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SPATIAL VARIATION OF EARTHWORM COMMUNITIES IN THE MOTORWAY PROXIMITY

Oleksandr Harbar [1], ***Viktoriia Moroz*** [1], ***Diana Harbar*** [1], ***Dmytro Vyskushenko*** [1], ***Oleksandr Kratiuk*** [2]

[1] *Zhytomyr Ivan Franko State University, 40 Velyka Berdychivska St., Zhytomyr 10008, Ukraine*
[2] *Polissia National University, 7 Stariy Bulvar St., Zhytomyr 10002, Ukraine*

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Background. The spatial features of the structure of earthworm communities in the area of influence of motor vehicles were analyzed. Five species of lumbricides belonging to three families were found in the studied biocenosis located near the M06 Kyiv–Chop motorway (Ukraine): *Aporrectodea caliginosa* (Savigny, 1826), *A. rosea* (Savigny, 1826), *A. trapezoides* (Dugesi, 1828), *Lumbricus terrestris* (Linnaeus, 1758) and *Dendrobaena octaedra* (Savigny, 1826).

Materials and Methods. Earthworms were collected during 2021–2022 in the biocenosis near the M06 Kyiv–Chop motorway (Berezyna village, Zhytomyr region). The material was collected by excavation and layer-by-layer analysis of soil samples. The thickness of each layer was 10 cm. The maximum depth – 0.5 m. Samples were taken every 10 m from the road to a distance of 210 m. The distance between the rows of samples along the road was 30 m. STATISTICA software package was used for statistical analysis of the data. Biodiversity assessments were calculated using the PAST software package. SAGA and Q-GIS software packages were used for spatial analysis and mapping of the data.

Results and Discussion. The key factor that influences the structure of earthworm communities in the area of road transport impact is the distance from the source of impact. The maximum values of the dominance, Margalef and Berger–Parker indexes and the number of species are observed in areas near the motorway, while the values of the Shannon, Simpson, Menhinik and Brillouin indexes have the opposite trend. There is a correlation between the spatial variability of the structure of earthworm communities and the values of reflectance in the bands B3, B5, B11 of the Sentinel-2 satellite image. It allowed us to apply a geographically weighted regression algorithm with several predictors that indirectly reflect environmental parameters to the data.

Conclusion. The results obtained show that the use of predictors allows us to obtain a more mosaic model of the distribution of indicator values compared to interpolation by kriging, which can be used to predict the values of earthworm biodiversity indicators within the study area.

Keywords. Lumbricidae, biodiversity, biocenosis, road traffic impact

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INTRODUCTION

Environmental pollution from motor vehicle emissions has become a threatening problem. The increase in the number of cars is exponential, which undoubtedly affects the level of pollution of habitats, especially those along the roads (Serbenyuk, 2018). It is known that harmful emissions from motor vehicles are several times higher than the total of all other sources of pollution (Chuvaev, 2013; Regional report …, 2021).

Road transport causes soil pollution through fine particulate matter, carbon oxides and dioxides, nitrogen oxides, organic oils, solvents, and heavy metals (Ni, Hg, Pb, Cr, Cd, Zn, As) (Rusilo *et al.*, 2008; Stoyko & Koynova, 2012). These emissions in low concentrations are quite toxic and can change the chemical and biological properties of the edaphotope. Pollutant emissions are known to depend on the power, operating mode, and type of engine, the technical condition of the vehicle, its speed, road conditions, and fuel quality (Rusilo *et al.*, 2008; Bordyug & Lagovska, 2014; Pylypenko & Skok, 2015; National report..., 2020). The constant influence of transport on the soil system makes it impossible for it to perform important ecological functions (Khokhryakova, 2016). The accumulation of toxic substances in the soil is gradual and persists over a long period of time (Fotheringham *et al.*, 1998; Bordyug & Lagovska, 2014). According to (Malovichko & Holovnya, 2008), the content of heavy metals in soil samples taken at a distance of more than 100 meters from the road can exceed the maximum permissible levels by several times. Over the past 40 years, the rapid increase in vehicle emissions has had a large-scale impact on the spatial distribution and function of habitats, including soil, leading to ecosystem degradation (Yuxing *et al.,* 2023). As a result, there is a growing trend of land cover change, environmental pollution, land degradation, and biodiversity loss on a global scale (Ban *et al.,* 2015). The anthropogenically transformed biocenoses create unfavorable living conditions for representatives of all groups of soil fauna, including lumbricids, which can explain the reduction in the number and diversity of its representatives (Amossé *et al.*, 2016; Ooms *et al.*, 2020; Maréchal *et al.*, 2021). The formation of anthropogenic biocenoses as a result of vehicle emissions causes a change in the structure of soil fauna communities and the loss of synecological links with neighboring communities, while a dense road transport network negatively affects the reproduction of animal populations in roadside areas (Seiler, 2001; Stoyko & Koinova, 2012). It has been established that soils transformed under the influence of motor vehicles are characterized by a reduced diversity of species and higher taxonomic groups of animals, but include functional communities that are able to maintain soil structure and regulate the balance of phytophages and their food supply (Amossé *et al.*, 2016). In the biocenoses located next to the road, the structure of the complex of earthworms, spiders and millipedes is being restructured in the direction of reducing their number. One of the reasons is soil pollution with polymetallic dust in combination with SO_2 and lead compounds. The high content of heavy metals in the soil also causes structural changes in soil nematode communities, which are manifested in an increase in the number of parasitic species (Rusilo *et al.*, 2008; Stoyko & Koinova, 2012).

