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THE DIAGNOSTICS AND CARTOGRAPHIC-ANALYTIC ASSESSMENT OF THE ARABLE SOILS DEGRADATION IN UKRAINE BY SPACE SCANNING DATA

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Abstract

The using of multispectral space scanning data of high spatial resolution is justified for definition and description of degraded soils on arable lands. It is established main criteries of degradation processes in soils, which can be reliably determined by the decoding results of space images. Methodological principles for multispectral satellite imagery data decoding are developed for mapping of soil cover, as well as for quantitative estimation of its complexity and lateral heterogeneity of degraded soils. A coherent analysis of satellite images decoding results and data obtained from field surveys in different regions proves the soil decoding technology for multispectral satellite imagery data in the optical range, developed herein, is highly effective for determining the elements of local soil heterogeneity, which have soil degradation. The results of verification of cartographic-analytical assessments by space survey data are presented, which will allow introducing of space-differentiated soil quality management system to their rationally use, protect and prevent the development of soil degradation.

Key words: *arable soil, diagnostics, degradation, multispectral space scanning.*

INTRODUCTION

The United Nations (UN) Report on Status of the World's Soil Resources highlights that most of the world's soil resources are in poor conditions and identifies that soil degradation continues to be one of the major environmental and agricultural threats worldwide (FAO, 2015) which affects food security and the environment.

Modern soil studies (Medvedev et al., 2020; Vozhehova et al., 2019; Shein et al., 2007; Li et al., 2020; Lema et al., 2019; Sanchez, 2019; Zhang, 2019) confirm that the condition of the soil cover has deteriorated in recent decades and has become close to catastrophic. In particular, according to the international project "The Global Assessment of Soil Degradation", it is determined that the processes of soil degradation are spread over an area of about 1.7 billion hectares (Dobrovolsky, 2002). At the same time, physical degradation of soils, defined as a set of processes that cause destruction, movement and deposition of soil particles and mass, simplification of soil structure and microstructure and negative changes in its regimes (water, air and temperature), is the greatest threat (Medvedev, 2013). Usually, physical degradation is an inevitable companion of unbalanced and excessively intensive soil use (Baliuk et al., 2012). Thus, according to the National Report on the State of Soil Fertility of Ukraine, the risk of over compaction exists on almost 22 million hectares of arable land, which causes losses of $ 160-500 million annually. In particular, the content of agronomically valuable aggregates is lower than the permissible level by almost 30% of the area of arable soils, while the probability of formation of lumps during tillage reaches 12%, which is about 3.5 million hectares (National Report on the State of Soil Fertility of Ukraine, 2010).

For Ukraine, which is characterized by a large area of arable land (32 million hectares), for which the risk of physical soil degradation is too high, an unalterable approach to monitoring adverse events on agricultural land is to use multispectral space scan data as primary digital source of information about state of soil resources. The use of space images with high-quality and spatial resolution makes it possible to do quantitative description of the state of the soil surface at the level of detailed or large-scale surveys and compared to ground research and aerial photography is much less labor-intensive and costly (Ge, Thomasson, 2011). In this regard, in Ukraine there is a usage of space survey data to create a national system of geographic information support and environmental monitoring as part of the European program "Copernicus" in the global system "GEOSS".

The logic and expediency of using space scanning data for a comprehensive study of degradation phenomena in the soil cover is confirmed by world experience (Zhang et al., 2018; Filep et al., 2016; Mirzaee et al., 2016). For example, Cavalli et al. (2020) used advanced high-resolution radiometer`s (AVHRR) data to assess soil erosion in the southeastern region of São Paulo, Brazil. X.H. Wang et al. (2011) studied the problem of soil and water loss using TM Landsat on the Loess Plateau (China). AVHRR images from the NOAA meteorological satellite, which are rapidly updated and cover a large area, are often used to monitor vegetation status by calculating a set of vegetation indices that indirectly characterize the degree of soil degradation (Thiam, 2003; Symeonakis et al., 2004).

The experience of scientists from the University of São Paulo (Brazil) (Nascimento et al., 2021) is also valuable. They proposed the use of a soil degradation index (SDI) by temporal satellite images. The results of their research indicate that soils with a higher content of physical clay have a lower risk of degradation.

