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Methodological approaches to assessing anthropogenic impact on agrocenoses

Olena Naumovska*

PhD in Agricultural Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-5938-8471

Yevhenii Berezhniak

PhD in Agricultural Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0001-5945-1285

Denys Aponiuk

Postgraduate Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0009-0009-1998-6272

Abstract. The relevance of the study is conditioned by the increase in the anthropogenic load on agrocenoses caused by the intensification of agriculture, the increase in chemical load and changes in the structure of land use. At the same time, these factors change the soil state, structure of the accompanying phytocenosis and the state of the biotic communities. This study aimed to systematise and compare the existing methodological approaches to assessing the effect of human impact on agrocenoses in the framework of the "pressures – state – impact" concept. A thematic synthesis of publications for 2019-2025 was carried out; sources that had clearly formulated indicators and an explicitly described procedure for their calculation were selected for the analysis. The generalisation was carried out according to the following analytical blocks: soil, biota, vegetation and geospatial tools. The results show that the most reliable estimates were obtained using a complex application of physical, chemical and biological indicators of the soil state; single-dimensional indicators lose their sensitivity to the management impact and do not reflect systemic changes. Bioindication based on enzymatic activity, microbial processes and reaction of soil fauna was found to be effective for early diagnostics of the degradation process and toxicological danger before irreversible changes in physico-chemical properties occur. Indices of plant diversity and dominance, as well as functional indicators, respond to the selective impact of intensification of agriculture and herbicide load, reflecting the simplification of communities and the change in the species composition. It was found that the application of geographic information systems and remote sensing of the Earth increases the comparability of estimates due to the possibility of spatial and temporal extrapolation, revealing within-field heterogeneity and risk zoning. Integral indices contribute to improving the comparability of territories; however, their application requires a harmonised interpretation of the direction of indicators, transparent weighting and an explicitly

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*Corresponding author

described uncertainty consideration. The results confirmed that a comprehensive approach that combines soil, biotic, plant and geospatial indicators is the most effective for monitoring, comparison of territories and decision-making for agrotechnical measures to minimise the negative environmental effect of agroproduction

Keywords: intensification; soil health; bioindication; landscape heterogeneity; remote sensing

INTRODUCTION

The agrocenoses are among the most strongly modified biotic systems in which the structure of the biota, the directions of the flow of matter and energy, and the type of ecosystem functions are determined not only by natural, but mainly by management conditions. The anthropogenic factor in the cultivation of crops and keeping of livestock is represented by a complex of directed technological impacts, chemical, mechanical and spatial, that change the physico-chemical properties of the soil, the structure of the phytocenosis and the state of the other biotic components functioning in it. In intensive technologies, the growth of productivity is usually provided by growing inputs of resources, the concentration of impacts, and increasingly complicated environmental costs. This tendency was clearly demonstrated in the analysis of the drivers, consequences, and alternatives of intensification in the dairy sector carried out by N. Clay *et al*. (2020). For this reason, the methodological estimation of the anthropogenic impact involves not only the description of the separate factors, but also the development of integral approaches to their quantitative measurement and comparison at the levels of the field, farm, and agrolandscape. One of the main methodological problems arises from the nonlinearity of the ecological reactions, when the growth of the pressure does not lead to commensurate changes in the indicators of the state; in certain situations, the system may move to another mode of functioning. The problem of threshold transitions in ecosystem services of agrolandscapes and the likelihood of intensification inducing "tipping points" was grounded in the research of S.C. Watson *et al*. (2021). It was pointed out that there is a need not only to reveal the average changes, but also the critical changes in the development trajectories. In this situation, indicator systems narrowed down to separate indicators lose their informative value, while systems that formalise cause-and-effect relationships and allow distinguishing between the driving forces, pressures, state, and impacts gain value. The Driving Force – Pressure – State – Impact – Response methodological framework, which has been elaborated for the evaluation of land, soil and water resources in agriculture, was systematised by A. Bhaduri *et al*. (2022) to provide the grounds for comparative analysis and for transforming diagnostic results into management decisions.

In the majority of agrocenosis assessments, soil has retained its position as the key object because, on the one hand, it performs a productive function, and, on the other hand, it serves as an accumulator of risks of degradation and pollution. The development of systems of indicators of soil health in relation to long-term fertilisation was shown by X. Li (2025), who proposed the construction of sets of indicators and rules for their aggregation for typical agricultural territories in conditions of long-term application of fertilisers. Such investigations are necessary to ensure comparability, as long-term fertilisation changes not only the nutrient regime but also microbiological and structural properties of soils, which, in their turn, affect the reaction of vegetation and biotic communities. The national dimension of methodological provision for risk analysis has been expanded through a discussion of methods for evaluating environmental risks proposed by A. Lishchuk *et al*. (2023b). According to the authors of that study, it is necessary to formalise the procedures for analysis and to strictly distinguish risks from their sources and from conditions of their manifestation. Therefore, the coordination of soil indicators with risk analysis has been viewed as a step from the level of local observations to the level of inferences significant for managerial decisions.

