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MODERN APPROACHES FOR THE IMPLEMENTATION OF BACKGROUND SOIL MONITORING

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Abstract

FAO's conclusions on the rate of soil degradation in the light of climate changes and the necessity of global soil monitoring actualize improvement of the methodology for research of reference or virgin soils. This is especially relevant for Ukraine, which is characterized by a high level of agricultural land plowing. Results of developing the fundamentals of multilevel thematic processing of satellite imagery data for diagnostics of virgin soil heterogeneity as the groundwork for establishing an information support system for soil research, as well as automated monitoring systems for agricultural land, are presented on the example of the soil studies of the Mikhailovskaya virgin land which is the only preserved area of virgin meadow steppe in the Forest-Steppe zone of Ukraine. Parameterization of soil properties and vegetation indices in classes derived from decoding of satellite imagery data and presented as a power-law probability distribution or geostatistical indicators are shown to provide a quantitative description of soil heterogeneity and are recommended for the purpose of comparison multitemporal satellite images as a high-sensitivity method to determine changes in their condition due anthropogenic influences.

Key words: *heterogeneity, geostatistical analysis, soil monitoring, virgin lands, remote sensing.*

INTRODUCTION

Global climate change and the intensification of soil degradation processes (FAO, 2015) highlight the consistent improvement of the methodological framework for background (reference) monitoring (Israel, 1982), including soils (Medvedev, 2012), which is an integral and important part of the global monitoring system of environment and is necessary for the development of a unified state system of environmental monitoring in Ukraine. It should be reminded that the main task of background (reference) soil monitoring is to provide data on the input (initial or zero) assessment of soil properties and soil cover in the natural state. This allows determining the direction and intensity of anthropogenic transformation of soils and soil cover by comparing with soil data on agricultural lands (Monitoring…, 2008).

Analysis of world experience in establishing modern soil monitoring systems shows its focus on creating and periodically updating cartographic and analytical materials on soil state, the functioning of automated information system for forecasting soil changes depending on the type and intensity of anthropogenic activity; substantiation of soil protection measures, as well as evidence of the variety of used methods and approaches (Proposal for an European soil monitoring…, 2001; Medvedev et al., 2012; Kibblewhite et al., 2008; King et al., 1995; Soil monitoring in Europe, 2021). At the 13th meeting of the Parties to the United Nations Convention to Combat Desertification in Ordos, China, the countries emphasized the importance of involving space scanning data as the latest source of objective information on the state of the Earth's surface in existing systems on monitoring the state of the environment and environmental management (UNCCD documents…, 2017). The use of high-resolution multispectral satellite images, which typically have geographical compliance, continuity, and are regularly updated, seems to be the promising approach to ensuring compliance to high requirements for the accuracy and impartiality of the data on the national soil resources. Additionally, satellite images, as up-to-date digital materials, in conjunction with modern geographic information systems, provide means of precise determining the soil heterogeneity, both in detailed and large-scale surveys.

In connection with the above, the purpose of the study is to determine the fundamental possibility and methodological basis for the use of space scanning data for background monitoring of soils. The main tasks of the research include analysis and generalization of existing theoretical and methodological principles of background monitoring in Ukraine, improvement of soil monitoring based on the results of thematic decoding of space scanning data, as well as the definition and development of methodological approaches to combining the results of decoding space images and sample ground research to determine the dynamics of changes in the state of the Earth's surface within protected areas.

MATERIALS AND METHODS

A practicing of a creation of system for using high-resolution multispectral space scanning data to research of reference or virgin soils based on space scanning data was carried out on the example of the Mykhailivska virgin land. This polygon occupies 50 ha in Sumy region.

The test polygon is located in one of the northeast physical and geographical areas of the Livoberezhno-Pridneprovsky Territory of the Forest-Steppe Zone of Ukraine (National Atlas of Ukraine, 2007), which has the predominantly flat broad-wavy relief. Annual rainfall in this territory is from 550 to 450 mm, the average annual air temperature is 6-7 C (Marinich & Shishchenko, 2005). On the territory of the Mykhailivska virgin lands it is preserved a forb-fescue meadow steppe with northern and southern species of steppe plants, in the development of which seasonal changes are well expressed.

