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An integrated method for assessing the state of biodiversity of disturbed ecosystems

Интегральный метод оценки состояния биоразнообразия нарушенных экосистем

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Ключевые слова: антропогенное воздействие, степень негативного воздействия, комплексная оценка, интегральный показатель состояния экосистемы (ИПСЭ), индикаторные таксономические группы, беспозвоночные животные, растения, Норильский промышленный район.

Abstract. The description and test results of a quite simple and yet universal integrated method for quantifying the state of ecosystems and the degree of negative impact on them by industrial facilities based on biodiversity parameters are presented. The approach is based on the normalisation of diversity parameters of indicator groups of animals and plants relative to the background (reference territory) with subsequent averaging of the obtained values to calculate the multimetric index. The resulting Integrated Indicator of the State of the Ecosystem (IISE) reflects the extent of biodiversity change in the study area. Preliminary testing of the proposed method was carried out on the basis of materials collected during the Great Scientific Expedition (2022 and 2023) in the north of the Krasnoyarskii Krai in the Norilsk Industrial District and adjacent territories. Invertebrates (soil microarthropods, carabid beetles, spiders), vascular plants and lichens were used as indicator groups. The results of the preliminary testing confirmed the effectiveness of the proposed approach for the assessment of the state of ecosystems and the degree of their disturbance. The integrated method of quantitative assessment of the state of ecosystems, based on the IISE calculation, made it possible to define quite clearly the boundary of the belt of intensive impact on biodiversity, as well as to show a smooth gradient of reduction of negative impact towards the background area. This indicates great promise and wide potential possibilities for using this method, including for assessing the situation around large industrial facilities. However, to substantiate the possibility of wider application of the proposed method in monitoring studies, it is necessary to thoroughly test its performance and efficiency on the basis of longer time series data, as well as on materials collected under other natural conditions and under different types of anthropogenic impacts.

Резюме. Приводится описание и результаты апробации достаточно простого и в то же время универсального интегрального метода количественной оценки состояния экосистем и степени негативного воздействия на них промышленных объектов на основании параметров биоразнообразия. В основе подхода лежит нормирование параметров разнообразия индикаторных групп животных и растений относительно фона с последующим усреднением полученных величин для расчёта мультиметрического индекса. Полученный таким образом интегральный показатель состояния экосистемы (ИПСЭ) отражает степень изменения биоразнообразия на исследованном участке. Предварительная апробация предложенного метода проведена на основании материалов, собранных в ходе Большой научной экспедиции (2022 и 2023 гг.) на севере Красноярского края в Норильском промышленном районе и на прилежащих территориях. В качестве индикаторных групп использованы беспозвоночные животные (почвенные микроартроподы, жуки-жужелицы, пауки), а также сосудистые растения и лишайники. Результаты предварительной апробации подтвердили эффективность предложенного подхода к оценке состояния экосистем и степени их нарушенности. Интегральный метод количественной оценки состояния экосистем, основанный на расчёте ИПСЭ, позволил достаточно отчётливо определить границу пояса интенсивного воздействия на биологическое разнообразие, а также показать плавный градиент снижения негативного воздействия по направлению к фоновой территории. Это свидетельствует о больших перспективах и широких потенциальных возможностях использования данного метода, в том числе для оценки ситуации в окрестностях крупных промышленных объектов. Однако для обоснования возможности более широкого применения предложенного метода в мониторинговых исследованиях необходима тщательная проверка его работоспособности и эффективности на основании данных более длинных временных рядов, а также на материалах, собранных в других природных условиях и при разных типах антропогенного воздействия.

Introduction

In the modern world, the scale of anthropogenic impact on the biosphere is steadily increasing. This inevitably leads to significant, and in some cases even critical, transformation of the habitat, which can have a negative impact on biodiversity and lead to a reduction in the species richness and abundance of certain groups of plants and animals. Under these conditions, the need to develop relatively simple, but at the same time sufficiently effective methods of assessing the degree of negative impact on ecosystems to enable regular monitoring of the state of disturbed areas is even more acute.

There are currently quite a few different methods and approaches used to assess impacts on biodiversity [Vorobeichik et al., 1994; Damiani et al., 2023]. The methods differ in the breadth of coverage of biota components and types of impacts, as well as in the degree of complexity of the models used to describe the mechanisms of interaction between ecosystem components. Ideally, an ecosystem assessment should consider many nuances, including the full range of impacts on biodiversity. However, a detailed review of the many proposed valuation options has shown that there is currently no method that fully meets all of the requirements [Damiani et al., 2023].

Typically, areas with a particular type of disturbance are assessed on the basis of data obtained for individual groups of organisms. For example, lichens can be used to assess changes in air quality and pollution levels in urban ecosystems based on their species composition and projective cover [Nash, Gries, 1991; Conti, Cecchetti, 2001]. The number of birds of higher trophic level (predators) can be used to indirectly assess the state of phytocenoses [Martín, Ferrer, 2013; Burgas et al., 2014], in some cases the diversity and abundance of butterflies is monitored [Kremen, 1992; Thomas, 2005; Rákosy, Schmitt, 2011; An, Choi, 2021]. The promising objects for zooindication are representatives of soil fauna, including ground beetles and microarthropods [Gulvik, 2007; Kuznetsova, 2009; Mordkovich, Lyubechanskii, 2019].