In the scientific works by Omuto C.T. it is emphasized that the control of the manifestation of physical soil degradation remains a challenge for many scientists due to the lack of proper assessment protocols. The author investigated soil degradation in Eastern Kenya and consistently applied a soil testing model to determine the phases of physical degradation. Visual assessment of signs of degradation, RUSLE model and diffuse infrared spectral reflection were used in the model of soil testing as predictors (prognostic parameters) of physical degradation. Visual assessment proved to be a cheap and fast method of determining the final stages of physical degradation with an accuracy of 60%. Visual evaluation in combination with the RUSLE model increased the evaluation accuracy to 80%. Infrared spectral reflection, which is sensitive to slight changes in soil physical conditions, was also identified as a potential predictor of early signs of physical soil degradation (Omuto, 2008).

Belarusian scientists (Olshevsky et al., 2018) emphasize that the development of technologies for collecting, processing, storing and using space surface scanning data, reducing their cost, the ability to select channels for spectral scanning of the Earth's surface and observation period, as well as obtaining relevant data and applications of automation software allows us to consider these methods as the most acceptable for detecting and mapping the processes of degradation and degraded lands.

The above highlights the need to develop a system for using multispectral high-resolution space scanning data to identify and quantify areas of soil cover within agricultural lands that are prone to degradation processes, in particular, physical degradation.

MATERIALS AND METHODS

A practicing of a creation of system for using high-resolution multispectral space scanning data to identify and qualitative assessment of soil cover areas within agricultural lands, based on space scanning data was carried out on the example of the Romaniv polygon. This polygon occupies 60 ha in Volyn Region.

The test polygon is located in one of the northern physical and geographical areas of the Volyn upland region (Volyn Opillya) of the Western Ukrainian region of the zone of deciduous forests of Ukraine (National Atlas of Ukraine, 2007), which is a flat and hilly areas that emerged among forests in the process of their ancient agricultural development. The main features of this area are due to the spread of forest rocks and the increase of Upper Cretaceous sediments, which are soil-forming rocks together with sands, sandy clays and Lower Sarmatian limestones (Marinich, Shishchenko, 2005). The most common are dismembered hills with dark gray and gray forest soils, forming a wavy plain, which is divided by beams with slopes, which have wide waterlogged bottoms. The sandy loam composition of most soils contributes to the development of erosion processes, which necessitates the implementation of soil-protective agriculture.

We have tested developed technologies for determination of degraded soils using Sentinel-2 satellite data that provides digital images of the Earth's surface in the multispectral bands with a resolution of 10 m. These data is a multispectral operational imaging mission within the GMES (Global Monitoring for Environment and Security) program, jointly implemented by the EC (European Commission) and ESA (European Space Agency) for global land observation at high resolution with high revisit capability (Sharing Earth Observation Resources…). Imagery was acquired on 29 April 2018 from the bare, dry soil surface.

Research included: statistical analysis of the image, creation of a provisional soil map and system of soil sampling, field investigation of the soil pattern 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.

With the aid of a GPS, a regular grid of elementary sites was established (one per 2 ha) for 35 soil sampling were collected from the 0-10 and 10-20 cm layer, and 6 soil pits 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).

Statistical and data processing methods used SNAP ESA 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

According to basic research on the description of anthropogenic soil degradation by individual elementary soil processes and their combinations, 13 main types were identified (Krupenikov, 2005), which, in our opinion, can be used for a large list of soil types. The analysis of these types of degradation showed that most of them can be directly or indirectly determined from high-resolution space survey data, in particular: humus degradation and dehumification; physical and hydrological degradation; deflationary degradation or wind erosion of soils; irrigation degradation and deterioration of soil material composition and significant reduction of soil bioproductivity and quality, crop yield. The aggregate manifestation of various degradation processes causes geographical or spatial degradation of the soil, which is manifested in the complication of the structure of the soil cover within agricultural lands.