We tested developed technologies for determination of the Earth's surface state using Landsat-8 satellite data that provides digital images of the Earth's surface in the multispectral bands. It should be recalled that the Landsat 8 satellite payload consists of two science instruments - the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). These two sensors provide seasonal coverage of the global landmass at a spatial resolution of 30 meters (visible, NIR, SWIR); 100 meters (thermal); and 15 meters (panchromatic). USGS leads post-launch calibration activities, satellite operations, data product generation, and data archiving at the Earth Resources Observation and Science (EROS) center.

Research included: statistical analysis and clasification of multitemporal images of virgin lands, analysis of archival data of field investigation of virgin soils and laboratory analysis of soil samples, expert assessment of image complexity and analytical results as the basis for image classification and soil-cover models, parameterization and geo-statistical analysis of the spatial variation of soil indicators, and extrapolation procedures based on interpretation of spectral signatures.

Using a GPS, a regular grid of elementary sites was established (100 × 100 m) for 48 soil sampling were collected from the 0-30 cm layer, and 2 soil cuts were dug to characterize the soils (morphological structure of the soil profile, depth of humus profile, spatial configuration of plow layer) in the field. Samples were collected according to Soil Survey Standards of Ukraine (ISO 10694:1995, DSTU 4287:2004, DSTU 4728:2007, DSTU 4730:2007). Also in the field it was investigated the physical soil properties (bulk density, soil penetration resistance - according to DSTU 5096:2008). At the laboratory-analytical stage of the research, it was determined: total humus content (DSTU 4289:2004); pH (DSTU ISO 10390:2007); granulometric composition by the method of pipetting in the modification by N.A. Kaczynski (DSTU 4730:2007); the content of mobile compounds of phosphorus and potassium by Chirikov's modified methods (DSTU 4115:2002).

Statistical and data processing methods used ENVI and TNT programs for pre-processing of space images, NDVI calculation, primary image processing, transformation, general statistical analysis and image classification; and STATISTICA 10 for variance, correlation and regression analysis.

RESULTS AND DISCUSSIONS

The concept of background monitoring was introduced and developed in the scientific works of Yu.A. Israel (1974; 1978; 1984). According to modern ideas, background monitoring is a spatio-temporal observation of components of the natural environment or factors that lead to their change, in given spatio-temporal intervals to assess variations in their quality and quantity V.V. Medvedev (2012). Despite significant theoretical elaboration of the issues of creating a system of integrated background monitoring (Israel et al., 1980; Gromov et al., 2015), it should be recognized that background monitoring in Ukraine as a system of constant monitoring changes in the properties of soils in space and time, which have state status and reflect natural diversity, as well as all types of economic use of soils, is at the stage of initial restoration.

One of the main factors is the lack of clear reference criteria, in particular for the assessment of soil parameters. However, there are developments on this issue in Ukraine. Thus, V.V. Medvedev (2012) substantiated the idea of multiple standards. For example, in the study of ancient arable soils, it is recommended to use as standard the soil parameters obtained at the beginning of observations, including materials of large-scale soil survey of Ukraine 1957-1961 and the results of the first round of observations for agrochemical land certification (Bylugin et al., 2019).

Scientists also allow the use of optimal parameters of physical, physicochemical (pH), agrochemical (humus and nutrients) properties of soils, which are known for most crops grown in Ukraine (Medvedev, 2012; Optimal parameters…, 1984; Medvedev, 1988; Nadtochiy et al., 2003; Nadtochiy et al., 2019; Nadtochiy, 2013) and indicators of particularly valuable soils, which are characterized by optimal or close to them parameters of morphological, physical, chemical, physicochemical and technological characteristics that allow to realize the potential of climate, plants to develop accurate agricultural technologies (Medvedev et al., 2015).