The anthropogenic load on agrocenoses comes not only from external but also from internal sources of chemical stress that affect not only the state of the soil but also the interaction of biotic components and the environmental safety of agrolandscapes. An ecotoxicological assessment of the effect of landfills for solid communal waste on neighbouring agrocenoses was made by P.V. Pysarenko *et al*. (2022), who showed that agrosystems can be exposed to essential loads not related to agricultural technologies and that those loads should be integrated into the general framework for evaluation. Among technological factors, the pesticide burden is one of the most powerful, because its impact can be implemented in the form of both acute toxic action and selective effects on the biota and the structure of communities. Regional studies on the environmental risk of pesticide loads in agrocenoses of predecessors of cereal crops were presented by A. Lishchuk *et al*. (2023a); the authors emphasised the need for integration of data on the application of pesticides with state indicators and disturbance indicators. A more general synthesis of the approaches to the management of pesticide risk in agrocenoses stressed the importance of indicators capable of diagnosing early negative shifts and of spatial heterogeneity of the impacts that would provide a basis for management decisions not built on the observance of the standards.

The analysis of the plant component is methodologically important not only as a characteristic of the impacted object but also as a tool for fixation of the system response of the agrocenosis to management impacts. The approach to the use of functional indicators for the explanation of the anthropogenic changes in the species composition was justified by L. Bonilla-Valencia *et al*. (2020). The authors showed that the interpretation of changes becomes more informative if based on functional traits related to disturbance and stress rather than on taxonomic inventories. For the transition from the field level to the agricultural landscape level, the quantitative description of the spatial structure is of principal importance because it defines ecological connectivity, potential of recovery, and stability of biodiversity. The quantitative evaluation of agrolandscape heterogeneity by land-cover structure metrics was shown by N.P. Seidl & M. Golobič (2020). The authors offered methodological instruments for comparison of territories and for consideration of the landscape context in the interpretation of "state" indicators. This created a demand for a methodological complex capable of integrating technological impacts, soil and biotic processes, plant indicators, and spatial structure of the environment within a single conceptual system of evaluation.

This study aimed to incorporate modern methodological tools for evaluating anthropogenic effects on agrocenoses into the "pressures – state – consequences" analytical framework, ensuring the comparability of assessments at sites and spatial scales. To implement this aim, the following tasks were formulated: to generalise indicator-based approaches for assessing the state of the soils and environmental risks at different types of impact; to describe approaches to identifying changes in the structure of the plant community and landscape heterogeneity as modifying environmental consequences; to justify the rationale for integrating indicators into causal schemes, convenient for territorial comparisons and decision-making.

MATERIALS AND METHODS

The analysis of methods for assessing anthropogenic effects on agrocenoses was carried out as a narrative (thematic) review with elements of evidence synthesis (scoping review) aimed at systematising and comparing indicator-based approaches for the soil component, plant communities and associated biological components, primarily soil biota. The analysis of methods for assessing anthropogenic effects on agrocenoses was carried out as a thematic synthesis of modern approaches, including bioindication, ecological indices of plant communities and geospatial methods, with a focus on the soil component, plant communities and related biological elements, primarily soil biota. In the context of agrocenoses, anthropogenic effects were understood as a comprehensive impact of controlled agrotechnical measures and land-use spatial transformations leading to changes in the physical-chemical and biological state of the soil, the structure of accompanying vegetation and the functioning of biotic communities. The analysis was structured according to the "pressures – state – consequences" scheme, which allowed associating specific drivers of agricultural intensification with measurable indicators of the system state and indicators of ecological consequences.

The analysed materials consisted of publications from 2014 to 2025, with a focus on the latest research published from 2019 to 2025, during which the intensification of the development of indicator systems for soil health, geospatial methods, and remote sensing occurred. The search of literature was carried out in the main bibliographic and full-text bases: Scopus, Web of Science Core Collection, PubMed, and Google Scholar. In addition, methodological and technical documents of normative character were analysed. Among them were the materials of the European Union (EU) on monitoring soil (Directive (EU) 2025/2360, 2025); metadata for statistical data from Eurostat (n.d.); and documentation for Earth observation programmes for agriculture (Sen4CAP, 2017). Requests were formed in Ukrainian and English and combined into thematic blocks: agrocenoses and land-use intensity; technological pressures; soil indicators; plant communities; geospatial methods; vegetation indicators; and modelling. The analysis included articles, reviews, systematic reviews, and methodological materials that contained an explicit description of the indicator, procedure for its calculation, or the presentation of the required data. Materials not related to agrocenoses, those without methodological descriptions, and declarative articles were excluded. The preference was given to studies whose methods could be compared in terms of the scale of application, the type of data (field, monitoring, satellite or model), and the ability to integrate into comprehensive indices.

The state of soils was considered as a combination of physical, chemical and biological indicators; single-dimensional assessments do not allow for the identification of systemic changes. The greatest attention was paid to indicators of soil compaction and structure, content of organic matter or organic carbon, acidity, nutrient regime, and, if necessary, salinisation and pollution. The biological component of soil was represented through indicators of microbial activity, enzymatic tests and indicator groups of soil fauna, which reflect the functional consequences of agricultural pressures and respond sensitively to the intensity of tillage, chemical loads and deficiencies of organic matter. The selection of bioindicators was interpreted with regard to the fact that their values depend strongly on season, moisture conditions and soil type. For this reason, the synthesis emphasised the need to compare data obtained under comparable natural conditions.