Over the past decades, remote sensing methods have been increasingly used to study biodiversity. Their use for biodiversity monitoring is especially appropriate in the case of studying large areas or hard-to-reach territories. In addition, remote sensing data provide efficiency, constant updating of information, orderliness, and processing of a large amount of information. For example, satellite imagery has been used to estimate the aboveground biomass and the impact of land cover changes on ground temperature (Zhou & Wang, 2011; Bai *et al.*, 2020), bird numbers (Culbert *et al.*, 2012), and vegetation structure (Wood, 2012). Compared to other invertebrates of the soil mesofauna, earthworms are the most sensitive indicators of the level of pollution of the edaphotope, as they are in continuous contact with the soil. Therefore, the aim of this study is to assess the impact of motor vehicle pollution on the spatial structure of the earthworm complex.

MATERIALS AND METHODS

Earthworms were collected during 2021–2022 in the biocenosis near the M06 Kyiv–Chop motorway (Berezyna village, Zhytomyr region). The material was collected according to the generally accepted method (Amossé *et al.*, 2016) by excavation and layer-by-layer analysis of soil samples. The thickness of each layer was 10 cm. The maximum depth was 0.5 m. Samples were taken every 10 m from the road to a distance of 210 m. The distance between the rows of samples along the road was 30 m. The sampling scheme is shown in **Fig. 1.** A total of 930 lumbricides from 105 samples were processed.