A wide range of different parameters can be used to characterise the state of biota. Indicators characterising the number of species (diversity indices), biomass, community structure, population characteristics, and physiological and biochemical indices are considered to be the most informative for environmental rationing [Vorobeichik et al., 1994]. Each component of the biota, or group of organisms, can be described by several, often correlated, parameters. It should be noted, however, that such «redundancy» of the indicators used can at the same time serve as a guarantee of the reliability of the results obtained and the accuracy of the estimates. Obviously, for a more accurate assessment of the state of ecosystems and biodiversity, it is advisable to adopt an integrated approach, which implies the involvement in the study of different ecosystem components (groups of organisms) that are sensitive to different environmental changes and can serve as bioindicators, and the use of their characteristics [Vorobeichik et al., 1994; Dunger, Voigtländer, 2009; Lehmitz et al., 2020]. However, when selecting «tools» for assessing the state of ecosystems, it is important to consider not only their advantages but also their disadvantages. Multivariate comparative methods (multivariate indices of biodiversity intactness), including the principal component method, rank abundance curves, taxonomic diversity ordination, may be preferred by researchers [Clarke, 1990; Clarke, Warwick, 1998; Magurran, 2004; Hewitt et al., 2005; Abramov, Vinogradov, 2014], but they are more sensitive to errors associated with the absence of species known to inhabit the study area in the collected materials [Lamb et al., 2009]. The high mathematical complexity of the calculations also creates certain difficulties for their widespread use in monitoring.

Despite the complexity of ecosystem processes, various one-dimensional analytical indices are more suitable for practical purposes in nature management. These complex indicators are sensitive enough to provide a rapid assessment of the state of biodiversity in the study area, allowing appropriate management decisions to be made. At the same time, one-dimensional indices also have certain disadvantages (limitations), in particular, when calculating them, relatively speaking, information about specific biological processes is «lost». For example, indices do not reflect information on the taxonomic composition and structure of the community or the abundance of organisms, but this information is of course still available at the primary data level and can be used for in-depth analysis. However, despite some disadvantages and limitations, due to the simplicity of calculation and interpretation of results compared to multidimensional indices, it is the one-dimensional indices that remain the most in-demand in various monitoring systems. Among the great variety of approaches used to calculate such indices [Vorobeichik et al., 1994; Lamb et al., 2009; Teillard et al., 2016; Damiani et al., 2023], we consider one of the most promising to be the approach using the operation of normalising indicators relative to a benchmark or reference territory (background). In Russia, the first steps in this direction were taken by A.M. Stepanov [Stepanov, 1988, 1991; Stepanov et al., 1991], but the results of his work were not appreciated at the time. The present study is a continuation of his work and a development of this direction.

As part of the Great Scientific Expedition (2022 and 2023), a large-scale project to study biodiversity in the areas where Norilsk Nickel's (hereinafter referred to as the Company) facilities are located, a quite simple and at the same time universal integrated method for assessing the degree of negative impact on biodiversity was proposed and tested using a multimetric index based on bioindicator parameters normalised against the background. The main goal of this study was to assess the state of biodiversity at different distances from the Company's industrial facilities/groups of facilities and to define the boundary of the negative impact zone with preliminary differentiation of belts with different levels of impact (intensive/significant, moderate/medium, insignificant). The material collected during the expedition provided a good and reliable basis for the development and testing of an integrated method for assessing the state of ecosystems at different distances from industrial facilities.

Materials and Methods

Universal method for assessing the state of an ecosystem

The method used to assess the state of an ecosystem is based on a comparison of biodiversity in a disturbed area with its indicators in a background or reference natural area, where the negative impact is absent or negligible. To quantitatively assess the degree of change in biodiversity of disturbed areas, the diversity parameters of the plant and animal indicator groups were normalised relative to the background, and the values obtained were averaged to calculate the multimetric index.

The use of normalisation relative to the background is a fairly rough but universal assessment, and can be applied to almost any quantitative indicator characterising the state of the biota. Normalisation converts all indicators to a single dimensionless scale, allowing the normalised values of all assessed parameters to be averaged over the relevant site. Comparative studies of different ways of summarising and representing changes in diversity have shown that the most effective for use in large-scale biodiversity monitoring programmes is the arithmetic mean of parameters normalised relative to a benchmark [Lamb et al., 2009].

Averaging is the simplest and most complete way of summarising («collapsing») information, but it is demanding in its choice of parameters: the basic requirement is unidirectional changes in components with similar rates in response to the factor being analysed [Vorobeichik et al., 1994]. This problem is easily solved by preliminary selection for the calculation of the multimetric index of only normalised indicator parameters that change unidirectionally in response to a negative impact.

Averaging these parameters over the study area provides an assessment of the degree of change in biodiversity for a given area, generalised for different groups of organisms and selected parameters — a kind of «Integrated Indicator of the State of the Ecosystem» (IISE). The IISE index can be calculated both for individual study sites (polygons) located at different distances from industrial facilities/groups of facilities and for zones/belt areas (belts) of a certain degree of anthropogenic impact.

Study sites (polygons). The integrated indicator is calculated using the following formula:

$$\mathrm{IISE} = \frac{\sum_{i=1}^{n}\left(\frac{P_i}{P_i(\mathrm{background})}\right)}{n},$$

P_i — is the average value of a particular i-th parameter (biodiversity indicator) obtained at a certain polygon/sampling station; P_i(background) — is the value of the same indicator obtained for the background (reference) area; n — is the total number of indicators used for the assessment.

If data on the level of contamination are available, the IISE values obtained can be used to construct a dose-effect curve. In the absence of such data, and in the case of cumulative effects of different factors, the IISE values obtained allow a preliminary grading of the polygons according to the degree of impact and the assignment of each of the polygons to one of the impact belts or to the reference area (background). The ranges of IISE values for assignment to an impact belt depend on the objectives, the number of belts to be identified, and are based on preliminary data analysis. At the same time, it is important to take into account the influence of all impact factors identified in the study area. Thus, in some cases, for example, in the presence of significant fragmentation of the disturbed area, there may be an increase in species richness of certain groups due to the expansion of the range of microhabitat conditions. In this regard, when assigning polygons to a particular belt, it is also necessary to use additional key group parameters that can serve both to verify and clarify (if necessary) the degree of negative impact.

