Ecological scales of indicator plants in an industrial region

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Abstract. The article presents the results of a long-term monitoring experiment (26 years) to identify indicator plants and their indices for assessing the state of ecosystems in the industrial region of Eastern Europe – Donbass. Ecological scales are discrete calculated or metric indicators that are important for quantification and examination of anropogenically transformed ecotopes. It is proposed to use four categories of ecological scales with a different mechanism for calculating the indices and different conditions of the experiment: 1) the principle of varying absolute metric parameters, 2) the calculated principle of correspondence of the percentage value; 3) the indices of the survival strategy implementation (vegetative and reproductive success); 4) the frequency of occurrence (or appearance) of characteristic features or the degree of specialization of functional discrete structures. Names of plant species of Donbass are given and their characteristics of variation are indicated in fractional 10-point scales.

1 Introduction

The law of homologous series in variation formulated by Nikolai Vavilov [1, 2] is still relevant from the point of view of scientific developments [3]. Plant organisms constantly depend on environmental factors (ecological factors) and are forced to adapt [4, 5]. Such changes form phenotypic series, which are largely correlated with genotypic transformations [6, 7].

In the gradient of stress factors (pollution [8], emissions from industrial enterprises [9], mechanical disturbance of the vegetation cover [10]), ecological series of genetic and phenotypic diversity of natural flora species are also formed [11, 12]. And it is precisely in this similarity of discrete transformation of plant structures that we find an analogy between the plant breeding developments of Nikolai Vavilov with the recorded ecological and toxicological transformations in the structure of plants [13].

Donbass is a large ethnographic region of Eastern Europe, where conditions for a high anthropogenic transformation of natural ecosystems have been formed [14, 15]: a high level of development of the metallurgical complex, mining, chemical industry, etc. [16].

Under these unfavorable environmental conditions, programs for environmental monitoring [17], phytoindication [18], quantification [16] and expertise [19] of the level of

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harmful effects on natural plant communities [20] are being implemented. In the gradient of toxic load in distance from the source of pollution, wild plant species of natural flora demonstrate phenotypic plasticity [21].

The established difference can be represented in the idea of a scale of variation of indices – the ecological scale of the phytoindication criterion [17].

The purpose of this work is to consider the options for ecological scales of phenotypic diversity of indicator species of the natural flora in Donbass to highlight the more significant ones in environmental monitoring of the industrial region.

2 Methods

In the period between 1996 and 2021, studies have been carried out in different ecotopes: industrial zones, urban conditions, in the territories of an agrarian complex, in protected areas. The sites for collecting plant materials were organized within the framework of a dense ecological observation network. Sampling points (survey sites) were set in such a way as to evenly represent the entire area of industrial Donbass with the centre in the city of Donetsk and large industrial facilities in the cities of Yenakiyevo, Makeevka, Gorlovka, Khartsyzsk. We used the methods of monitoring studies in urbanized areas [22, 23]. The territories of the natural reserve fund were used as a control area (42 sampling points) for background monitoring in accordance with the general principles of ecological studies of landscape complexes and floristic observations [24, 25].

Impact monitoring was organized at the enterprises of the metallurgical complex, at the dumps of coal mines (waste heaps), thermal power plants, coke and chemical plants, chemical enterprises with a high level of emissions into the atmosphere. Particular attention was paid to collecting material from industrial and domestic waste landfills – at places of incineration and storage of waste. Cartographic analysis was used [26] according to methodological developments [27] planning an experiment on location according to geoecological rules.

The principles of conducting biomonitoring studies in places of increased anthropogenic influence [28] were considered as a way to obtain important information about the state of the transformed environment in an industrial region. The concentration of heavy metals was determined by the atomic absorption technique. The structural features of plants were established using the methods of light microscopy: to study surfaces under external light and internal tissues of plants in a beam of transmitted light, individual functionally significant parts being stained. The main connection between the state of plant organisms was considered in combination with the peculiarities of the soil environment [29] and other natural environments in the zone of contact of main abiotic pollutants [30] with plant organisms.

An important part of the experiment is the principle that all analyzed facts of plant structure are evidence of phenotypic plasticity. We used plant seeds from a genetically homogeneous population to place them in areas of medium to high industrial pollution. The features of the phytoindication experiment with various examples for the territory of Central Donbass are given in previous publications: using geographic information systems and analysis [14], for various industrial facilities [15], in a phyto-qualimetric experiment [16], in assessing individual processes of a large industrial city [17], when analyzing the seed bank of phytoindicators in a technogenically stressed region [18], in the system for registering teratological manifestations and recording anomalous cases of the structure of certain plant species in Donbass [21].