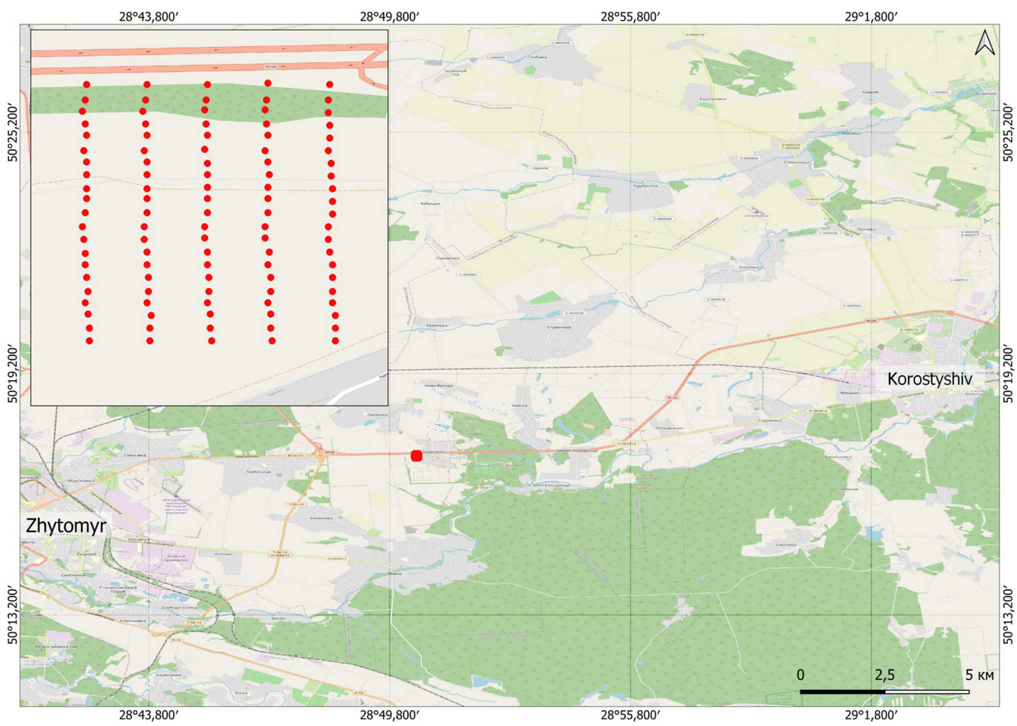

Fig. 1. Location of the test site and earthworm sampling scheme

STATISTICA software package was used for statistical analysis of the data. Biodiversity assessments were calculated using the PAST software package. SAGA and Q-GIS software packages were used for spatial analysis and mapping of the data.

RESULTS AND DISCUSSION

Species diversity. A total of five species of earthworms belonging to three genera were found in the study area: *Aporrectodea caliginosa* (Savigny, 1826), *A. rosea* (Savigny, 1826), *A. trapezoides* (Dugesi, 1828), *Lumbricus terrestris* (Linnaeus, 1758) and *Dendrobaena octaedra* (Savigny, 1826). The first two species were the most abundant, being represented in almost all samples (**Fig. 2**). However, their number in individual samples varied significantly. For example, the maximum number of individuals of *A. caliginosa* reached 13 in some samples, and *A. rosea* – eight individuals. At the same time, as can be seen from the diagrams in Fig. 2, the samples located closer to the road were characterized by a significantly lower number of these species. The other three species were less numerous. So, the maximum number of *A. trapezoides* in the sample did not exceed four, and *L. terrestris* – three individuals. The spatial distribution of these species in the samples is noteworthy. The first of them regularly occurs at a distance of 40–50 m from the road, and for the second this distance is twice as large. The latter species, *D. octaedra*, was represented by single individuals only in some samples, but also at a considerable distance from the motorway. The obtained results indicate different sensitivity of the identified species to the traffic load. As a rule, in mass eurybiont species, this effect is reflected only in changes in abundance, while more stenobiont species practically disappear from the zone of maximum impact of the studied factor.