The evaluation of the effect on plant communities was represented by the analysis of accompanying flora as an indicator of disturbance and selection pressure, as well as by applying ecological indices of diversity and dominance. It was shown that these indicators allow tracing the simplification of communities, changes in species composition, and an increase in the proportion of dominant species in response to intensive technological impacts. At the scale of the agricultural landscape, the role of semi-natural elements and spatial mosaics was also considered, as these factors contribute to the conservation of biodiversity and the buffering of agricultural pressures. For comparing between fields, crops and regions, the articles reviewed here consistently used species richness and community diversity indexes, such as the Shannon diversity index and the Simpson dominance index. Their use ensured the comparability of assessments under differing levels of technological pressure. New analytical techniques have been developed in combination with Geographic Information System (GIS) and remote sensing to describe spatially and temporally the status of the crops and the structure of the land cover. Remote sensing data were used as a proxy for providing indicators of seasonal, phenological and intra-field variability, which allowed the extrapolation of point measurements to larger areas. Geoinformation techniques were used to combine point data with mapping data layers, to consider the landscape context and to define risk areas for degradation.

Special emphasis was placed on aggregated indices, which allow the combination of multiple variables into a composite index for soil, biota and vegetation, making possible the comparison between areas or between different time periods. The discussion emphasised that aggregating indexes requires consensus on the direction of the indexes' interpretation, a clear weighting procedure and a clear uncertainty analysis in order to prevent the index results from depending too heavily on the mathematical framework. The last part of the review was related to the comparison of methods used to predict the response of management practices, where models were used to evaluate scenarios of change in nutrient cycling, soil erosion, carbon cycle, and other environmental impacts. It was concluded that the combination of monitoring data, remote sensing indexes and model outputs improves the confidence of the results and the practical use of the methods for the sustainable use of natural resources, biodiversity and minimisation of the environmental impact of agricultural practices. Limitations of the study consisted of the fact that the results are based on a qualitative comparison between articles and not on a common dataset of field measurements. In addition, the diversity of methods, scales of study and environmental conditions among the studies considered here limits the extrapolation of critical levels and ranges to other regions.

RESULTS AND DISCUSSION

Structuring causal relationships within the framework of "pressures – state – consequences"

The synthesis of selected studies showed that most replicable and analytically powerful approaches were those where human impact on agrocenoses was described through an analytically clear and sequentially consistent differentiation between technological pressures, the state of system components and ecological consequences. This three-level logic was used both as a tool for results structuring and as a tool for the control of typical methodological mistakes in causal inference in agroecological studies. The synthesis revealed that, in the absence of a distinct separation between "pressure" and "state", most indicators become non-informative: the same indicator starts to be read simultaneously as cause and effect. This ambiguity leads to circular readings and overestimates the apparent logic of inferences. This is why causally structured frameworks are the only ones ensuring the comparability of results between studies, territories and time periods.

In the synthesis, pressures in agrocenoses were understood as managed regimes of intensity, not as particular technological interventions. The intensity of tillage, agrochemical loads, simplification of crop rotations and land-use changes were found to have a cumulative nature and often synergise. This is why the same doses or technologically similar measures can cause different effects: they depend not only on the "dose" but also on the "exposure" defined by the toxicological properties of substances, transport conditions, frequency of applications and landscape-soil situation. As a result, in methodologically valid studies, the pressure was not reduced to its mere application but was characterised by frequency, dose, seasonality, application technology and landscape-soil conditions.

The DPSIR scheme (Driving forces – Pressures – State – Impact – Response) appeared to be an adequate tool for ordering such causal chains, since it enables the separation of levels of description and helps to maintain logical coherence in the identified relationships. In agroecosystem applications, DPSIR formalises the connection between agricultural intensification and changes in ecosystem functions by aligning driving forces and pressures with sets of state and impact indicators (Moss *et al.*, 2021). The practical significance of this scheme is that it makes it possible to identify "gaps" in the causal chain: if any pressure has no state indicators or they are weakly connected to the impact mechanism, then the subsequent reasoning about the consequences is methodologically incomplete.

When evaluating the sustainability of agricultural territories with the help of the DPSIR, the combination of diverse indicators made it possible to create comparable "pressures" and "state" profiles, which allowed the understanding of the differences in the ecological efficiency of management at the level of territorial units (Chen *et al.*, 2024). It turned out that high values of pressure indicators should not be considered as an unambiguous sign of degradation in the absence of confirmation by state indicators, whereas satisfactory state parameters do not exclude risk in conditions of accumulation of pressures or in the presence of a delayed reaction of the soil-biotic complex. As a result, the most reliable estimates were those that took into account the delay, nonlinearity and the variable buffer capacity of systems depending on the soil and landscape situation. In the works systematising the interaction of agriculture with aquatic ecosystems, the DPSIR logic made it possible to clearly distinguish agricultural pressures from the natural variability of the hydrological regime and to build transparent causal chains between agricultural production and the state of aquatic ecosystems (Troian *et al.*, 2021). This demonstrated the relevance of the agrolandscape scale, because some impacts occur outside the field, as a result of matter transfer and changes in other environmental compartments. Hence, a causally structured approach was most effective when field-level indicators were combined with indicators of landscape structure and material flux.

That the "pressures – state – impacts" logic is consistent with the policy level of observation was supported by the fact that normative documents on monitoring of soils are focused on systematic observation and comparable characteristics of soil sustainability and degradation that can be compared in dynamics and between territories (Directive (EU) 2025/2360, 2025), which makes the necessity of transparent connection between indicators, specific pressures and expected responses even more obvious. At the same time, it was stressed that striving for comparability does not remove the contextuality, but only increases the requirement for adequate accounting for the natural background, primarily through stratification by soil types and landscape features.