Due to the fact that aerospace methods in soil science are based on the study of the spectral reflectivity of the soil surface layer (Gebrin-Baidi, 2016; Orlov, 2001; Schmid et al., 2016; Žížala et al., 2017) it is possible to determine and monitor degraded soils based on the results of contour decoding of space scanning data with high and ultrahigh spatial resolution. In the development of this direction, as a result of the conducted research the system of cartographic-analytical definition of degraded soils on the basis of decoding of space survey data is developed (Figure 1).

The information block of this system is a meaningful basis, which is stored in the form of databases for further analysis, processing, assessment, multi-purpose search and replenishment. Data are collected both from surveillance networks for environmental monitoring, primarily from those that use space scanning data, and from third-party sources (administrative bodies, design and production organizations, foundations, scientific libraries, archives, etc.).

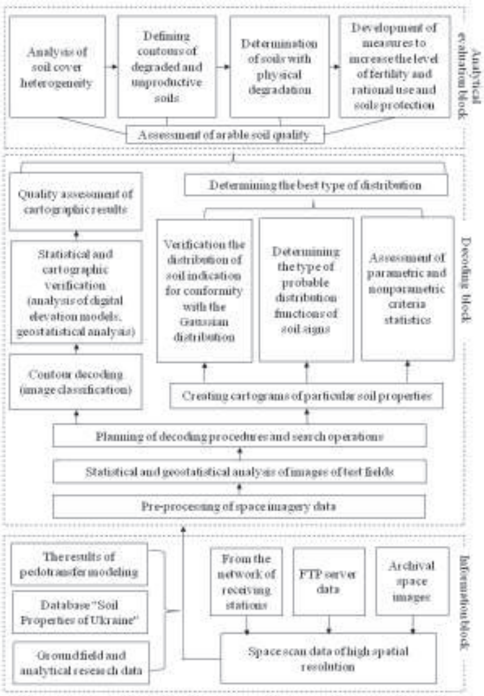

Figure 1. System of cartographic-analytical determination of degraded soils on the basis of space scanning data

The information that is received and stored is usually unified, i.e reduced to a form that is convenient for further use in a database for decoding space scanning data.

The decryption (decoding) unit is a set of basic procedures aimed at transforming digital information of multispectral high-resolution space images into useful information for soil scientists on the patterns of distribution of soil differences and their quantitative description. It implies the use of various methods and technologies, including: technology for collecting and transmitting information, collecting and maintaining long-term archives of information, pre-processing of space scanning data and their classification, conducting ground research and analysis of soil samples, and methods of coherent data analysis ground and remote sensing of agrocenoses, dynamic mapping and operative presentation of the results of cartographic modeling of the soil cover on the basis of space images.

The block of analytical estimation provides the complex analysis of results of decoding by use both exact methods of data processing (mathematical modeling), and their expert estimation directed on definition of degree of degradation of arable soils, and first of all their physical degradation, and on development of measures for increasing their fertility, rational use and protection.

Elaboration of the developed methodical approaches is carried out on the example of the polygon "Romaniv".

Preliminary data analysis included collecting thematic information about the study area and schematic linkage of thematic data with major interpretive features of the satellite imagery: brightness and structure of the image (the size and shape of features of the land surface and the nature of brightness distribution within them). The first stage in decoding the imagery was definition of common statistical indicators and analysis of distribution curves of its optical brightness, which showed that the variation has several modal values and, thus, the image of the bare soil surface encompasses diverse objects. Analysis of plots of the optical brightness of the image suggested that the soil cover of polygon could best be depicted by three distinct mapping units. The provisional soil map (Figure 2) was created in the final stage of image processing by the K-means method of cluster analysis.