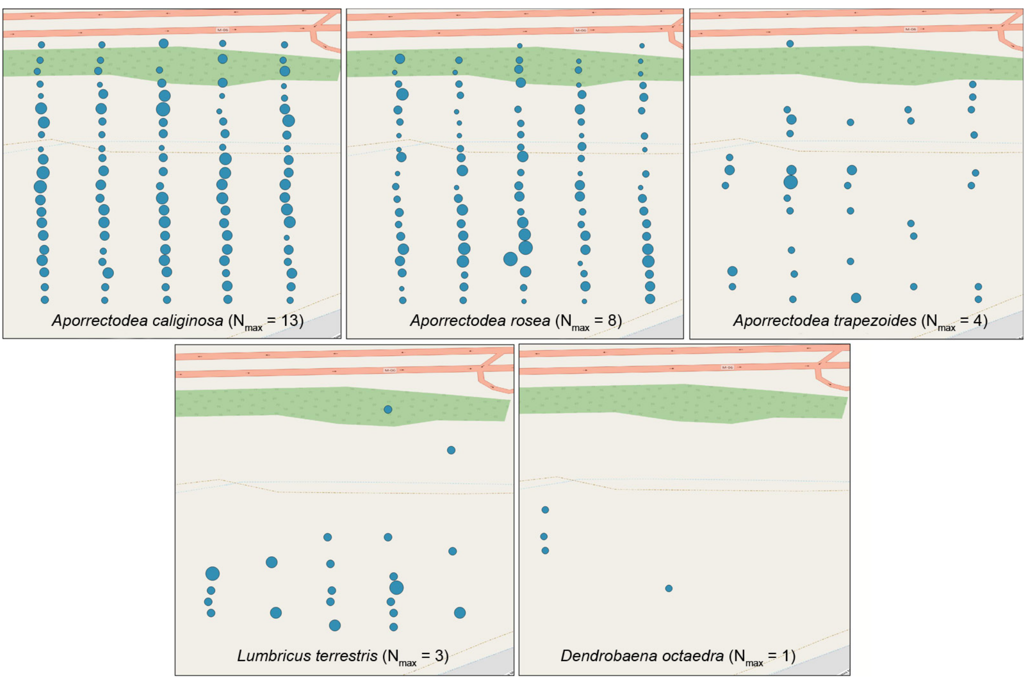

Fig. 2. Representation of the identified earthworm species in the samples

Such features of the distribution of earthworm species in the area affected by road traffic have a significant impact on the species structure of individual samples (**Fig. 3**). In most cases, the eurybiont species *A. caliginosa* and *A. rosea* are the clear dominants. Only in some samples *A. trapezoides* and *L. terrestris* are co-dominant. At the same time, samples close to the motorway are usually represented by one or two species. As the distance from the road increases, species diversity increases.

Fig. 3. Species structure of the studied samples

Biodiversity estimates and total abundance. To analyze the spatial distribution of biodiversity values, we used the simple kriging interpolation procedure implemented in the SAGA software package. The statistical algorithm of distance-weighted regression was used to analyze the dependence of biodiversity values on the distance to the motorway.

As can be seen from **Fig. 4.1–4.2**, there is a fairly clear tendency for the total number of earthworms to increase with distance from the motorway. However, the spatial distribution of the indicator values is not uniform, which may indicate the influence of local factors. For example, after a gradual increase in the indicator with distance from the road, there is the zone with its slight decrease, whose localization almost coincides with the zone of the power line influence. Next, there is a zone of high values of the indicator, which is replaced by a zone with lower values of the number of animals. This zone is also likely related to local factors – there is another power line and a dirt road. Other factors, such as soil moisture or structure, are also possible.

As for other biodiversity assessments, two types of spatial dynamics are observed. The first type is characteristic of dominance indices (**Fig. 4.3–4.4**), Margalef and Berger–Parker indices, and species number estimates. In the case of these indices, their maximum values are observed near the motorway, and as you move away from it, the values of these indices decrease. The opposite trend is observed in the case of the Shannon, Simpson, Menhinik and Brillouin indices.