Impact belts (belts with different degrees of negative impact). To characterise each of the identified impact belts, an Integrated Indicator of the State of Ecosystem ($\mathrm{IISE}_{(IB)}$) is calculated. This indicator is the arithmetic mean of all polygons assigned to a particular impact belt:

$$\mathrm{IISE}_{(IB)} = \frac{\sum_{i=1}^{n}\mathrm{IISE}_i}{n},$$

IISE_i — the IISE indicator value obtained for a certain i-th polygon in a particular impact belt; n — the total number of polygons in a particular impact belt.

Impact zone. The integrated indicator of the ecosystem state for the entire impact zone of the individual facility or groups of facilities under study ($\mathrm{IISE}_{(IZ)}$) is calculated using a formula that takes into account the state of the biota in all impact belts of the individual facilities/groups of facilities ($\mathrm{IISE}_{(IB)}$) and the scale of the negative impact (area of each impact belt):

$$\mathrm{IISE}_{(IZ)} = \frac{\sum_{i=1}^{n}(\mathrm{IISE}_{(IB)_i} \times W_i)}{\sum_{i=1}^{n} W_i},$$

$\mathrm{IISE}_{(IB)i}$ — the IISE indicator value obtained for a certain i-th impact belt; W_i — area of the corresponding i-th impact belt; n — total number of impact belts identified in the impact zone of the individual facilities/groups of facilities under study.

Conditional biodiversity «loss» (or «gain»). To show changes in biodiversity in a more familiar and illustrative form for polygons and impact belts, we used the CBL (Conditional Biodiversity «Loss» (or «gain»)) indicator, which is a kind of analogue of the IISE and reflects changes in biodiversity relative to background in %. The value of the conditional «loss»/«gain» of biodiversity for a particular impact belt is estimated using the formula:

$$\mathrm{CBL}_{(IB)} = (\mathrm{IISE}_{(IB)} - 1) \times 100\%.$$

Similarly, the CBL for an individual polygon can be estimated using the appropriate IISE values. Negative values of CBL indicate a decrease («loss») of biodiversity, while positive values indicate an increase («gain»).

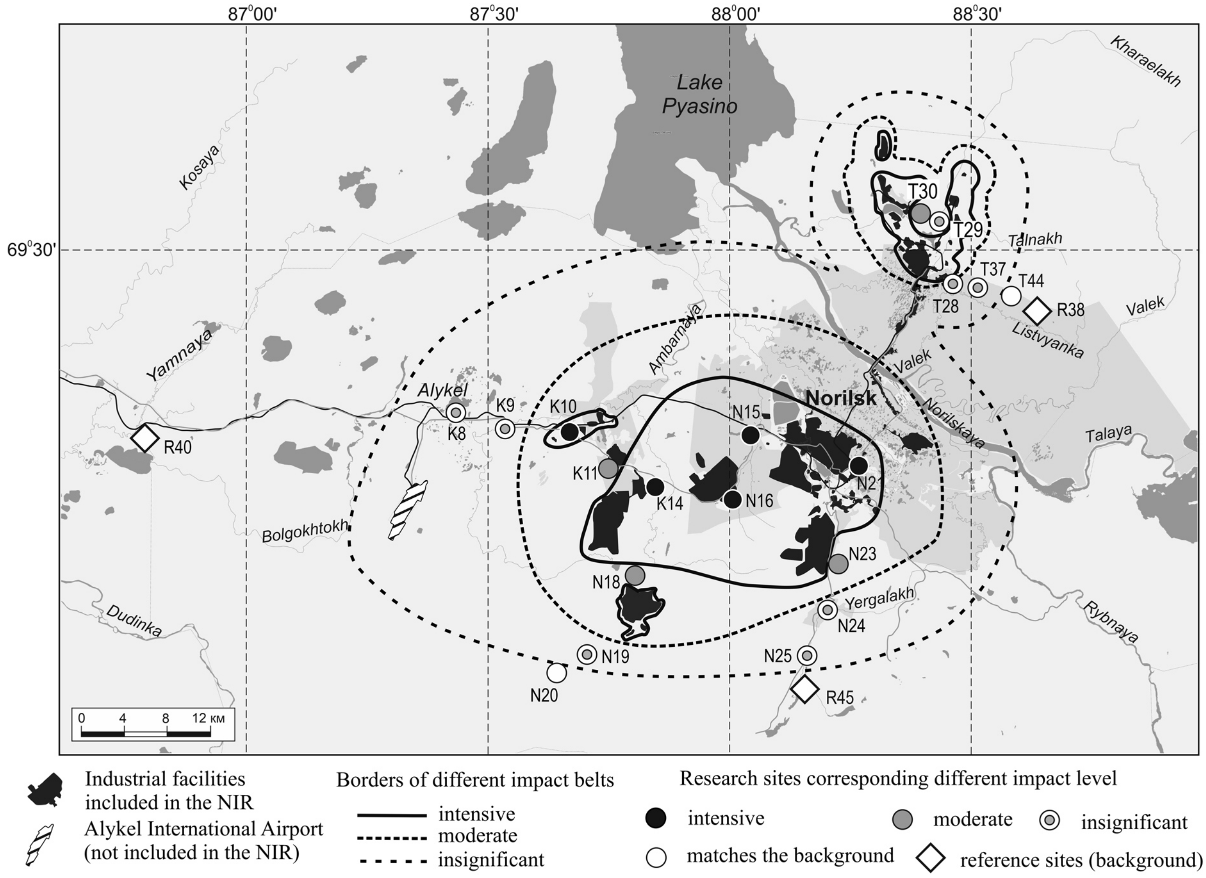

Fig. 1. Location of biodiversity study sites (polygons) and proposed boundaries of the impact belts of the group of production facilities located in the NID, based on the results of biodiversity monitoring of terrestrial ecosystems in 2022 and 2023.

Рис. 1. Расположение участков исследования биоразнообразия (полигонов) и предполагаемые границы поясов воздействия группы производственных объектов, расположенных в НПР, по результатам исследований биоразнообразия наземных экосистем в 2022 и 2023 гг.