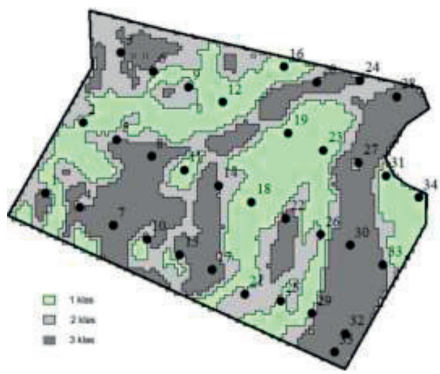

Figure 2. Soil map of the Romaniv polygon, with derived from classification of Sentinel-2 satellite data (the processing of a space image and the construction of a schematic map was carried out with the participation of leading engineer of Soil Erosion Control Laboratory and Remote Sensing Alexander Sherstyuk)

Further, we observed correspondence between soil delineations and individual elements of the micro-relief (micro-watershed, breaks in slope, bottom of a drainage hollow, etc.) so the map reflects a certain orderliness of the soil cover; its boundaries separate soil bodies with specific internal structure and variability characteristics. Joint analysis of the constructed contour map, the results of the field survey and the archival soil map confirmed the effectiveness of the decoding of multispectral imagery for identification of soils with different physical properties, which are the main criteria for physical degradation of soils. The taxonomic units represented by the mapping units in Figure 2 are listed below, according to the Ukrainian soil nomenclature and the World Reference Base (WRB), using the scheme for harmonisation drawn up by Medvedev and others (Medvedev et al., 2003; Soil heterogeneity…, 2009):

1. Conformed with the combination of Chernozem podzolized, Meadow-chernozemic and Meadow soils (Chernic chernozem, Phaeozems Haplic and Umbrisols Greyis in WRB);
2. Conformed with the combination of Light gray and Gray podzolized soils and Dark gray podzolized soil (Eutric Podzoluvisols, Gleyis Greyzems, Haplic Greyzems in WRB);
3. conformed with the combinations soddy medium podzolic soils loamy sand and Dark gray podzolized soil (Gleyic podzoluvisols and Haplic Greyzems in WRB).

Graphical representation of the variation of the main indicators of soils, determined according to ground sample surveys (training sample), showed a significant difference in classes, determined on the basis of the cosmic image by median value and interquartile distance (Figure 3). The most significant difference was between class 1 and two other classes - 2 and 3. The identified soil classes are well differentiated by the total humus content (Figure 3*a*) and pH (Figure 3*b*). There is also a significant difference for soil penetration resistance in layers of 0-20 and 20-30 cm (Figure 3*e*, 3*f*). In particular, the lowest values of soil penetration resistance are characteristic of the most humus class of soils – the combination of Chernozem podzolized, Meadow-chernozemic and Meadow soils (Chernic chernozem, Phaeozems Haplic and Umbrisols Greyis in WRB). At a time when for low humus soils there was an increase in soil penetration resistance from 18 to 24 kgf/cm^2 in the layer of 0-20 cm, from 24 to 36 kgf/cm^2 in the layer of 20-30 cm.

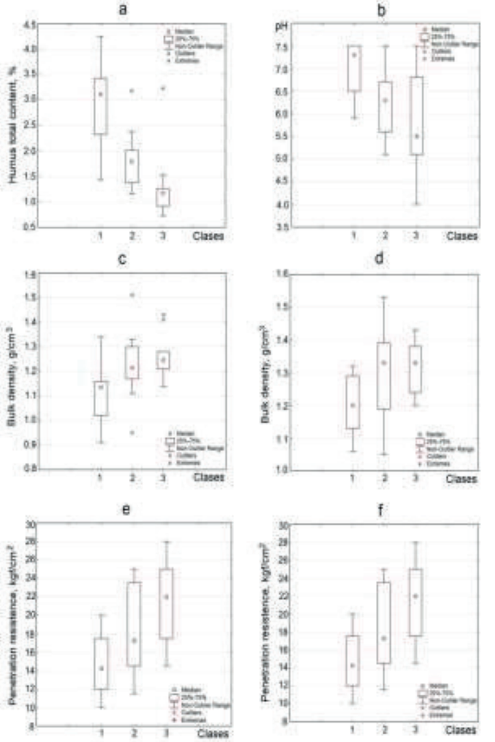

Figure 3. Graphical representation of the main statistics of soil indicators for soil classes, which determined by space survey data

For the density of the soil structure, the difference between 2 and 3 classes is less significant. The density of Light gray and Gray podzolized soils and Dark gray podzolized soil (Eutric Podzoluvisols, Gleyis Greyzems, Haplic Greyzems in WRB) and soddy medium podzolic soils loamy sand and Dark gray podzolized soil (Gleyic podzoluvisols and Haplic Greyzems in WRB) in the surface layer is about 1.2 g/cm^3, for a layer of 15-20 cm - more than 1.3g/cm^3 (Figure 3*c*, 3*d*). At a time when the more humus soils was characterized by a value of about 1.1 g/cm^3.