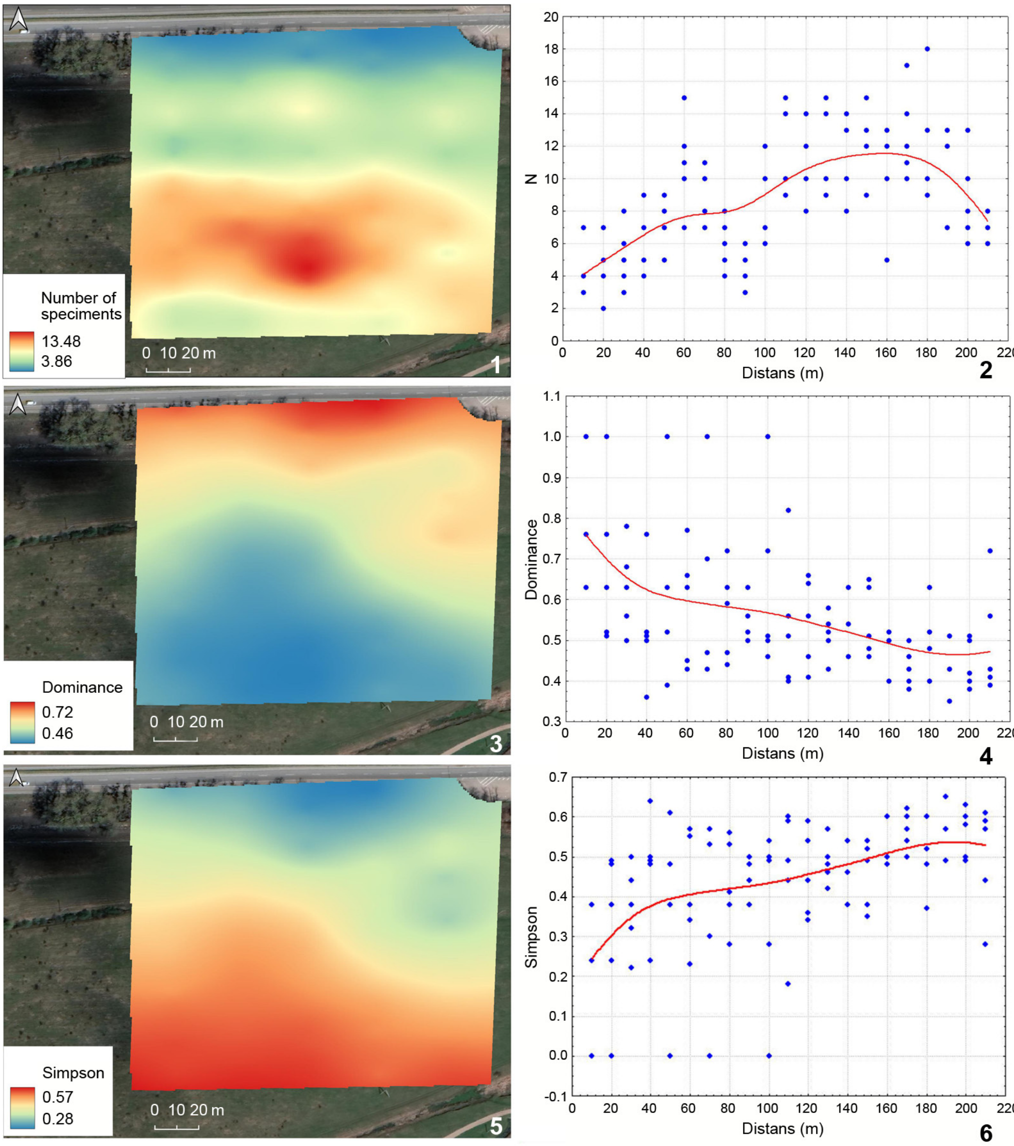

Fig. 4. Spatial distribution: number of individuals in the sample (1) and their dependence on the distance to the motorway (2); dominance index values (3) and their dependence on the distance to the motorway (4); Simpson's index values (5) and their dependence on the distance to the motorway (6)

In contrast, these values increase with distance from the road (**Fig. 4.5–4.6**). It is noteworthy that in the case of relative biodiversity assessments, which include the analyzed indices, there is no such pronounced influence of local factors on the distribution of their values as in the case of the absolute indicator – the total number of earthworms in the sample.

Such a spatial distribution of index values indicates a depleted species composition of the communities in the immediate vicinity of the motorway and the presence of well-defined dominants in this area. As you move away from the road, the species diversity of the communities increases, and their structure becomes more even.

The results obtained indicate that the key factor affecting the structure of lumbricide communities in the area of impact of motor vehicle traffic is the distance from the source of impact. However, the nature of the spatial distribution of the data suggests the possibility of the influence of a number of local factors related or not related to the level of traffic load. For a comprehensive assessment of the impact of such local factors, the use of remote sensing data may be promising. Remote sensing is known to have great potential as a source of information on biodiversity (Foody, 2005; Congedo, 2021). For example, this type of data is widely used in agriculture and forestry and a number of other fields (geology, cartography, ecology, hydrology, climatology, meteorology, landscape science, urban planning, and emergency monitoring). Remote sensing data is used to assess the condition of crops, identify areas of crops and forests damaged by pests, determine certain soil characteristics, temperature, humidity of the object under study, etc. In other words, different ranges of satellite imagery can provide important information about the characteristics and condition of vegetation cover and biotope in general.

Environmental parameters derived from remote sensing data, as a comprehensive representation of climate and environmental factors, are used in large-scale biodiversity studies (Liu *et al.*, 2019). Satellite remote sensing methods are a valuable alternative source of information on the characteristics of forest ecosystems at different spatial and time scales (Maselli *et al.*, 2014; Furukawa *et al.*, 2020). Equally effective is the use of remote sensing data for the analysis of flora species diversity (Coops *et al.*, 2019; Damtew *et al.*, 2021). As for the invertebrate fauna, there are examples of successful use of remote sensing data to assess the species diversity of the entomofauna of agricultural landscapes (agrocenoses, forest belts, ecotones, remnants of natural ecosystems) (Vagalyuk *et al.,* 2016). Therefore, we used remote sensing data (Sentinel-2 satellite image, 08.08.2021) to assess the possible impact of environmental parameters on the number of earthworms and the structure of communities. The analysis included bands 2 – 12 of the satellite image, as well as the normalized differential vegetation index (NDVI = (B08 – B4) / (B08 + B4) and the normalized differential moisture index (NDMI = (B08 – B11) / (B08 + B11). The most related to the structure of earthworm communities are such indicators as distance to the road and reflectance in the bands B3, B5, B11 of the Sentinel-2 satellite image. There is a positive correlation between these parameters and almost all the biodiversity indicators used. In addition, a positive correlation is observed between the values of earthworms in the sample and the reflectance in bands B6, B7, B8 and B8A of the satellite image. At the same time, the NDMI index values correlate with only one biodiversity indicator (the number of individuals in the sample), and the vegetation index NDVI showed no significant correlation with any of the indicators used.