It should be noted that the use of $IISE_{(IZ)}$ to calculate conditional «loss»/«gain» of biodiversity for a site/group of sites is not applicable. Only $IISE_{(IZ)}$ values can be used to compare the degree of environmental impact of individual facilities/groups of facilities with each other.

Study area

To test the proposed approach, we used materials collected during the Great Scientific Expedition conducted in June–July 2022 and 2023 in the north of Krasnoyarskii Krai in the Norilsk Industrial District (hereinafter NID) and adjacent territories (Fig. 1). The study area is located in the southern part of the Taimyr Peninsula in the forest-tundra zone. Woody vegetation is mainly represented by larch, birch, willow, and alder. Ledum, blueberry, and lingonberry prevail in the shrub layer, while cereals, sedges, horsetails, mosses, and lichens prevail in the herbaceous layer. The proximity of permafrost favours low evaporation and waterlogging, and there are many rivers, streams and small water bodies.

The study area is characterised by the cumulative anthropogenic effect of the impact of a group of facilities of the mining, and processing energy complex located in the NID, as well as urban infrastructure and municipal facilities. One of the main factors of negative impact in this area is air pollution by emissions from mining and processing enterprises containing copper, nickel, cobalt, iron, manganese and sulphur compounds [Yakovlev et al., 2008].

The largest enterprises that contribute, or have contributed in the past, to environmental pollution in the NID include the Nadezhda Metallurgical Plant, the Copper Plant, the Nickel Plant (closed since 2016), several CHPPs and the Talnakh Concentrator. This group of facilities represents a kind of «industrial centre», which was taken as a basis for selecting sites for material collection and surveys.

A total of 22 sites (polygons) were selected for the study. They were located at varying distances from the industrial facilities along transects that diverged radially from the industrial centre (Fig. 1). The selection of polygons on each transect was based on landscape and biotope similarity. Background polygons, depending on the direction, were located at a distance of 20–45 km from the main industrial facilities.

The territory of the Norilsk Industrial District has a heterogeneous landscape, including foothill and plain areas, therefore different reference (background) sites were used for different groups of polygons in the calculation of IISE according to the character of the terrain: for «foothill» polygons located in the Talnakh area — background site R38; for «plain» polygons to the west of Norilsk — R40; for polygons south of the settlement of Nadezhda, along the Bear Creek and the Yergalakh River — the average value of parameters for reference sites R40 and R45, as the area has a mixed plain and mountainous landscape.

Selection of indicator groups of organisms and parameters

According to existing concepts, indicator species/ taxonomic groups should not only be well studied, but also have a wide range and eurytopicity, sedentary nature, ecological plasticity and sufficiently high abundance rates, while the census and material collection should be carried out using simple methods [Stepanov, 1988]. During the two years (2022–2023) of the Great Scientific Expedition, the diversity indicators of the main functional (key) groups of terrestrial organisms were monitored at the same phenological dates (periods) in selected polygons: vascular plants, lichens, birds, small mammals, predatory herpetobionts (spiders and beetles), and soil microarthropods. All these groups are known to be more or less sensitive to different types of anthropogenic impacts, i.e. to have certain indicator properties [Nash, Gries, 1991; Stepanov et al., 1991; Conti, Cecchetti, 2001; Gulvik, 2007; Kuznetsova, 2009; Martín, Ferrer, 2013; Burgas et al., 2014; Mordkovich, Lyubechanskii, 2019].

Standard methods were used to collect material for each group, following the norms of ecological research to obtain representative data [Ravkin, Dobrokhotov, 1963; Ravkin, 1967; Byzova et al., 1987; Karaseva et al., 2008; A manual of acarology, 2009; Sheftel, 2018]. The collection of specimens and determination of taxonomic affiliation of all organisms was carried out by qualified zoologists of the Institute of Systematics and Ecology of Animals SB RAS (Novosibirsk) and botanists of the Central Siberian Botanical Garden SB RAS (Novosibirsk) — specialists in the respective groups. Diversity of soil microarthropods was assessed by metabarcoding for the COI gene (primers: mlCOIint и jgHCO2198) at the Genomics Centre (Novosibirsk)).

When selecting indicator groups for assessing the state of the ecosystem at the preliminary stage of the analysis, we took into account not only the potential of the taxonomic group but also regional specifics (species richness, abundance, population dynamics, etc.). At the preliminary stage of selection, indicator groups were checked for compliance with two main parameters: (i) sufficient level of abundance at polygons, including background study sites, to allow adequate comparative analyses; (ii) higher sensitivity to negative anthropogenic impact relative to the influence of natural factors. If these parameters were not met, groups were excluded from the analysis. The abundance of small mammals in the study area remained extremely low during the survey years, making it impossible to estimate species richness and density to be made for most of the study sites. Preliminary analysis of the data on bird numbers in the study area showed that the mosaic nature of the area (alternation of aquatic, bog, tundra and forest habitats, as well as the presence of residential areas) has a more significant impact on the results of bird counts than the moderate impact of industrial facilities. Therefore, according to the results of the preliminary analysis, data on small mammals and birds were not used in further analyses and testing of the proposed biodiversity assessment approach was based on data on invertebrates (soil microarthropods, carabid beetles and spiders), vascular plants and lichens.

At the next stage of the analysis, the correlation relations between the pre-selected parameters and their sensitivity to the anthropogenic impact factor were assessed. For this purpose, the ordination of all the studied sites, including the background polygons, in the principal components space was carried out on the basis of the correlation matrix of the initial parameters. By evaluating the deviation of parameters between the reference (background) and the observed communities by comparing the position of their centroids in the space of principal components, we identified the direction (principal component) characterising the anthropogenic impact, in the general case — the distance from industrial facilities.