In our opinion, the best standard is the parameters of virgin soils, which are not subject to intense anthropogenic impact and have purely natural cycles of substance transformation and soil genesis, are characterized by high stability of textural and structural components, moisture balance and chemicals. Therefore, the comparison of such soil with the developed one is able to provide useful information about the change of soils and soil cover in the conditions of economic activity. In Ukraine, which is characterized by a high level of plowed land, the use of fallow lands that have not been cultivated for at least 20-25 years can be considered an acceptable standard. In general, at present, in Ukraine, background monitoring has not been introduced in any department, and there is no uniform methodology for its conduct and there is a lack of accumulated data on background indicators of virgin soils.

Two main trends in diagnostics and evaluation of soil cover state were determined by addressing the multivariateness of the problem of soil monitoring and considering the specifics of satellite imagery digital data. The first one is determination and evaluation of the estimated heterogeneity of the Earth's surface image, which involves spatial and structural, abstract mapping of units, as well as representation of their relative spatial position and their spatial structure with a pre-set geometric and topological similarity. The second trend comprises a quantitative evaluation of a soil heterogeneity by certain characteristics of soils using methods of statistics and geostatistics. The primary outcome of a soil lateral heterogeneity evaluation is a range of geostatistical parameters, which confirm the predictability of spatial variation of soil characteristics; while intermediate outcomes include digital soil maps.

Both directions of using space survey data to determine the heterogeneity of the Earth's surface and soil cover are well developed on arable soils of Ukraine. However, background soil monitoring is a more complex case for space-based observations, as the soil surface is always covered with vegetation or residues, making it impossible to determine soil properties and soil peds by direct decoding features. In this regard, a possible way to observe the state of virgin soils is to determine the system of vegetation indices within virgin lands, construction of different time cartographic materials based on them and conducting periodic ground surveys during which soil samples are taken to determine a wide range of indicators, pedotransfer modeling and soil state assessment. At the same time, the prerequisites for effective background monitoring of soils and soil cover are a regular network of main sampling points, identification of permanent sites for detailed geobotanical description and use of landscape indication methods, equidistant observations, a wide range of indicators, in situ and on- line, cartographic identification of areas characterized by the greatest changes in the state.

The testing of methodological bases of using multispectral space scanning data for background monitoring was performed on the example of the soil studies of the Mykhailivska virgin land which is the only preserved area of virgin meadow steppe in the Forest-Steppe zone of Ukraine. The soil cover of the reserve is mainly represented by typical medium loam chernozems, which are confined to placors and low slopes. These soils are characterized by sufficiently high natural fertility, high humus content, significant reserves of nutrients, saturation of the soil colloidal complex with metabolic bases and, especially, calcium, neutral (or close to it) reaction of soil solution.

A more detailed description of typical chernozems of the Mykhailivska virgin land is given in the works of O.A. Chesnyak et al. (1970), N.M. Breus (1968), N.I. Laktionov (1974), V.V. Degtyarev (2011). Some average parameters of virgin soil are presented in Table 1.

Table 1. Average parameters of virgin typical medium loam chernozem of Sumy region (Mykhailivska virgin reserve) (Medvedev, Plisko, 2005)

Indicator, units of measurement	Value	Indicator, units of measurement	Value
Total humus content, % mass	6.3	Content of agronomically valuable aggregates (10-0.25 mm), %	80-85
Equilibrium structure density, g/cm^3	1.1-1.2	Clusters of blocks (>10 mm), %	5-7
Water permeability at equilibrium density, mm/year for 6 hours	65-70	Coefficient of water resistance of the structure	0.7-0.8
Dispersion factor	4.0	Dust content (<0.25 mm), %	8-10
Suction coefficient	1.1-1.2	Coefficient of water resistance of the structure	0.7-0.8

Since the cosmic image of virgin lands is determined mainly by natural associations of plants, we also analyzed information about the vegetation of the meadow steppe of Mykhailivska virgin land, which is highlighted in detail in the scientific works by Ye.M. Lavrenko and I.G. Zoza (1928), S.S. Kharkevich (1956), G.I. Bilyk and V.S. Tkachenko (1972; 1973) and confirmed by ground surveys. In particular, it is determined that the characteristic formations for this meadow steppe are (Geobotanical zoning of the Ukrainian SSR, 1977):

1. *Cytiseta ruthenici* with the association *Cytisus ruthenicus*, *Stipa capillata* + *Poa angustifolia* + motley grass;

2. *Stipeta pennatae* with the association *Stipa pennata* + *Poa angustifolia* + *Salvia pratensis*, *Fillipendula hexapetala*;

3. *Stipeta capillatae* with the association *Stipa capillata* + *Festuca sulcata* + *Carex humilis* + *Salvia nutans*, *Fillipendula hexapetala*, *Carex nutans*;

4. *Helyctotrichoneta pubescontis*.