To simulate the spatial distribution of biodiversity indicators, we used the multivariate geographically weighted regression algorithm (Fotheringham *et al.*, 1998). This method allows interpolation of data to the study area based on one or more predictors specified in the rasters. Geographically weighted regression is a statistical method that can reflect the spatial characteristics of relationships, taking into account factors of spatial heterogeneity, by building local regression equations for each raster. It can also be used to capture spatial and temporal variations in area change and their causes (Liu *et al.*, 2019;

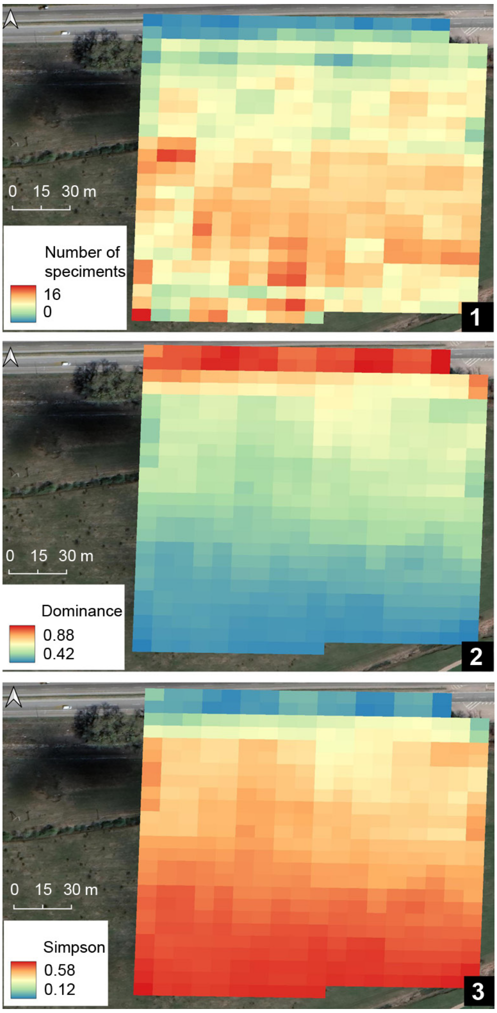

Fig. 5. Spatial distribution of the predicted values: of earthworm population (1), dominance index (2), Simpson's index (3)

Zhu *et al.*, 2020; Zheng *et al.*, 2021). There are examples of successful use of geographically weighted regression to investigate the level of impact of urbanization and landscape change on the quality of habitat for living organisms (Zhu *et al.*, 2020). In the case of this study, the distance to the motorway, the reflectance of the Sentinel-2 satellite image bands, and some of the most commonly used vegetation indices were used as predictors. At the same time, environmental indicators that could be useful for model building were selected based on the analysis of their correlations with biodiversity indicators. According to the results obtained, the use of predictors allows us to obtain a more mosaic model of the distribution of indicator values compared to interpolation by kriging. For example, in the case of the total number of earthworms (**Fig. 5.1**), a more or less smooth gradient is observed with a gradual increase in the value of the indicator as it moves away from the motorway. At the same time, there are localized pockets of reduced and increased numbers of these animals. Such a model, which indirectly takes into account abiotic parameters of the environment, and not only the results of field assessments of biodiversity indicators, seems to be more adequate in general.

For the other biodiversity indicators, modeling their spatial distribution using geographically weighted regression yields results similar to those obtained by the kriging method. Two types of spatial dynamics of indicators are also distinguished: 1) the values of the dominance indices (**Fig. 5.2**), Margalef and Berger-Parker and the estimates of the number of species gradually decrease with distance from the motorway; 2) the values of the Shannon, Simpson (**Fig. 5.3**), Menhinik and Brillouin indices increase with distance from the road. However, even in the case of these indices, the inclusion of environmental parameters in the model allows us to obtain a more mosaic model (compared to the results of interpolation by the kriging method).