In the case of a more complex data structure with additional biological associations, the anthropogenic impact may be associated with more than one component, requiring consideration of the position of centroids along more than one axis. The value and sign of the loadings (correlation coefficients of the parameters with the component) on the desired component reflect the relationship between the parameters characterising the biota, as well as their relationship with the latent variable reflecting the degree of anthropogenic impact. Therefore, only parameters with large positive loadings on the principal component reflecting anthropogenic impact were selected for the calculation of IISE.

Key and additional parameters for impact assessment

The indicators most commonly used in community ecology were chosen to calculate the IISE: species richness (S); Shannon diversity index (H); and Simpson index (1-D) [Bigon et al., 1989]. It is known that these indicators tend to have higher values in prosperous and stable communities. The indicator properties (indicator capacity) of each of the diversity (and evenness) indices are often criticised because of the difficulty in interpreting the actual value of the indices, which raises some doubts about the effectiveness of their use in monitoring [Vorobeichik et al., 1994; Teillard et al., 2016]. However, this study proposes to analyse not the value of the indices, but their changes relative to a certain reference value, thus avoiding the risk of misinterpretation [Lamb et al., 2009]. In addition, the simultaneous use of several indices to calculate the multimetric indicator makes it

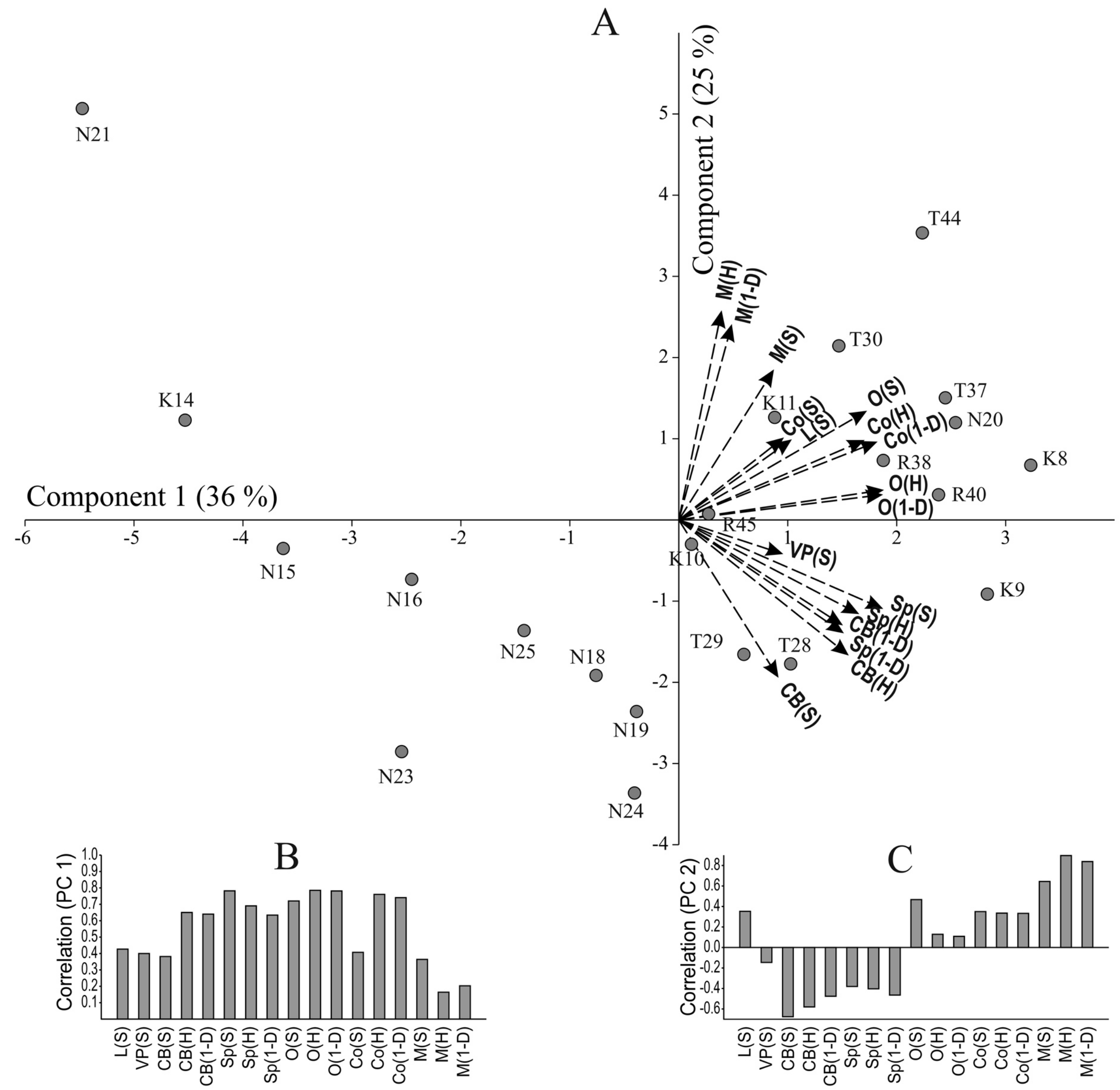

Fig. 2. Ordination of the study sites in the plane of principal components 1 and 2 (A) and the correlation coefficients (loadings) of the initial parameters with principal components 1 (B) and 2 (C). The arrows indicate the initial parameters, their proximity to the axes and length reflect the correlation strength of the initial parameters with the corresponding principal components. Indicator groups: L — lichens (S); VP — vascular plants; CB — carabid beetles; Sp — spiders; O — Oribatida; Co — Collembola; M — Mesostigmata. Biodiversity indices: species richness (S); Shannon diversity index (H); and Simpson index (1-D).

Рис. 2. Расположение исследовательских полигонов в плоскости 1 и 2 главных компонент (A). Стрелками обозначены исходные параметры, их близость к осям и длина отражают силу корреляции исходных параметров с соответствующими главными компонентами 1 (B) и 2 (C). Индикаторные группы: L — лишайники (S); VP — сосудистые растения; CB — жуки-жужелицы; Sp — пауки; O — Oribatida; Co — Collembola; M — Mesostigmata. Индексы биоразнообразия: видовое богатство (S), индекс разнообразия Шеннона (H) и индекс Симпсона (1–D).

possible to increase the accuracy of the assessment of the state of the ecosystem in relation to the background (reference territory).