In general, it was found that structuring assessment according to the DPSIR scheme provides methodological reliability (prevents confusion of causes and responses), readability (provides an explanation for the variability of responses under the same technologies) and is the basis for management recommendations (connection of certain management practices with expected changes in state), which are the reasons why causally-oriented schemes remain relevant for integration of soil, biotic and phytometric indicators as well as remote-sensing data into a unified system for diagnostics of anthropogenic influence on agrocenoses.

Dependence of interpretation on soil indicators

The synthesis of approaches to assessing the state of soils showed that modern methods are mainly represented by combinations of physical, chemical and biological indicators, single-dimensional assessments do not embrace system-wide changes and often lose sensitivity to management pressures (Guo, 2021). The analysed publications demonstrate a clear tendency to abandon universal singleindicator solutions in favour of sets of indicators, where each block of indicators corresponds to a specific mechanism of degradation or functional transformation. Physical indicators were most often considered markers of mechanical exposure and structural destruction, primarily compaction and loss of porosity, which directly restricts the infiltration, gas exchange and availability of moisture for the root system. Chemical indicators were found to be more appropriate for estimating long-term changes in the regimes of buffering capacity, acidity, salinity and nutrients, which appeared as a result of fertilisation, elements leaching, amelioration activities and soluble compounds transfer. Biological indicators were considered as a "functional layer" of assessment, because they reflect the intensity of soil processes, the response of the microbial community to changes in the availability of organic matter, and the capability of the soil to maintain a stable biogeochemical cycle.

It was concluded that the main methodological justification for the comprehensive approach was uncertainty in the interpretation of individual indicators in different types of impact. Thus, a decrease in organic matter content or in the content of soil organic carbon can be caused both by intensive tillage and enhanced aerobic decomposition, and by the structure of crop rotation, reduced input of plant residues or erosion losses. A change in soil acidity can testify to technological solutions (types of fertilisers, amelioration) as well as to differences in the natural soil background. For this reason, sets of indicators were regarded as essential for "isolating" the causal chain: physical indicators for relating changes to the level of mechanical disturbance, chemical ones for the input and mobility of substances, and biological ones for the reactivity of processes and functions. In such a combined approach, the resolution of the diagnosis was increased, and the likelihood of wrong causal conclusions was minimised.

It has also been shown that the variability in soil health status within agroecosystems was not only determined by the differences between farms, but also by the variability of practices within the same crop and even within the same region (Omer *et al.*, 2024). This has direct methodological consequences. First, the need for matching the scale of assessment with the real scale of heterogeneity of management increases, since agronomic solutions are often differentiated at the level of individual fields or even parts of fields. Second, when comparing locations, the history of management should also be taken into account, not just the current year, as some soil changes have a certain degree of inertia. Therefore, the evaluation of the soil status cannot be based on a single snapshot of indicators, without management context, since the same indicator value in different systems could have a different meaning (i.e. stabilisation, degradation, recovery from previous impacts).

A prerequisite for the correct interpretation of biological indicators is their dependence on soil context. It has been demonstrated that the use of soil classification improves the interpretation of biological soil health indicators and reduces the risk of false conclusions when comparing territories with different natural backgrounds (Congreves & Wu, 2024). This is because the basic soil properties determine the natural range for the variations in microbial and enzymic activities and faunal structure. Thus, direct comparison without stratification or normalisation may mask the management effect by mixing it with the inherent typological soil effect. In practical terms, this meant that the same tillage or fertilisation intensity could generate different amplitudes in the biological response, depending on texture, organic matter, carbonates, water regime, and thus a contextual interpretation was needed.

The comparison of the scientific results with the legislative framework of the European Union evidenced that moving toward systematic soil monitoring and evaluation of its resilience needed comparable indicators to capture the process of degradation and the changes in the stability over time (Directive (EU) 2025/2360, 2025). In this sense, sets of indicators acquired an additional value: they enabled the evaluations to be normalised, while keeping the sensitivity to local mechanisms of degradation. Thus, the soil indicators are viewed as the nucleus of the evaluation of anthropogenic impacts on agrocenoses, but their practical utility is enhanced only through the application of multicomponent approaches, synchronisation with the history of management and an explicit account for the soil-typological context.

Enzymes, microbial processes and soil fauna as risk indicators

It was evidenced that the biological indicators were more frequently used as an early warning tool to detect soil changes at an early stage, when the process of degradation was not always registered by conventional physico-chemical indicators. In the practice of assessing anthropogenic impacts, bioindication complements classical soil measurements, as it allows for the description not only of environmental conditions but also of the activity of soil processes associated with the transformation of organic matter and nutrients. In this sense, biological indicators are viewed as part of the "state" component within the "pressures – state – impacts" concept, as they directly reflect the response of the soil biota to the intensity of tillage, fertilisation or pollution.