In general, with the spatial analysis of the distribution of experimental soil characteristics it is determined that this landfill is characterized by low supply of organic matter (50% of the area contains less than 2% of the total humus content), moderate (17% of the area) and high (1%) acidity. At the same time, approximately 70% of the landfill area has a structure density in the seed layer of less than 1.3 g/cm^3. Not more than 30% of the field is over compacted at the depth of the plow sole (structure density is more than 1.4 g/cm^3).

According to the known approaches to the assessment of physical properties of soils, the structure of the soil with values of equilibrium density from 1.2 to 1.4 g/cm^3 is considered to be insufficiently stable and potentially susceptible to physical degradation (Kuznetsova, 1979). And thus, we can conclude that according to this indicator, a third of the area of the landfill (distribution of class 3 according to the decoding) has signs of physical degradation, which requires the development of differentiated agricultural technologies.

At the next stage of data processing, two-dimensional models of soil penetration resistance distribution within the landfill were analyzed (Figure 4). It was found that the spatial distribution of this indicator does not coincide with the contour of the archival soil map (scale 1:25000), while it is interrelated with the contour of the allocations, which is determined by space survey data.

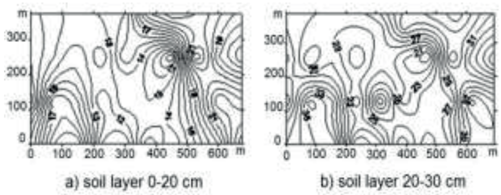

Figure 4. Two-dimensional models of soil penetration resistance distribution (Medvedev, 2009)

Comparison of the contour of the newly created map (Figure 2) with the archival soil map of the polygon allowed determining their significant difference, which is explained, first of all, by the difference in approaches to their creation.

Thus, the traditional approach in genetic soil science (thanks to which all existing soil maps in Ukraine were created in the period from 1961 to 1990 of the last century) is dominated by the use of soil-geographical principle in determining soil differences, which to some extent ignores the lateral heterogeneity of soil properties complex: morphological, physical, physico-mechanical, etc. Data from space scanning and decoding results make it possible to determine another type of soil contour, which provides, above all, accurate information about the regular variation of the complex of soil properties in the soil surface, which often allows an experienced specialist to determine its genetic affiliation.

In this regard, the analysis of the contours of soil maps, built on multi-temporal data from high-resolution space scanning, is appropriate and informative enough to determine the degradation processes in soils due to unbalanced agriculture. At the same time, at the initial stages of development of physical degradation there is an increase in the lateral heterogeneity of the whole complex of soil properties, which directly or indirectly form the optical characteristics of the soil surface. The constant increase in soil heterogeneity causes a very negative phenomenon for precision agriculture – "motley field". Thus, the increase in the total number and complexity of contours, which is established by the results of contour decoding of different time space information, may be evidence of the cumulative manifestation of various degradation processes within agrocenoses.

In general, according to the results of research on the test polygon, taking into account the ratio of areas characterized by different values of soil penetration resistance and density of the soil structure, the implementation of precision farming technologies is recommended. In particular, within the polygon it is advisable to practice no-till and minimum tillage instead of zonal pre-sowing and plow tillage for 1 class of soils, which is determined by space scanning data. It is also appropriate to use technologies of differentiated deep tillage to eliminate excessive density in the plow sole and eliminate acidity by liming for 2nd and 3rd classes.

CONCLUSIONS

The use of the results of decoding the data of multispectral space scanning of high spatial resolution to determine the contours of arable soils prone to degradation is updated.

A system of cartographic-analytical determination of degraded soils on the basis of space scanning data is proposed, which provides a comprehensive and expert analysis of the results of decoding space images by accurate data processing methods, aimed at determining the degree of degradation of arable soils by physical properties.