To verify the correctness of the assignment of the polygons to one or the other impact belt, as well as to adjust their status, taking into account the main set of negative factors on the territory of the NID, additional indicators were used: the general condition of the vegetation cover, the presence of traces of chemical burns on plant leaves, the taxonomic composition and community structure of indicator groups, and the dominance structure of oribatid mites.

Results

Since the analytical approach used requires that all indicators change in a similar way in response to the analysed factor (in this case, anthropogenic), we first performed an ordination of the studied sites using the principal component method based on the correlation matrix

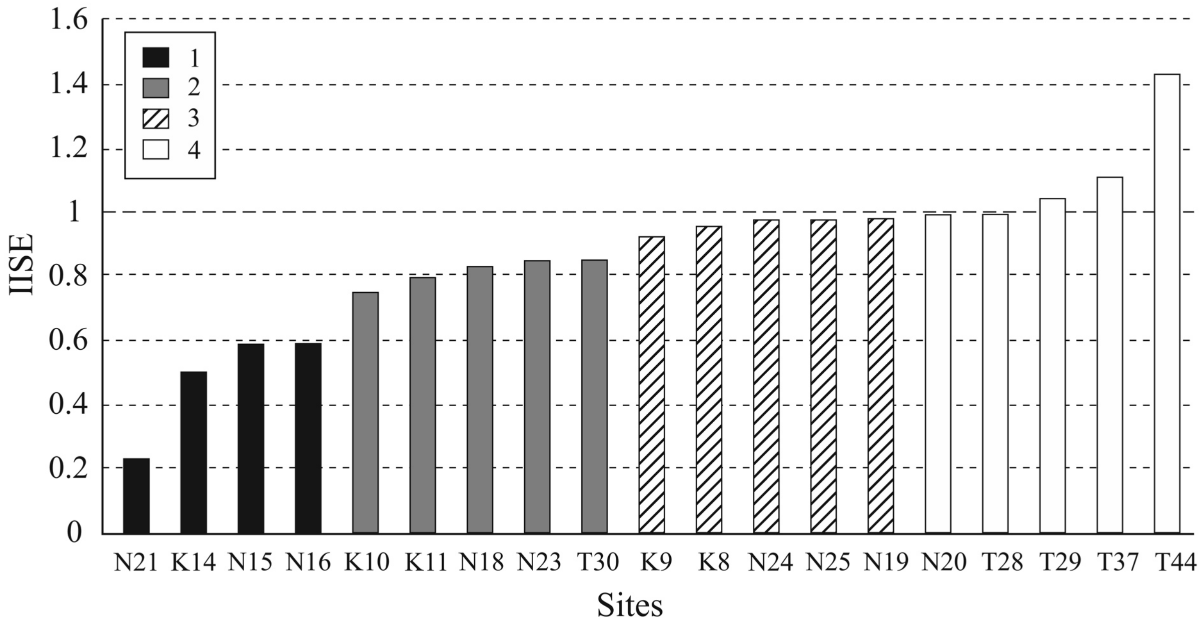

Fig. 3. IISE values for the study sites (polygons) based on the results of the research in 2022–2023. Impact: 1 — intensive; 2 — moderate; 3 — insignificant; 4 — absent (background).

Рис. 3. Значения ИПСЭ для отдельных полигонов по результатам исследований 2022–2023 гг. Воздействие: 1 — интенсивное; 2 — умеренное; 3 — незначительное; 4 — отсутствует (фон).

between the diversity parameters used. Differences between the most and least anthropogenically transformed polygons (i.e. the least and most distant from industrial enterprises, respectively) were only found along the first principal component (Fig. 2). For the other components, no differences were found between polygons with different levels of disturbance. Figure 2 clearly shows that all diversity parameters are positively related to the first principal component (PC 1), indicating an increase in diversity indicators for all tested groups of organisms as a function of the degree of impact.

IISE values for the polygons were calculated using data from selected indicator groups of invertebrates, vascular plants and lichens. The correlation between the IISE values calculated for polygons based on 2022 and 2023 data was 0.7 ($p=0.01$). Figure 3 shows the average of the IISE values over the two years. The lowest values correspond to the sites located in close proximity to large industrial facilities, and the highest values correspond to sites located at a considerable distance from them.

The IISE values obtained during the preliminary analysis were divided into 4 ranges (intervals), presumably corresponding to different levels of biodiversity conservation and, accordingly, different degrees of impact from industrial facilities: <0.80 — intensive impact; [0.80–0.90) — moderate impact; [0.9–1.0) — insignificant impact; 1.0 and above — background area.

The final status of the surveyed polygons (belonging to a particular impact belt) shown in Figure 1 was determined based on the IISE indicators obtained from the 2022–2023 surveys, taking into account the ad-

Table 1. General characteristics of the state of biodiversity of the terrestrial ecosystem in the Norilsk Industrial Region, preliminary boundaries and areas of the negative impact zone and belts based on the results of studies in 2022–2023

Таблица 1. Общие характеристики состояния биоразнообразия наземных экосистем в Норильском промышленном районе, предварительные границы и площади зоны и поясов негативного воздействия по результатам исследований в 2022–2023 гг.

Parameters	Impact degree (impact belt)			Background	Impact zone
	Intensive	Medium	Insignificant		
$IISE_{(IB)}$	0.68	0.83	0.99	1	–
$CBL_{(IB)}$, %	–32 %	–17 %	–1 %	0	–
Position of the belt borders relative to the SPZ, km	1	1–5	5–11	–	11
Area, km^2	394	475	847	–	1716

Note: SPZ — sanitary protection zone; $IISE_{(IB)}$ — integrated indicator of the state of ecosystem for the impact belt; $CBL_{(IB)}$ — conditional biodiversity «loss» (or «gain») for the particular impact belt. Background — the reference territory.