The westernmost locations of *Zerna riparia* Nevski and *Phlomis pungens* Willd (Geobotanical Zoning) are also marked on the Mykhailivska virgin land.

Since soil quality can be considered as a measure of how soil functions (it is the capacity of a soil to sustain its functions, including biomass production, storage, filtering, buffering and transformations of natural and anthropogenic produced substances, a biological habitat and gene reservoir and a sink for carbon (Schjønning et al., 2004) so the use of vegetation indices obtained by satellite imagery data can be considered as indirect indicators to the integral assessment of soil quality and state of soil cover.

The state of natural vegetation quite often reflects changes in the physical properties and regimes of the soil, which are determined by both anthropogenic human activity and climate change.

With this approach, significant changes in soil regimes or properties will affect the optical characteristics of the leaf surface of natural plants, especially in the initial stages of its vegetation, as the area, number of leaves and their sizes are important phytometric indicators that depend on plant growth conditions and

play an important role in their photosynthetic activities.
We selected two images of Landsat 8 (shooting dates 07.05.2014 and 10.05.2019), which were taken in the absence of clouds, had a complete set of metadata, which allowed us to develop a complete algorithm for thematic decoding, which involved radiometric and atmospheric image correction, NDVI calculation, its statistical analysis and classification.
Comparative analysis of algorithms of uncontrolled classification of space scan data showed greater efficiency for determining the contours of a small area of the ISODATA method compared to the K-means algorithm, which implements only local minimization of the functional.
Statistical analysis of the data showed that the classification of NDVI values from the 2014 space image allowed us to distinguish the virgin land and establish the confinement of classes to certain areas of the surface that differed in steepness and solar exposure (Figure 1).

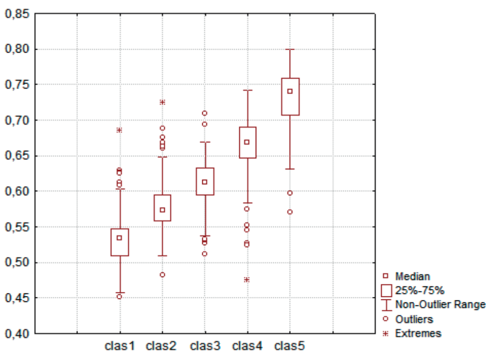


Figure 1. Statistical analysis of NDVI values (from the 2014 space image) allowed to classification the virgin land

Geostatistical modeling of sample field data was carried out on a complex of soil indicators for interpretation and spatial analysis of the constructed NDVI cartogram.
The research also used the method of dynamic mapping, which consists in the creation and analysis of differential spectral images obtained from different time space images in digital format.
In our case, the use of difference images was in finding differences between NDVI cartograms obtained during image processing in 2014 and 2019 and was achieved by calculating the difference between NDVI values to determine areas of the Earth's surface that did not change much over time and were very contrasting in comparison with sites that significantly changed their optical characteristics and NDVI values.
Comparison of cartograms of soil properties obtained by geostatistical modeling, as well as difference images revealed that the largest changes in the optical characteristics of vegetation were characteristic of virgin areas in the upper part of the slope and had the lowest values of total humus content (about 6.5-7.0%).
Also in our opinion, the results of this study make it possible to use probabilistic-statistical modeling of the lateral heterogeneity of the soil and vegetation cover based on satellite imagery for monitoring purposes. It is determined that the representation of variation of NDVI and soil properties within the highlighted contours in the form of a probability distribution law completely solves the task of quantitative description of soil heterogeneity, which is recommended for comparing the results of decoding of different temporal images of the virgin land.
Comparative analysis of the results of decoding of different-time space images of the Mykhailivska virgin land was carried out on a quantitative assessment of the complexity of spatial differentiation, which is known from the theory of geographical science. In particular, the information model of territorial differentiation of Mykhailivska virgin land was calculated by calculating several information indicators of complexity. It should be reminded that the indicator of complexity in the information model of territorial differentiation is the information (entropic) diversity function, which is based on the probabilistic formalization of territorial dismemberment, which is represented as the ratio of the area of each contour (S_i) to the total area ($S_з$). (Gerenchuk et al., 1975):