Enzymatic assays were recognised as a widespread type of bioindication. It was stated that enzyme activity data supply valuable information on soil quality in agricultural soils and may also be employed for monitoring contaminated soils (Adetunji *et al.*, 2020; Lee *et al.*, 2020). The most popular enzymes were dehydrogenase, phosphatase, and urease because they are indicative of overall microbial metabolic activity, phosphorus transformation, and nitrogen cycling in soil. These tests are very handy as they are quantitative and can be compared between different managements or sites under varying pressure. Simultaneously, it was pointed out that the results of enzymatic bioindicators should be associated with soil conditions. Significant correlations were shown between pH of the soil solution and the activities of individual enzymes and between clay content and urease and phosphatase activities to illustrate the dependence of biological tests on native properties of soils (Lee *et al.*, 2020). A threshold concentration was also mentioned for residual mixed hydrocarbons in the soil at 1,000 mg/kg, above which the activity of individual enzymes can be shifted either to stimulation or inhibition (Lee *et al.*, 2020) (Table 1). In practical terms, such numerical benchmarks are used to justify that bioindicators should be analysed in conjunction with the fundamental properties of the soil and contamination data, rather than in isolation.

Table 1. Examples of numerical values for bioindicators and soil context

Indicator	Context	Value
Correlation pH – dehydrogenase (DH)	Relationship between soil properties and enzymatic activity	r = -0.704
Correlation pH – phosphatase (PHO)	Relationship between soil properties and enzymatic activity	r = -0.875
Correlation pH – urease (UR)	Relationship between soil properties and enzymatic activity	r = -0.784
Correlation clay – phosphatase (PHO)	Relationship between soil properties and enzymatic activity	r = 0.873
Correlation clay – urease (UR)	Relationship between soil properties and enzymatic activity	r = 0.930
Correlation of organic matter (OM) – phosphatase (PHO)	Relationship between soil properties and enzymatic activity	r = 0.698
Correlation dehydrogenase (DH) – phosphatase (PHO)	Relationship between enzymes	r = 0.804
Correlation phosphatase (PHO) – urease (UR)	Relationship between enzymes	r = 0.959
Threshold value for residual hydrocarbons in soil	Level at which enzyme activity changes were observed	1,000 mg/kg

Source: S.H. Lee *et al.* (2020)

Indicators of microbial processes and microbial biomass were described as tools reflecting differences between cropping systems and fertilisation regimes. In a case study performed on Indian vertisols, it was shown that enzymatic activity and microbial biomass characteristics can be employed as bioindicators of soil quality for comparison of different cultivation systems and fertilisation management practices (Ghosh *et al.*, 2020). These arguments are in line with those where bioindicators are not only toxicant-sensitive but also reflect changes in the intensity of biogeochemical soil processes. Soil fauna, in particular earthworms, was mentioned in specialised reviews as a promising object for soils contaminated with pesticides. To sum up, in these studies, it was concluded that applying such approaches provided the possibility of using the population-level indicators, behavioural responses, and biomarkers to evaluate and characterise the state of soil under pesticide application, helping in monitoring activities (Duan *et al.*, 2025). In Ukrainian agrocenoses, bioindication appeared to be an adequate tool for analysing the risks of using pesticides and detecting ecological risks caused by heavy metal pollution, thus confirming the applicability of biotic indices for agroecological diagnostics (Lishchuk *et al.*, 2023a).

Generally, biotic indices appear to be best regarded as an early diagnosis, which complements the soil physico-chemical properties, thus increasing the sensitivity of agroecosystem state assessment to management variations. Their main practical value is seen in the possibility of comparing different technologies and fertilisation levels, as well as of evaluating the risks in the conditions of various types of chemical impact before irreversible changes are observed. At the same time, the correct interpretation of these indices requires taking into account the type of soil, the current season, and the observation scale to distinguish changes occurring under the natural variability from those caused by anthropogenic impact.

Diversity, dominance, and sensitivity indices in response to herbicide regimes and intensification

In a review of methods used to diagnose the state of the plant component of agrocenoses, it was concluded that the associated flora, mainly weeds, was most commonly used as an indicator of disturbance and selection pressure due to management. Across the disciplines, species richness and structure of plant communities, expressed by means of the Shannon diversity index and the Simpson dominance index, were the most frequently applied across crops and regions. Both indices were found to be useful in the context of quantifying the "simplification" of the plant communities due to intensive weed management and in detecting shifts toward communities with a limited number of taxa dominating cover and biomass. In the context of the assessment of human impacts, plants were most often used in the "state" part of the framework as they express the current structure of the phytocoenosis influenced by the repeated disturbances (tillage, herbicides, reduced crop rotation diversity) and as the "bridge" to the consequences such as the reduction of the floristic diversity, the loss of resource bases for other related trophic levels, and the reduction of the buffering capacity of field biota.

For cereals, it was revealed that the structure and diversity of weed communities were significantly different between crops and varied regionally, whereas diversity and dominance indices were considered suitable for the comparison between fields and regions. For example, in the cereal fields of South-Eastern Poland, the mean values of the Shannon diversity index of weed communities ranged from 2.11 to 2.52 (depending on the type of cereal), while the Simpson dominance index was relatively low and ranged between 0.08 and 0.18 (Table 2). This indicated a community structure without clear dominance of one species and the presence of differences between crop types, which confirmed the suitability of these indices for monitoring time and spatial changes (Sawicka *et al.*, 2020).