Примечание: SPZ — санитарно-защитная зона; $IISE_{(IB)}$ — интегральный показатель состояния экосистемы для пояса воздействия; $CBL_{(IB)}$ — условные «потери»/«прирост» биоразнообразия для конкретного пояса воздействия. Фон — эталонная территория.

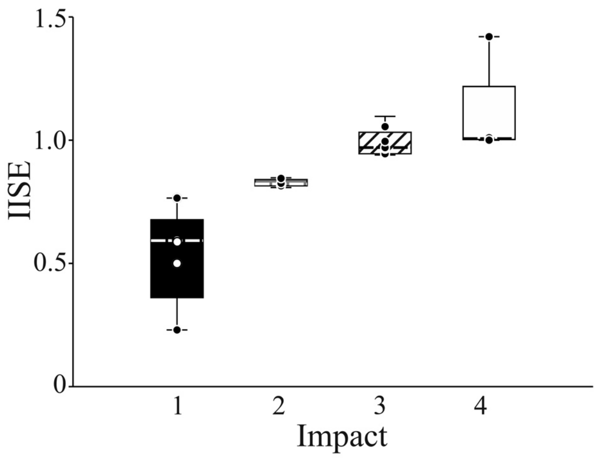

Fig. 4. Variability of the integrated indicator of the state of ecosystem (IISE) for the different impact belts. Median — horizontal line inside the «box»; «box» — 25 % and 75 % quartiles; dots — IISE values for individual study sites. Impact: 1 — intensive; 2 — moderate; 3 — insignificant; 4 — absent (background).

Рис. 4. Значения интегрального показателя состояния экосистемы для поясов воздействия (ИПСЭ$_{(ПВ)}$). Медиана — горизонтальная черта внутри «ящика»; «ящик» — 25 % и 75 % квартили; точки — значения ИПСЭ для отдельных полигонов. Воздействие: 1 — интенсивное; 2 — умеренное; 3 — незначительное; 4 — отсутствует (фон).

ditional parameters mentioned above in the Materials and Methods section.

The integrated indicator of the state of ecosystem for different impact belts (IISE$_{(IB)}$) and the results of the assessment of the conditional biodiversity «loss» (or «gain») within the boundaries of the preliminarily identified impact belts (CBL$_{(IB)}$) are presented in Table 1. Based on the available data, the approximate location of the boundaries of the impact belts of the complex of industrial facilities in combination with urban infrastructure and utilities in the Norilsk Industrial District was determined and a preliminary assessment of the area covered by individual impact belts and the overall impact zone was made (Fig. 1, Table 1).

The intensive anthropogenic impact on biota is clearly manifested in the reduction of biodiversity indicators in the vicinity of industrial facilities (Table 1, Fig. 4). At the same time, it is rather problematic to determine the exact location of the outer boundaries of the belts of moderate and insignificant impact due to the smooth transition associated with the continuous and non-threshold action of a whole complex of natural and anthropogenic factors (Fig. 3, 4). The location of the proposed boundaries of the impact belts based on the data obtained varies significantly depending on the facility type and direction.

The IISE$_{(IZ)}$ indicator calculated for the impact zone of the group of facilities located in the Norilsk Industrial District was 0.87. Such a dimensionless indicator is useful both for the long-term monitoring of a particular object/group of objects in order to identify trends in the situation (improvement/deterioration) and for comparing the degree (magnitude) of the impact of different enterprises, including those that are surrounded by different natural ecosystems.

Discussion

Preliminary testing of the proposed method for assessing the state of ecosystems based on two years of monitoring data in the Norilsk Industrial District and its surroundings at 22 polygons located on radial transects from the industrial centre showed its rather high efficiency. As a result of the analysis of the two-year monitoring data conducted in the NID, the intensive anthropogenic impact on the biota was quite clearly shown in the reduction of biodiversity indicators in the vicinity of large industrial enterprises, such as the Nadezhda Metallurgical Plant. At the same time, it is quite difficult to determine the exact location of the outer boundaries of the belts of moderate and insignificant impact due to the smooth transition associated with the continuous and non-threshold action of a number of different factors. The location of the proposed boundaries of impact belts depends significantly on the size of the enterprises or other facilities and the nature (type) of negative impact on the biota. The data obtained in the 2023 study have a high degree of similarity with the 2022 data, including confirmation of the proposed ranges for assigning polygons to a particular impact belt (<0.80 — intensive; [0.80–0.90) — moderate; [0.9–1.0) — insignificant; ≥1.0 — background). However, there are some important points to consider when using this method, which have been taken into account during the testing of the method, both at the preliminary stage and at the stage of calculating the multimetric index.

One of the fundamental conditions for obtaining adequate results with this method is a careful and verified approach to the selection of study sites (polygons), which should be ecologically similar, i.e. located in the same landscapes and biotopes of similar type. The polygons selected for the study on each of the transects fully met this condition, which guarantees the appropriateness and reliability of the results obtained.

The choice of indicator groups for the calculation of the IISE also requires special attention. Not all of the groups of organisms monitored for various tasks during the Great Scientific Expedition proved to be suitable for assessing the degree of negative anthropogenic impact in the study area. The rather low species diversity and abundance of small mammals combined with the pronounced population dynamics in the area [Yudin, 1980; Litvinov, Chupin, 2018] make it very difficult to use this group of organisms as a bioindicator in the NID. The abundance of small mammals remained extremely low in the study area during the survey years (2022–2023), which prevented an assessment of their species richness and density in most of the study sites. As for birds, the mosaic character of the area (alternation of aquatic, bog, tundra and forest habitats, as well as the presence of residential areas) had a more significant impact on the occurrence of different bird species than the impact of industrial facilities. As a result, the proposed methodological approach to assessing the state of biodiversity in the NID and its surroundings was tested using data on invertebrates (soil microarthropods, carabid beetles, and spiders), vascular plants and lichens. The advantage of choosing invertebrates as indicator groups is obvious. They are more sensitive bioindicators than vertebrates: any changes in habitat conditions are more vividly manifested and more accurately reflected in their species richness and community structure, as they are more diverse and abundant [Kremen et al., 1993; Bisevac, Majer, 1999; Gerlach et al., 2013]. Furthermore, in contrast to small mammals, the abundance of all selected invertebrate groups in the study area during the survey period was sufficient for a comparative analysis.