$$p_i = S_i / S_з,$$

where:
p_i - probability of the i-th element of territorial division;
s_i - area of each contour, m^2;

s_3 - total area, m^2.

Spatial systems, the elements of which can be given by probabilities with the prerequisite that the sum of all probabilities is 1.0, have an information index of diversity or complexity of morphological division, which is calculated by the K. Shannon's formula:

$$H = -\sum p_i \log_2 p_i ,$$

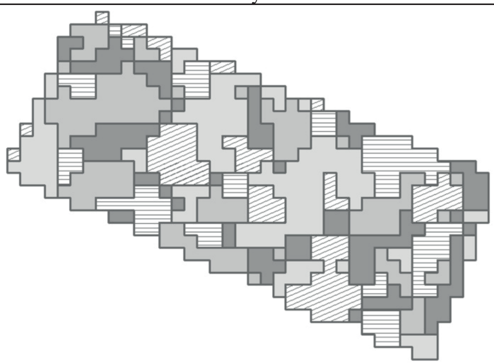
where:

H - information indicator of diversity;

p_i - probability of the i-th element of territorial differentiation.

Let's illustrate its calculation on the example of the results of the classification of NDVI values within the Mykhailivska virgin land by different time space images (2014 and 2019). Information modeling of this landfill was carried out in several stages. Firstly, the area of each of the *Si* areas selected as a result of image classification was determined using GIS. Secondly, for each area the value of the probability *pi* is set, according to which the value of the function - $p_i log_2 p_i$ is found (Table 2). Thirdly, these values were summed up to determine the information indicator of the complexity of the territorial division of the landfill, which amounted to 5.26 in 2014 and 3.99 in 2019.

Table 2. Comparative analysis of the results of the classification of NDVI values within the Mykhailivska virgin land, conducted by the method of Isodata at the level of 5 classes

Cartographic results of NDVI value classification	
2014 year	2019 year
	

Class number, symbol on the map	General characteristics of the contours		Class number, symbol on the map	General characteristics of the contours	
	Number of contours	Area (m^2)		Number of contours	Area (m^2)
1	12	82800	1	4	94000
2	14	120600	2	13	65050
3	12	99000	3	10	114354
4	13	118800	4	6	158696
5	12	77400	5	5	66490
The total area of virgin land - 498600 m^2					

Indicators of the information model of territorial differentiation		
2014	Indicators of the information model	2019
5.26	Information complexity indicator - *H*	3.99
5.98	Theoretical the maximum possible degree of complexity of dismemberment for this division - *Hmax*	5.04
0.72	Indicator of imbalance - *ΔH= Hmax-H*	1.06
0.12	Indicator of relative imbalance - *I = ΔH/ Hmax*	0.21

Correct interpretation of this indicator is that a single degree of complexity (1 bit) has the simplest structure, which represents the division of the territory into two equal, and therefore equally likely parts (Gerenchuk et al., 1975). Undifferentiated territory, represented by one whole contour, has zero degree of complexity, because its probability is 1.0. An increase in the number of elements of territorial division or a change in the ratio of their areas is recorded by the corresponding changes in the information indicator of complexity (Gerenchuk et al., 1975). Thus, the established parameters show how the complexity of territorial differentiation depends on the number of elements of territorial differentiation and how much on the ratio of their areas.