The principal mechanism of the ecological scales formation was the choice of an indicator plant. This species must necessarily be characterized by a wide ecological amplitude and degree of tolerance to toxic factors. Then the degree of variation of an individual characteristic in the structure of plants was determined or a calculation scheme was used according to the frequency of occurrence or the degree of manifestation of the characteristic.

3 Results

All scales were proposed for indexing each monitoring point for the purpose of further correlation analysis in comparison with the factors of toxic load on soil, air and hydrosphere in direct contact with plant organisms. The proposed scales (range from 1 to 10) represent a discrete ordination model of the amplitude of plant species tolerance in the gradient of toxic load from the norm to the maximum recorded pathology.

The first category of ecological scales involves record of metric diversity in terms of absolute indicators of a plant organism morphology – the general appearance (habitus) or individual organs and tissues. As a rule, this is the most accessible method for collecting information during expeditions and for rapid environmental assessment. For this kind of research, conclusions about the complex state of organisms are suitable – under the influence of factors of nonspecific stress. The main values of the scales of the first category are presented in Table 1. At the same time, the main indices from 1 to 10 include the entire range of the dimension of the attribute.

Table 1. Ecological scales of phytoindicators in an industrial region based on the principle of varying absolute metric parameters.

Species of plant	**10-point indicator scale**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	Name and metric value of the indicator attribute									
General architectonics of the shoot structures formation by one individual										
Echium vulgare L.	1-2	3	4	5	6	7	8	9	10	11
Reseda lutea L.	0.5-1	1-2	2-3	4	5	6	7	8	9	10
Tripleurospermum inodorum (L.) Sch. Bip.	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-4	5	5-6	6	7-8
Leaf blade length, cm										
Berteroa incana (L.) DC.	4.5	4.3	4.1	3.9	3.7	3.5	3.3	3.1	2.9	2.7
Echium vulgare L.	28	24	20	18	16	14	12	10	8	6
Plantago major L.	18	17	16	15	14	13	12	11	10	9
Cuticle thickness of the upper layer of the leaf epidermis, microns (μ)										
Capsella bursa-pastoris (L.) Medik.	0.5-1	1-1.5	1.5-2	3	4	5	6	7	8	9-10
Plantago major L.	4	5	6	7	8	9	10	11	12	13
Tanacetum vulgare L.	0.5-1	1-2	2-4	4	4-5	5	5-6	6	6-7	7
Number of stomata on the underside of the leaf, pcs.										
Amaranthus retroflexus L.	230	235	240	245	250	255	260	265	270	275
Artemisia vulgaris L.	270	275	280	285	290	295	300	305	310	315
Diplotaxis muralis (L.) DC.	250	252	254	256	260	270	280	290	300	310
Reseda lutea L.	220	223	226	229	232	235	238	241	244	247
Fruit sclerenchyma layer thickness, microns (μ)										
Centaurea diffusa Lam.	1-2	2	2-3	3	3-4	4	4-5	5	5-6	6
Cichorium intybus L.	1-3	2-3	3	4	4-5	5	5-6	6	6-7	7
Tragopogon major Jacq.	4	5	6	7	8	9	10	11	12	13

The second category of ecological scales (Table 2) is based on calculating the percentage composition of the studied characteristic in the total set of recorded cases. Mostly such signs are typical as a reaction to unfavorable environmental conditions. These scales are characteristic for calculating frequency of occurrence of deviations in the structure of plant flowers, pollen and the structure of the cotyledon apparatus. Most of the scales used have a significant correlation with the level of soil pollution by heavy metals, which is typical for emissions from metallurgical plants.

Table 2. Ecological scales of phytoindicators in the industrial region according to the calculated principle of correspondence of the percentage value.