CONCLUSIONS

Using the method of geographically weighted regression with several predictors that reflect environmental parameters, we obtained a model that makes it possible to predict the values of earthworm biodiversity indicators within the study area. The applied methodology can be promising for the rapid assessment of anthropogenic impacts on the biodiversity of soil mesofauna and a number of other ecological groups of animals. In addition, the use of remote sensing data and indices calculated on their basis as predictors allows covering large areas (including hard-to-reach ones) and makes it possible to predict biodiversity indicators even in areas with little field research coverage. This approach can be useful for identifying potential areas of high biodiversity, confined to local conditions, which may be valuable from a zoological point of view.

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Conflict of Interest. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Animal studies. All national and institutional guidelines for the use of laboratory animals were followed.

AUTHOR CONTRIBUTIONS

Conceptualization, [O.H.]; methodology, [O.H.]; validation, [O.H.; V.M.]; formal analysis, [O.H.; V.M.]; investigation, [O.H.; V.M.]; resources, [O.H.; V.M.; D.H.; D.V.; O.K.]; data curation, [O.H.]; writing – original draft preparation, [O.H.; V.M.]; writing – review and editing, [O.H.; V.M.; D.H.]; visualization, [O.H.; V.M.] supervision, [O.H.].

All authors have read and agreed to the published version of the manuscript.

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ПРОСТОРОВА МІНЛИВІСТЬ УГРУПОВАНЬ ДОЩОВИХ ЧЕРВІВ У ЗОНІ ВПЛИВУ АВТОТРАСИ

***Олександр Гарбар*[1], *Вікторія Мороз*[1], *Діана Гарбар*[1], *Дмитро Вискушенко*[1], *Олександр Кратюк*[2]**

[1] *Житомирський державний університет імені Івана Франка вул. Велика Бердичівська, 40, Житомир 10008, Україна*

[2] *Поліський національний університет, вул. Старий бульвар, 7, Житомир 10002, Україна*

Вступ. Проаналізовано просторові особливості структури угруповань дощових черв'яків у зоні дії автотранспорту. У досліджуваному біоценозі біля траси М06 Київ–Чоп (Україна) виявлено 5 видів люмбрицид трьох родин: *Aporrectodea caliginosa* (Savigny, 1826), *A. rosea* (Savigny, 1826), *A. trapezoides* (Dugesi, 1828), *Lumbricus terrestris* (Linnaeus, 1758) і *Dendrobaena octaedra* (Savigny, 1826).

Матеріали та методи. Дощових черв'яків збирали протягом 2021–2022 років у біоценозі біля траси М06 Київ–Чоп (с. Березина, Житомирська область). Матеріал збирали методом розкопок та пошарового аналізу проб ґрунту. Товщина кожного шару – 10 см. Максимальна глибина – 0,5 м. Проби відбирали через кожні 10 м від дороги на відстані 210 м. Відстань між рядами зразків уздовж дороги – 30 м. Для статистичної обробки даних використовували пакет програм STATISTICA. Оцінки біорізноманіття розраховано за допомогою програмного пакету PAST. Для просторового аналізу та картографування даних використовували програмні пакети SAGA та Q-GIS.

Результати. Ключовим фактором, який впливає на структуру угруповань дощових черв'яків у зоні впливу автомобільного транспорту, є відстань від джерела впливу. Максимальні значення домінування, індексів Маргалефа та Бергера–Паркера та чисельності видів спостерігали на територіях поблизу автомагістралі, а значення індексів Шеннона, Сімпсона, Менхініка та Бріллуїна мають протилежну тенденцію. Є кореляція між просторовою мінливістю структури угруповань дощових черв'яків і значеннями відбивної здатності в діапазонах B3, B5, B11 космічного зображення Sentinel-2. Це дало нам змогу застосувати географічно зважений алгоритм регресії з кількома предикторами, які опосередковано відображають екологічні параметри в даних.

Висновки. Отримані результати доводять, що використання предикторів дає змогу отримати більш мозаїчну модель розподілу значень індикаторів порівняно з інтерполяцією методом кригінгу, за якою можна прогнозувати значення індикаторів біорізноманіття дощових черв'яків у межах досліджуваної території.

Ключові слова: Lumbricidae, біорізноманіття, біоценоз, вплив автотранспорту

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