Table 2. Examples of plant indicators (indices, species richness, cover)

Object/context	Numerical indicators (examples)
Weeds in cereal crops, South-Eastern Poland	Shannon index (H): 2.11-2.52; Simpson dominance index: 0.080.18 (depending on crop)
Fallow land, 2014-2016, Northern China; annual applications of atrazine/tribenuron-methyl	Total species over 3 years: control 27; herbicide treatments 1923; number of species in control per year: 13 (2014), 14 (2015), 24 (2016)
Winter wheat, France; 1-20 years after conversion to conservation practices	Mean species richness: 23.9 species; mean Shannon index: 2.15
Forest-field ecotone, Poland; 1996-1998 vs. 2016-2018	Agrocenoses: 137 → 102 species; typical segetal species: 77 → 43; weed cover: ~32% → ~15%; QS (ecotone-agrocenosis): 0.47-0.64 → 0.30-0.55

Source: B. Sawicka *et al.* (2020), T. Skrajna (2020), Y. Qi *et al*. (2020), D. Derrouch *et al*. (2021)

The vulnerability of plant communities to herbicide applications was demonstrated mainly as a decrease in species richness and changes in the structure of plant communities. Changes occurred at both full and reduced exposure levels. This is important when evaluating risks to semi-natural components of the agricultural landscape and to the field boundaries, where the drift and run-off of active ingredients can be a chronically acting but "subtle" factor. According to the field experiment conducted by Y. Qi *et al*. (2020) on fallow plots in Northern China exposed to annual atrazine and tribenuron-methyl applications, the total number of species in the control was 27, and the number of species in the herbicide treatments ranged from 19 to 23, depending on the active ingredient and the dose. The authors also noted that the diversity indices were not always linearly related to the dose, and some effects were already observed at 25-50% of the recommended field concentration. Such observations (presented in this review) served as a methodological proof that the herbicide effect should not be considered as a separate factor, but as a regime, characterised by temporality, seasonality and transferability. In the "state" part, diversity indices should be accompanied by a species list and community structure.

For soil-conserving agriculture and reduced-tillage farming, it was found that the dynamics of floristic indicators can differ from those in intensive farming. After the introduction of conservation technologies, changes in the species composition of segetal communities and a trend towards homogenisation between fields were often registered, even against the background of a relatively stable mean diversity. In the network study of D. Derrouch *et al*. (2021), conducted on winter wheat in France (along the gradient of 1-20 years after the transition to conservation technologies), the average community was characterised by species richness of about 23.9 species and a Shannon index of about 2.15. This shows that it is not enough to judge intensification by a decrease in indices: some technological changes can lead to an increase in local species richness, and at the same time reduce the heterogeneity between fields, which in turn will change the ecological resilience of the agricultural landscape as a whole.

In the research of T. Skrajna (2020), which was aimed at long-term comparisons in the forest/woodland strip, ecotone, and field boundary system, it was found that intensification can lead to a direct impoverishment of the flora inside the agrocenosis, while the species pool in the ecotone has remained relatively preserved. In particular, in a 20-year comparison (1996-1998 and 2016-2018) in Poland, it was found that adjacent agrocenoses showed an approximately 30% decrease in the total number of species (from 137 to 102), a decrease in "characteristic" segetal species (from 77 to 43), and a decrease in the average weed coverage (from about 32% to 15%). At the same time, the ecotonal areas preserved a high taxonomic richness (about 171 and 169 taxa for the two periods), while there was a decrease in the floristic similarity between the ecotone and agrocenosis (the Sørensen coefficient QS decreased from 0.47-0.64 to 0.30-0.55) (Skrajna, 2020). This combination of evidence made it possible to infer a methodological implication that the context of the landscape and ecotonal diversity reservoirs should be taken into account when using plant indicators, as changes in the field may be obscured by the constancy of the surrounding semi-natural objects, but are associated with the increasing isolation of flora pools.

Geographic information systems, remote sensing, integral indices, and modelling as tools for scaling and scenario assessment

The collated evidence suggests that GIS and remote sensing (RS) of the Earth are not only used as additional "visualisation" tools, but as an independent level of analysis of the effects of anthropogenic impacts, which allow describing the state of agrocenosis in space and time, and extrapolate the results of local studies to the level of farms, river basins and regions. In practice, this became possible because the satellite time series contains repeated measurements over the growing season, while GIS provides the opportunity to combine the results of these measurements with the boundaries of fields, soil maps, management information and environmental context. Thus, RS is most often used to link point observations with generalisations at the level of the landscape, while GIS are used as a tool for integrating layers of data for spatial analysis and mapping risk zones.

In a review of phenological studies based on data from the Sentinel-2 satellite, G. Misra *et al*. (2020) found that the majority of studies employed traditional vegetation indices for characterising the phenological cycle. Red-edge and short-wave infrared (SWIR) bands were underutilised, although their inclusion can enhance the sensitivity to physiological conditions and stress of crops. In practical assessments of the impact of anthropogenic factors, this is important because simple indices are good at monitoring "greenness" and the overall productivity of plants, but are less able to identify the reasons for the changes. When the same decrease in an index could be caused by water stress, nutrient stress, herbicide stress or soil regime disturbance, the use of a wider spectral domain as well as phenological indicators (i.e. start, peak and end of the growing season, or integral of the growing season curve) is more robust for the interpretation of the "state" and for comparison between fields observed under different weather conditions.

The benefits of combining sensors for agromonitoring was further demonstrated in a multi-year phenology study, where the fusion of Sentinel-2 and Landsat 8 time series using the green Leaf Area Index (green LAI) in combination with Gaussian Processes Regression (GPR) increased the overall accuracy of growth period detection up to 74%, compared to 69% for Sentinel-2 and 63% for Landsat 8 (Amin *et al*., 2022). For the methodologies of anthropogenic impact, this was particularly valuable because, by stabilising the phenological signal, the fusion of satellite missions reduced time series gaps and decreased the dependence of assessments on isolated events of cloud presence or missing data. As a result, the comparability of satellite-based indicators across seasons, farming practices or areas, within a single growing season, was improved.