Another important point is the selection of the main parameters to calculate the IISE. At present, the most promising indicators at the moment seem to be those commonly used in community ecology: species richness (S), Shannon diversity index (H) and Simpson index (1–D). They are quite simple and clear, and allow to take into account not only the species richness but also the structure of the communities of indicator groups at the study sites (Shannon index and Simpson index). At the same time, species diversity is a more stable indicator than abundance indicators, which are more dependent on population dynamics. As for the abundance of indicator groups, the possibility and feasibility of using these parameters «in their pure form» to calculate the IISE requires additional studies on extended material (taking into account longer time series) in order to assess and take into account the impact of inter-annual population dynamics. Nevertheless, abundance values of indicator species/groups can be used as additional parameters to verify and clarify (if necessary) the correctness of the assignment of the polygon to a certain impact belt, together with parameters such as total projective cover, presence of chemical burn marks on plant leaves, oribatid dominance structure, etc. When assigning polygons to a particular impact belt, such a verification of the results obtained, taking into account additional parameters of key groups, is not only important but mandatory, because in some cases (e.g. when there is significant fragmentation of the disturbed area), an increase in species richness of certain groups is observed due to the expansion of the range of microhabitat conditions. This is generally the case for polygons in the moderate and insignificant impact belts, where the IISE values of individual polygons may fall outside of the proposed thresholds.

The main negative factors in the Norilsk Industrial District include global and local environmental pollution from chemical emissions into the atmosphere, emissions and spills of petroleum products, contamination of the territory with waste material residues, etc., which can change the vegetation cover and animal population and incorporate pollutants into food chains. This type of impact has resulted in a significant reduction in biodiversity indicators in the vicinity of the Nadezhda Metallurgical Plant. The relatively favourable state of biodiversity in the study sites in the Talnakh area appears to be due to the absence of significant enterprises emitting pollutants into the atmosphere.

Another important anthropogenic factor is the mechanical disturbance of the micro-landscape and land cover as a result of traffic, construction, geological exploration and mining, leading to fragmentation of the environment, and formation of quasi-natural and artificial habitats. This type of impact is most typical of mining operations, especially open-pit mines and the creation of waste dumps and quarries. One of the examples of such enterprises is the Zapolyarny Mine of Medvezhy Ruchey, which develops the deposit using open-pit mining methods. However, unlike air pollution, disturbances associated with the activities of such enterprises are usually localised (strictly limited in space) and have a minor impact on adjacent areas.

It should be noted that in this area the cumulative anthropogenic effect of the impact of many closely located enterprises of the mining, and processing energy complex in combination with the objects of urban infrastructure and utilities is pronounced. This makes it very difficult, and in the vast majority of cases impossible, to assess the individual impact of individual industrial (or other) facilities and to determine their contribution to the overall (cumulative) effect of negative impacts.

Thus, the data collected over two years of research only allow us to draw preliminary conclusions about the extent and nature of ecosystem degradation in the NID. For a more accurate assessment, it is necessary to investigate the extent of inter-annual variability of the IISE indicator, as well as the diversity parameters of key groups of organisms used in its calculation. The status of individual polygons and the boundaries of the impact zone and impact belts can be adjusted in the future as monitoring progresses.

In general, the proposed approach of using only normalised relative to reference values of alpha diversity indicators of indicator groups that change unidirectionally in response to negative impacts allows us to address numerous issues. First, it allows the calculation of the multimetric index, which provides a preliminary but consistent assessment of the state of ecosystems in areas of current or potential impact. It should be noted that in this case, even a rough estimate can be very useful. It also makes it possible, if necessary, to compare the results obtained for different areas, e.g. industrial facilities located in different natural zones and/or differing in the set of potential indicator groups. It should be noted, however, that such comparisons are best made when several years of data are available to take into account of possible regional differences.

When using this approach in biodiversity monitoring, it is important to establish an initial «reference point» in order to adequately assess any changes occurring in the areas of negative impact (or potential impact). It is proposed to use the average IISE indicators obtained during the first three to four years of monitoring as such a reference point. This will help to understand the variability of the IISE index caused by natural factors (weather, annual dynamics, etc.). It is also recommended to periodically correct the position of the study sites, including the background sites, to avoid possible errors related to the selection of polygons. In addition, differences between IISE values for different years should be interpreted with extreme caution, as this indicator reflects a set of characteristics, relationships and parameters of the state of a dynamic system (ecosystem) that is fixed at a given point in time and that also has considerable inertia. A consistent trend over a number of years (at least 5–7 years) is needed to make an informed judgement about the decline or increase of biodiversity in a particular area. Small changes in diversity in either direction, if not systematic, should be regarded as random fluctuations.

In general, the preliminary testing of the proposed method on the material of two-year studies in NID in the forest-tundra zone has confirmed the effectiveness of this approach in assessing the state of disturbed areas. The new integrated method of quantitative assessment of the state of ecosystems made it possible to define quite clearly the boundary of the belt of intensive impact on biodiversity, as well as to show a smooth gradient of negative impact reduction towards the background area.

To achieve a reasonable possibility of wider use of the proposed method in monitoring studies, it is necessary to thoroughly test its performance and efficiency on the basis of longer time series data, as well as on materials collected under other natural conditions and different types of anthropogenic impacts.

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