Species of plant	**10-point indicator scale**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	Indicator name and percentage									
Teratological manifestations in the structure of the flower (populational)										
Berteroa incana (L.) DC.	2	3	4	5-6	7-8	9-10	11-12	13-14	15-16	17-18
C. bursa-pastoris (L.) Medik.	1	2	3	4	5	6-7	8-9	10-11	12-13	14-15
Cichorium intybus L.	2	2-3	3	4-5	6-7	8-9	10	11	12	13
Reseda lutea L.	3	4	5	6	7	8	9	10	11	12
Level of pollen grains defectiveness										
Cichorium intybus L.	2	3	5	6-7	8-9	10-11	12-14	15-20	21-25	26-30
Plantago major L.	1	2	3	4-5	6-7	8-9	10-11	12-13	14-15	16-17
Tripleurospermum inodorum (L.) Sch. Bip.	2-3	3-4	4-5	6-8	9-11	12-14	15-17	18-22	23-27	28-32
Manifestation of teratological syncotily										
Cichorium intybus L.	1	1-2	2-3	4-5	6-7	8-9	10-11	12	13	14-15
Tanacetum vulgare L.	1	1-2	2	3	4	5	6	7	8	9
Tragopogon major Jacq.	1-2	3-4	5	6	7	8	9	10	11	12
Manifestation of teratological schizocotily										
Cichorium intybus L.	1-2	3-4	5-6	7-8	9-10	11-15	16-20	21-25	26-30	30-35
Tanacetum vulgare L.	1-2	3-4	5-6	7	8	9	10	11-15	16-20	21-25
Tragopogon major Jacq.	1	2	3	4-5	6-7	8-9	10-11	12-14	15-17	18-21

The third group of ecological scales includes signs and calculated coefficients associated with the implementation of the vegetative and generative strategies for the survival of particular individuals of the species in difficult conditions of technogenic and anthropogenic load (Table 3). Such scales are most often used in urbanization conditions and high levels of air pollution as a result of waste incineration or dusty air during minerals extraction and coal mines dumps formation.

Table 3. Ecological scales of phytoindicators in the industrial region according to the indices of the survival strategy implementation (vegetative and reproductive success).

Species of plant	**10-point indicator scale**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	Indicator name and the value of the coefficient									
Structural heterogeneity of the leaf anastomosis mesh										
Cichorium intybus L.	1-2	2-2.5	2.6-3	3-3.5	3.6-4	4-4.5	4.6-5	5-5.5	5.6-6	6-7
Plantago major L.	1	1-1.5	1.6-2	2-2.5	2.6-3	3-3.5	3.6-4	4-4.5	4.6-5	5-6
Senecio vulgaris L.	1	1-2	2	2-3	3	3-4	4	4-5	5	5-6
Generative activity coefficient										
Echium vulgare L.	0.5	0.75	1	1.5	2	2.5	3	3.5	4	5
Tanacetum vulgare L.	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	3
Plantago major L.	1	1.5	2	2.5	3	3.5	4	4.5	5	6
Matrical heterospermia index										
Berteroa incana (L.) DC.	1	3	4	5	7	9	11	16	20	25
C. bursa-pastoris (L.) Medik.	2	5	8	11	14	17	20	25	30	35
Thlaspi arvense L.	2	4	6	8	10	15	20	25	30	35

Reseda lutea L.	1	3	5	10	15	20	25	30	35	40
Matrical heterocarpia index										
Berteroa incana (L.) DC.	3	6	9	12	15	20	25	30	35	40
C. bursa-pastoris (L.) Medik.	2	4	6	8	10	12	14	16	20	24
Cichorium intybus L.	5	10	15	20	25	30	35	40	45	50
Reseda lutea L.	2	3	4	10	15	20	25	30	35	40

Table 4 contains ecological scales, which were obtained as integral values of the state of tissue systems and microstructures of plant indicators. Thus, these are the most complex procedures for the qualitative and quantitative analysis of the ecotopes of Donbass – phytoquantification and expertise. Scales of the fourth category are the most accurate in establishing the level of anthropogenic load on natural ecosystems. This fact is confirmed by the statistical reliability in impact and background environmental monitoring.

Table 4. Integral ecological scales of phytoindicators in an industrial region by the frequency of occurrence (or appearance) of characteristic features or the degree of specialization of functional discrete structures.