The operational integration of satellite-based products in agromonitoring systems of policy monitoring was exemplified in the Sen4CAP approach (2017), which underlined the importance of harmonised production pipelines to convert satellite data into reproducible indicators for monitoring farming practices at the field level. This was a relevant example of the transition of RS from imagery to infrastructure, and the shift from maps to production quality control and harmonised procedures. For integrated "pressure" indicators, the application of the Harmonised Risk Indicator 1 (HRI 1) was standardised, where the 2011 to 2013 time slice was considered as a temporal reference for comparison, and the "use and risk" components were aggregated according to the classification of active substances (Eurostat, n.d.). This was useful since it allowed for the standardised comparison between the dynamics of pesticide pressure between different years and facilitated the inclusion of other layers in GIS analysis. For agrocenoses assessment, it facilitated the integration of pressure (e.g. regional risk profile of applications) with spatial "state" indicators (phenological anomalies, field heterogeneity) and with impact models.

In the sources reviewed, modelling was mainly seen as a tool for scenario-based analysis, as a way to build on observations, and to move beyond the description of a "state" to the prediction of potential "impacts". In the case of an integrated approach to modelling sustainable intensification, there was an emphasis on the usefulness of combining model predictions with monitoring and satellite data for decision support and scenario analysis of changes in practices (Brown *et al*., 2023). Studies related to the soil, land use, and climate interactions pointed out that the stability of the agroecosystem depends on the holistic consideration of those, since the human impact is coming from the interaction of the management and climate drivers, which are often confounded (Si *et al*., 2025). Therefore, GIS and RS provided spatial extrapolation and pattern recognition, integrated indices provided a standardised way of representing "pressures", and models allowed for scenario-based extrapolation of likely outcomes under different management regimes.

The comparison of the selected sources revealed that the highest level of agreement between studies occurred when anthropogenic pressure was conceptualised as a bundle of factors, rather than a single overriding pressure, and when the conditions for comparability (such as scale, natural baseline, management history) were clearly outlined. The highest levels of disagreement occurred when the same indicators were applied as generic proxies, without specific relation to soil, landscape or geochemical conditions, which necessarily changed the meaning of "state", even when the absolute values were the same. In the systematic review protocol by S.M. Beyene *et al*. (2025) stressed that several anthropogenic drivers can change both the direction and strength of plant and soil feedbacks; the agroecosystem is not expected to respond as a fixed function of a single driver. This claim was consistent with other research where agroecosystem status was assessed based on functional traits, but it was inconsistent with other research where indices were used outside of a covariate context, since in the latter case, the relationships between drivers are masked, leading to contradictory results among studies.

In the review on bioindicators by B. Gorain & S. Paul (2021), the authors showed that biotic indicators responded to changes in management sooner than less reactive physical-chemical attributes, and were useful for early warning signs of degradation. This was consistent with risk assessment methods based on sensitive bioindicators, but it was not entirely consistent with methods where limits are transposed between soils and seasons, since the authors concluded that soil type and season significantly affected the baseline variability of bioindicators. In the chapter on earthworms as bioindicators, V. Dhiman & D. Pant (2022) demonstrated that biomarkers and behavioural responses at the sub-individual level may respond faster to toxic effects than population-level responses, and may aid in early risk detection. This reasoning supported the idea of early bioindicators for soil quality, but it was not consistent with methods where bioresponses are interpreted in the absence of information on contaminants and soil, since in this case, the same biomarker may respond to different mechanisms of stress and may lead to contradictory results among studies.

In the study by J. Špulerová *et al*. (2022) on natural and semi-natural features as indicators of biocultural value, it was demonstrated that the features are not accidental but are structurally constitutive elements, which facilitate connectivity and the capacity to maintain biodiversity. This was consistent with perspectives that relate the stability of agroecosystems to environmental diversity and structure, but it was not consistent with evaluations carried out exclusively at the field scale and in the absence of a landscape context, since the same pressures in different contexts may have different ecological consequences. In the research on spatio-temporal dynamics of rural areas, D. Statuto *et al*. (2019) showed that using spatial metrics and multi-temporal map comparison enables quantifying the trend and speed of land cover changes; detecting areas where changes occurred at different intensities, and thus with a different capacity for sustainable planning. This is in line with a landscape-oriented approach, where the spatial structure of the mosaic is viewed as a contextual factor modifying the response to a treatment rather than as an independent factor with its own effect. Simultaneously, the authors stressed that temporal context is necessary for the interpretation of landscape metrics and that information on land use history is needed because the metrics express the footprint of past land uses, and when ignoring land use history, wrong conclusions could be drawn about the causes of land cover change. In the study on agro-biodiversity and agro-ecosystem stability, S. Wang (2021) found that agro-biodiversity within agro-ecosystems contributes to system resilience to disturbance and fluctuations, and thus should be considered a functional attribute of resilience, rather than a structural attribute. This is in line with the landscape-oriented approach, which stresses the importance of environmental mosaics; it is less in line with assessment approaches based on single productivity metrics because productivity and stability may not always be synchronised, especially when multiple drivers are involved.