Approbation of the developed methodological approaches to assessing the condition of arable soils, carried out by Sentinel-2 satellite data, proves their effectiveness for spatial differentiation of soil cover, which determines soil areas that are significantly different in terms of soil density and soil penetration resistance.

It is substantiated the expediency of the analysis of the contour of soil maps, based on multi-temporal data of space scanning of high spatial resolution, for determination of degradation processes in soils due to unbalanced agriculture.

Directions for further research include the systematization of equations which explain the relationship of optical properties of the soil surface with fundamental physical and chemical properties, so as to make real and useful differentiation of soil quality from satellite imagery.

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REFERENCES

Balyuk, S.A., Medvedev, V.V., Miroshnichenko, M.M., Skrylnyk, E. V., Tymchenko, D. O., Fateev, A. I., Khristenko, A. O., & Tsapko, Yu. L. (2012). Ecological condition of soils of Ukraine. *Ukrainian Geographical Journal*, *2*, 38–42.

Cavalli, A.C., Neto, F.L., Garcia, G.J., Junior, J.Z. (2000). Use of AVHRR/NOAA-14 multi-temporal data to evaluate soil degradation. *Acta Scientiarum*, *22*(4), 1037–1043.

FAO (2015). *The Status of the World’s Soil Resources: Main Report*. Rome, 650 pp.

Filep, T., Zacháry, D., Balog, K. (2016). Assessment of soil quality of arable soils in Hungary using DRIFT spectroscopy and chemometrics. *Vib. Spectrosc*. *84*(1), 16–23.

Ge, Y., Thomasson, I. A. (2011). Remote Sensing of Soil properties in Precision Agriculture: A review. *Frontiers of Earth Science*, *5*(3), 229–238.

Gebrin-Baidi, L.V. (2016). Deciphering space images to determine the particle size distribution of the soil. *Materials XVI International. scientific-practical conf. "Flight. Modern problems of science "*. Kyiv, 6-7.

Krupenikov, I.A. (2005). Typification of anthropogenic processes of chernozem degradation. *Soil Science, 12*, 1509–1517.

Kuznetsova, I.V. (1979). On some criteria for assessing the physical properties of soils. *Soil Science, 3*, 81–88.

Lema, B., Mesfin, S., Kebede, F., Abraha, Z., & Fitiwy, I. (2019). Evaluation of soil physical properties of long-used cultivated lands as a deriving indicator of soil degradation, north Ethiopia. *Physical Geography*, *40*(4), 323–338, doi: 10.1080/02723646.2019.1568148.

Li, G., Li, X., Chen, W., Li, J., Zhu, H., Hu, X., Zhou, H., & Sun, H. (2020). Effects of degradation severity on the physical, chemical and mechanical properties of topsoil in alpine meadow on the Qinghai-Tibet Plateau, west China. *CATENA*, 187, doi: 10.1016/j.catena.2019.104370.

Marinich, O.M., Shishchenko, P.G. (2005). *Physical Geography of Ukraine: Textbook*. Kyiv: Printing House Znannya, 511 pp.

Medvedev, V.V. (2013). *Physical degradation of chernozems. Diagnosis. Reasons. Consequences. Warning.* Kharkiv: City Printing House, 324 pp.

Medvedev, V. V. (2009). *Soil Penetration Resistance*. Kharkiv: 13 Press, 152 pp.

Medvedev, V.V., Laktionova, T.M., Kanash, O.P. (2003). *Soils of Ukraine (genesis and agronomic characteristics)*. Kharkiv: University Publishing House, 68 p.

Medvedev, V.V., Plisko, I.V., Krylach, S.I., Nakisko, S. G., & Uvarenko, K. Yu. (2020). *Physical degradation of arable soils of Ukraine (assessment, prevention, suspension)*. Kharkov: IE Brovin O.V. 110 pp.

Mirzaee, S., Dashtaki, S.G., Mohammadi, J., Asadi, H., Asadzadeh, F. (2016). Spatial variability of soil organic matter using remote sensing data. *CATENA, 145*, 118–127.