If the components of the territorial division were absolutely equal (equally probable), the informational degree of complexity of the division could depend only on the number of units of division and would be the maximum possible for this differentiation (Gerenchuk et al., 1975):

$$H_{max} = log_2 n,$$

where:

H_{max} - the maximum possible level of information complexity;

n - number of units of territorial differentiation.

Thus, to assess the results of the classification of images of Mykhailivska virgin land, taken in 2014, there are two informational estimates of complexity: real (equal to 5.26) and theoretical, i.e. the maximum possible for division into 63 areas, which is 5.98. Since the second (maximum possible) complexity indicator is calculated under the condition of absolutely equal dismemberment, it is clear that the difference between the actual and maximum estimates exists due to the deviation of the actual areas of territorial division from the theoretical equal. This difference is an indicator of the imbalance of territorial differentiation is calculated by the following formula (ΔH) (Gerenchuk et al., 1975):

$$\Delta H = H_{max} - H$$

Thus, the information index of complexity increases rapidly with increasing number of units and decreases with increasing fluctuations in their size. The imbalance index (H_{max}) is an absolute value that characterizes the imbalance of spatial differentiation as a whole. The ratio of this value to the maximum degree of complexity is an indicator of the relative imbalance of territorial differentiation (I) (Gerenchuk et al., 1975):

$$I = \frac{\Delta H}{H_{\max}} = \frac{H_{\max} - H}{H_{\max}}$$

The simplicity of the presented approach allows us to conclude about the prospects of its use in generalizations and comparative analysis of the results of processing different time space scanning data and the development of automated cartographic data analysis systems for remote monitoring of land resources. Since the complexity indicator takes into account the dependence of the complexity of dismemberment both on the number of constituent parts of the territorial division and the ratio of areas of its elements, therefore, this approach can be effective in quantifying changes in the complexity of the image of territorial objects due to degradation processes in the context of increasing anthropogenic pressure or global climate change.

However, it should be noted that the use of the above approach is appropriate only if you use images taken in similar conditions of the soil surface, as well as using the same methods and settings of image classification, which allows comparing results of contour decoding of the Earth's cover at different times of space images.

The analysis of the indicators of the information model of Mykhailivska virgin land allows us to conclude that there is a pronounced tendency to reduce the information indicator of the complexity of territorial division (more than 1.0) in five years, as well as a significant increase in imbalance and relative imbalance. In our opinion, this may indirectly indicate a decrease in the natural diversity of virgin areas and justify the need for terrestrial, detailed geobotanical and soil research in the near future. The obtained cartographic materials also allow us not only to plan ground research, but also to significantly optimize it, which will have a positive impact on the cost of field work.

CONCLUSIONS

Academic novelties in the results presented herein, include justification and development in the fundamentals of practical methodology for thematic processing of satellite imagery data for diagnostics of the state of virgin soils as a basis for creating a modern system of information support for background monitoring of soils.

We propose to establish the exact identification of components of soil evaluation system based upon the geoinformatics principle, including the number of samples and the distance between sampling points, involving a geostatistical analysis of optical characteristics of virgin lands according to the spatial imagery data. It ensures the identification of a predictable component within a variation of soil properties and its spatial direction (anisotropy) within a certain territory. The basic requirement for this approach to organizing surveys is the need for accurate georeferencing of sampling points and sites of soil profiles using GPS devices, as well as need for taking the number of entirely individual soil samples sufficient for the planned analytical research.

The results obtained from contour decoding of satellite imagery data for estimating the virgin land heterogeneity, justify the possibility of information modeling of soils, utilizing the entropy function of diversity. The simplicity of such approach allows us to recommend it for developing the automated cartographic systems designed for analyzing the data of remote monitoring of country's lands. Since the complexity factor accounts for dependence of territorial division on a number of components, as well as on a proportion of their areas, this approach appears to be preferable for rapid quantitative estimation of temporal changes in virgin soils, considering the increasing human impact or climate changes. Application of this approach is presumed to be appropriate only for images taken in similar conditions of Earth's surface, and processed by the same methods and settings for image classification, which ensures accurate comparison of results of decoding from satellite images taken in different times.

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