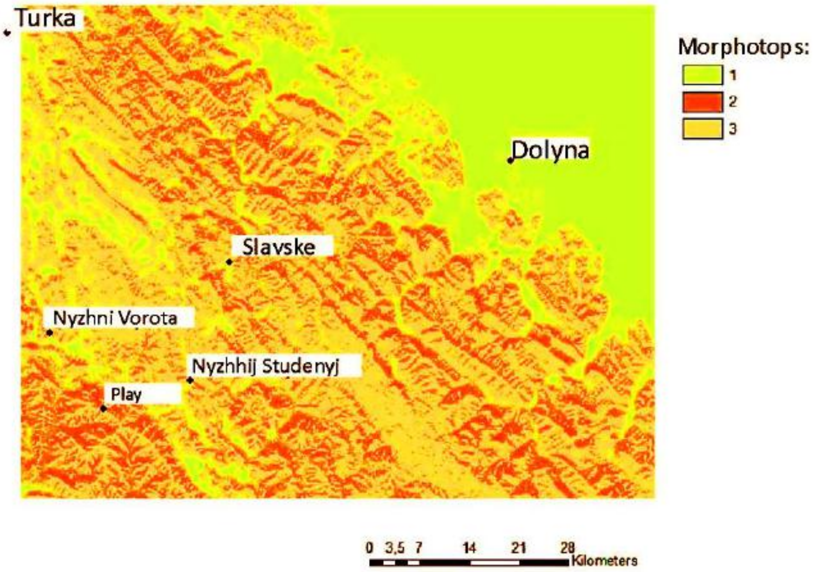

Fig. 5. Morphotops for study area in the central part of Ukrainian Carpathians.

Besides classification, another formal procedure – segmentation – can be applied if the aim is to produce spatially contiguous units. Special techniques are applied for this aim that consistently combine parts of the area deemed sufficiently homogenous with respect to the values of given topographic indices (the results of the application of this method for the mentioned study area – see (Mkrtchian, 2014)).

Conclusion. Land surface morphometry can be regarded as an indirect ecological factor sensu (Austin, Smith, 1989) that influences the distribution of ecological characteristics and processes (as related to biological entities: populations, species, and communities, as well as to human activities, like a suitability of land for a certain land utilization type). Ecological geomorphometry has been put forward as a field of research that applies quantitative data on terrain morphology as an indirect ecological factor to study ecosystems, to analyze, predict and map their properties. Three main concepts of ecological geomorphometry were expounded on: terrain attributes, topographic variables, and morphotopes.

DEMs and spatial imagery together with advanced tools of data processing offered by GIS and data analysis software present opportunities to more directly take into account ecological requirements and factors when selecting appropriate terrain attributes and topographic indices for their characterization. It has been shown how topographic indices that relate to major ecological factors like light and water availability, thermal regime, and nutrient availability can be used to automatically distinguish and map morphotops – spatial units that are distinguished by terrain morphology, with criteria relevant by a viewpoint of a certain ecological subject.

Terrain variables can be used for modeling the distribution not only of the single species but also of ecosystems as an whole. Such kinds of studies are methodologically akin to the mapping methods of the aforementioned landscape science. If the produced maps are based solely on such kind of data, then what is mapped is not the actual (real) ecosystems, but "potential eco-systems" that coincide with spatial distribution of those landform characteristics known to regulate the reception and retention of energy and water (Rowe, 1996). The authors of this work make such a strong claim as that "all fundamental variations in landscape ecosystems can initially (in primary succession) be attributed to variations in landforms as they modify climate (i.e. radiation and moisture regimes), select the ''fit'' plants and animals from the available biota, and thus control the formation of soils and their topographic facets'' (Rowe, 1996). It is essentially the same presupposition as that lying at the heart of the "classical" landscape science widespread in the realm of ex-USSR. As any ecological subject by definition possesses a degree of plasticity (independence from influencing ecological factors), being able to adapt to them as well as to change them to a certain degree, such presupposition is too strong. However, using terrain data widely available nowadays in form of detailed DEM to analyze and map ecological factors proves indispensable tool in modern spatial ecology, for analyzing the distribution of biological species as well and for assessment of the suitability of land for a certain land utilization type.

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