Species of plant	**10-point indicator scale**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	9	10
	Name and numerical value of the indicator									
Specificity of covering trichomes of the leaf surface										
Cichorium intybus L.	0.5	1	2	2.5	3	3.5	4	4.5	5	5.5
Cyclachaena xanthiifolia (Nutt.) Fresen.	1	2	3	4-5	6-7	8-9	10-11	12-13	14-15	16-17
Echium vulgare L.	1	2	3	4	5	6	7	8	9	10-11
Tripleurospermum inodorum (L.) Sch. Bip.	1	2	2-3	3	3-4	4	4-5	5	5-6	6-7
Frequency of occurrence and level of specialization of leaf glandular trichomes										
Achillea collina J. Becker ex Rchb.	0.25	0.5	1	2	3	4	5	6	7	8
Ambrosia artemisiifolia L.	1	2	3	4	5	6	7	8	9	10
Artemisia absinthium L.	0.5	1	2	3	4	5	6	7	8	9
Senecio vulgaris L.	0.5	1	1-2	2	2-3	3	3-4	4	4-5	5
Deformation index of leaf terminal phloem										
Cichorium intybus L.	1	2	3	4	5	6	7	8	9	10
Plantago lanceolata L.	2	3	4	5	6	7	8	9	10	11
Plantago major L.	1	1-2	2	2-3	3	3-4	4	4-5	5	6-7
Reseda lutea L.	0.5	1	1-2	2	2-3	3	3-4	4	4-5	5
Index of atypical pollen structure (lacunae, surface sculpture)										
Artemisia vulgaris L.	2	3	4	7	10	13	16	19	22	25
Cichorium intybus L.	1-2	3-4	5-6	7-8	9-10	11-15	16-20	21-25	26-30	31-35
Cyclachaena xanthiifolia (Nutt.) Fresen.	2-3	3-4	4-5	5-9	10-14	15-19	20-24	25-29	30-34	35-40
Centaurea diffusa Lam.	0.5	0.75	1	2-3	4-5	6-7	8-9	10-11	12-13	14-15
Echium vulgare L.	1-2	3-4	5-6	10	15	20	25	30	35	40
Senecio vulgaris L.	0.5	1	2	3	5	7	9	11	13	15
Tripleurospermum inodorum (L.) Sch. Bip.	2-3	4-5	6-7	8-9	10-11	15	20	25	30	35
The number of abnormalities in the structure of the embryonic apparatus										
Cichorium intybus L.	1	1.5	2	3	4	5	6	7	8	9
Diplotaxis muralis (L.) DC.	0.5	1	1.5	2	2-3	3	3-4	4	5	6
Melilotus officinalis (L.) Pall.	1	1-2	2	2-3	3	3-4	4	4-5	5	6-7
Reseda lutea L.	1	2	3	4	5	6	7	8	9	10
Tanacetum vulgare L.	0.5	1	2	3-4	4-5	5-6	6-7	7-8	8-10	10-15

It has been experimentally proved that all ecological scales of the used indicator plants (Achillea collina J. Becker ex Rchb., Amaranthus retroflexus L., Ambrosia artemisiifolia L., Artemisia absinthium L., Artemisia vulgaris L., Berteroa incana (L.) DC., Capsella bursa-pastoris (L.) Medik., Centaurea diffusa Lam., Cichorium intybus L., Cyclachaena xanthiifolia (Nutt.) Fresen., Diplotaxis muralis (L.) DC., Echium vulgare L., Melilotus officinalis (L.) Pall., Plantago lanceolata L., Plantago major L., Reseda lutea L., Senecio vulgaris L., Tanacetum vulgare L., Thlaspi arvense L., Tragopogon major Jacq., Tripleurospermum inodorum (L.) Sch. Bip.) have an internal system of gradation: indicators 1-3 correspond to the regional norm, 4-5 – to the permissible value of anthropogenic load, 6-8 – to a high level of impact, 9-10 – to the critical level of plant tolerance organism and the state of the natural ecosystem.

4 Discussion

The thematic direction of establishing the ecological valence of a species to certain ecological parameters is applicable to many processes of plant life: dispersal, appearance in new territories [24], disappearance [17], appearance of new species, appearance of temporary structures for survival [5, 20] or somatic neoplasms that are incompatible with survival [7, 10]. This entire range of adaptations allows us to consider plant organisms as informative indicators of the state of the environment, which is also indicated by other authors [4, 9, 13, 26].

Publications on indicator plants in the industrial region contain a large array of ecological data [31, 32]. Scientists associate the results obtained with individual environmental factors or complex pollution of natural environments [33, 34]. Publications on the indicator functions of plants contain a large number of recommendations for carrying out environmental monitoring in the regions [35, 36]. Our results also characterize the current state of the area – the territory of an industrial region (Donbass) for environmental monitoring.

5 Conclusions

Scales of variation of structural and functional characteristics in a certain range of parameter values reflect the degree of morphological tolerance of a plant to factors of an unfavorable environment.

Environmental scales are calculated in different ways. They are obtained empirically as a result of many years of observations.

The highlighted features of the structure of plants form the basis for determining the areas of ecological disaster. This happens when there is high level of pollution by products of the metallurgical and mining industries.

The use of ecological scales is a convenient way to further quantify the state of plant species in a geochemically contrasting region and at a high level of anthropogenic load in Eastern Europe.

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