In the comparative study of arsenic, T. Tarvainen *et al*. (2020) found that high concentrations of arsenic in agro-ecosystems may be due to elevated geochemical background or anthropogenic impact, and that the same concentrations may have a different environmental meaning depending on the source and geochemical context. This supports the need for contextual interpretation of the bioindicator, but does not support the widespread practice in applied studies where high concentration values are associated with high levels of anthropogenic impact without separating geochemical background concentrations, which leads to incomparability of results between regions and to the risk of misattribution. In this context, the study of P. Rendon *et al*. (2020) is of interest, which investigated the relationship between the state of an agroecosystem and the service of regulation of soil erosion. In this study, the indicator assessment was closely linked to the functional consequences with practical implications for risk management. This study has some similarities with the spatial approach, since erosion is a process that has marked spatial heterogeneity. Based on the results of all the studies, it was possible to identify which blocks of results were most similar and which were less comparable. The greatest comparability was found for the principle of multicausality and contextuality, as it was supported by both a mechanistic model of multiple drivers and geochemical comparisons that distinguish between background levels and anthropogenic load. In contrast, attempts to extrapolate absolute thresholds and scales of biological responses to different soil types and management conditions without standardising the context were less comparable, since some studies considered the context as a primary modifier, while in other studies it was implicit. In general, the most consistent explanation of the variability of the results was obtained by a comprehensive logic in which the structure of the landscape defined the framework of vulnerability, the bioindicators captured the early sensitive changes in state, the geochemical context prevented false attributions, and functional indicators such as the regulation of erosion allowed the understanding of the consequences in terms of ecosystem services.

CONCLUSIONS

A methodological review of the assessment of the anthropogenic impact on agrocenoses indicated that the most reproducible results were obtained when pressure indicators, state indicators, and consequence indicators were integrated into a cause-and-effect model suitable for territorial and temporal comparisons. It was verified that agrocenoses should be conceived as hierarchical systems, in which technological management regimes modify soil processes, the structure of the associated vegetation, and the functioning of the biota, while ecological responses are often non-linear and contextual. Under these conditions, indicator approaches based on a single block of indicators were insufficient, while a complete set of physical, chemical, and biological parameters of the soil provided a more consistent interpretation of the changes and prevented false attributions of causality.

It was corroborated that biological indicators -microbial processes, enzyme activity, and responses of soil fauna- constituted sensitive markers of the early changes in state and risk of degradation or pollution, and in addition, improved the functional interpretation of the results. In the plant compartment, diversity and dominance indices and functional indicatorscaptured the selective pressure of intensification and herbicide management, and were informative for the diagnosis of simplification of plant communities. Indicators of landscape heterogeneity calculated with the geographic information systems provided a complementary vision that considered environmental mosaics as modifiers of vulnerability and resilience. Remote sensing and integral indices were conceived as scaling tools that allowed articulating field data with spatial patterns and supporting the scenario-based justification of management practices. Future studies should be directed to standardising protocols for comparing indicators between different soil types and climates, validating integral indices against time series of long-term monitoring, and deepening the integration of remote sensing, biological, and modelling information to assess non-linear changes and predict management responses.

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Методичні підходи до оцінювання антропогенного впливу на агроценози

Олена Наумовська

Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-5938-8471

Євгеній Бережняк

Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0001-5945-1285

Денис Апонюк

Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0009-0009-1998-6272

Анотація. Актуальність дослідження зумовлена посиленнями антропогенного впливу на агроценози через інтенсифікацію землеробства, хімічні навантаження та просторові трансформації землекористування, що одночасно змінює ґрунтові процеси, структуру супутньої рослинності й функціонування біоти. Мета роботи полягала в систематизації та зіставленні сучасних методичних підходів до оцінювання антропогенного навантаження на агроценози в логіці «тиски – стан – наслідки». Виконано тематичний синтез публікацій 2019-2025 років із відбором джерел, що містили чіткі індикатори та правила їх обчислення; узагальнення здійснено за блоками ґрунт – біота – рослинність – геопросторові інструменти. Показано, що найбільш відтворювані оцінки забезпечувало комбінування фізичних, хімічних і біологічних показників ґрунту, оскільки одновимірні метрики втрачали чутливість до управлінських тисків і не відображали системних змін. Встановлено, що біоіндикація на основі ферментативної активності, мікробних процесів і реакцій ґрунтової фауни була придатною для раннього виявлення деградаційних зрушень і токсикологічних ризиків до появи стійких змін у фізико-хімічних властивостях. Підтверджено, що рослинні індекси різноманіття та домінування разом із функціональними індикаторами фіксували селективний тиск інтенсифікації та гербіцидних режимів, відображаючи спрощення угруповань і зміщення видового складу. Обґрунтовано, що геоінформаційні системи та дистанційне зондування Землі підвищували порівнюваність оцінок через просторово-часове масштабування, виявлення внутрішньопольової неоднорідності й картування зон ризику. Визначено, що інтегральні індекси підсилювали зіставність між територіями, але потребували узгодження напрямів інтерпретації показників, прозорого зважування та врахування невизначеності. Висновки підтвердили, що інтегрований підхід, що поєднував ґрунтові, біотичні, рослинні та геопросторові індикатори, був найбільш придатним для моніторингу, порівняння територій і підтримки управлінських рішень щодо мінімізації негативного впливу агровиробництва на довкілля

Ключові слова: інтенсифікація; здоров'я ґрунту; біоіндикація; ландшафтна гетерогенність; дистанційне зондування