Nascimento, C.M., Mendes, W. de S., Quiñonez, Silvero, N.E., Poppiel, R.R., Sayão, V.M., Dotto, A.C., Santos, N.V. (2021). Soil degradation index developed by multitemporal remote sensing images, climate variables, terrain and soil attributes. *Journal of Environmental Management*, *277*, doi:10.1016/j.jenvman.2020.111316.

National Atlas of Ukraine (2007). Kyiv: SRPE "Cartography", 440 pp.

National Report on the State of Soil Fertility of Ukraine (2010). In S. A. Balyuk, V. V. Medvedev, O. G. Tarariko, V. O. Grekov & A. D. Balaev (Eds.), 111 pp.

Olshevsky, A.V., Samsonenko, I.P., Yatsukhno, V.M. (2018). An experimental prototype of the technology for identifying, decoding and mapping degraded lands based on satellite data. *Materials of the II All-Russian Scientific Conference with International Participation "Application of Earth Remote Sensing in Agriculture".* Saint Petersburg, 273–279.

Omuto, C.T. (2008). Assessment of soil physical degradation in Eastern Kenya by use of a sequential soil testing protocol. *Agriculture, Ecosystems & Environment*, *128*(4), 199–211. doi:10.1016/j.agee.2008.06.006.

Orlov, D.S., Sukhanova, N.I., Rozanova, M.S. (2001). *Spectral reflectivity of soils and their components.* Moscow: Publishing house Mosk. Univ., 175 pp.

Sanchez, P. (2019). Soil Physical Properties. *Properties and Management of Soils in the Tropics,* 134–175. doi:10.1017/9781316809785.008.

Schmid, T., Rodriguez-Rastrero, M., Escribano, P., Palacios-Orueta, A., Ben-Dor, E., Plaza, A., Chabrillat, S. (2016). Characterization of soil erosion indicators using hyperspectral data from a mediterranean rainfed cultivated region. *Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *9*(2), 845–860.

Sharing Earth Observation Resources: eoPortal Directory. Report available: https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/copernicus-sentinel-2.

Soil degradation and protection (2002). In. G. V. Dobrovolsky (Ed.). Moscow: Moscow State University, 654 pp.

Soil heterogeneity and precision farming. Part 2. Research results (2009). In V. V. Medvedev (Ed.). Kharkov: KP "City Printing House", 260 pp.

Symeonakis, E., Drake, N. (2004). Monitoring desertification and land degradation over sub-Saharan Africa. *Int. J. Remote Sens*., *25*(3), 573–592.

Theories and methods of soil physics (2007). In. E. V. Sheina, L.O. Karpachevsky (Ed.). Moscow: Grif and K, 616 pp.

Thiam, A.K. (2003). The causes and spatial pattern of land degradation risk in southern Mauritania using multitemporal AVHRR-NDVI imagery and field data. *Land Degradation*, *14*(1), 133–142.

Vozhehova, R.A., Hranovska, L.M. (2019). Factors of degradation and directions of soil fertility reproduction of the Southern Steppe of Ukraine. *Balanced nature management*, *1*, 75–82.

Wang, X. H., Chen, Y. F., Chen, E. X., Luo, Y. L. (2011). Quantified evaluation of soil erosion in Zhongyang county, the Loess Plateau. *Journal of Moutain Science*, *29*(4), 442–448.

Zhang, J., Bruijnzeel, A., Quiñones, C. M., Tripoli, R., Asio, V. B., Meerveld, H. J. (2019). Soil physical characteristics of a degraded tropical grassland and a 'reforest': Implications for runoff generation. *Geoderma*, *333*, 163–177, doi:10.1016/j.geoderma.2018.07.022.

Zhang, X. F., Xu, Y., Li, L. J., Dai, E. F., & Xu, W. H. (2018). Regional differentiation and classification for carrying constraints on the resources and environment of China. *Journal of Resources and Ecology, 9*(2), 135–145.

Žížala, D., Zádorová, T., Kapička, J. (2017). Assessment of soil degradation by erosion based on analysis of soil properties using aerial hyperspectral images and ancillary data, Czech Republic. *Remote Sensing*, *9*(1), 28.