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ENVIRONMENTAL MANAGEMENT: RESTORATION OF THE BIOTIC COMPONENT OF ANTHROPOGENICALLY LOADED ECOSYSTEMS

Purpose. Development of principles for managing restoration processes in anthropogenically stressed ecosystems.

Methodology. Standardised methods of laboratory and field research were used, as well as methods of statistical processing of experimental results. To assess the state of anthropogenic load, standardised methods based on the use of maximum permissible concentrations of substances were applied. The dynamics of intra-ecosystem processes were studied using quantitative and qualitative assessment methods, including biodiversity, soil condition, surface water bodies, and anthropogenic impact factors. Statistical analysis was performed using the Corel Quatro Pro 7 statistical package.

Findings. The main theoretical and methodological provisions of the developed concept of hyperadaptation are presented. The patterns of the relationship between the hormetic effect and the tolerance range are established, and it is proven that the hormetic effect for ecosystems is a shift in stability (adaptability) towards optimality. The regulation mechanisms of ecosystem processes have been studied by examining direct and reverse links. It has been proven that reverse links preserve the integrity of the structure and functions of anthropogenically loaded ecosystems, and the duplication of reverse links increases their biotic potential and, consequently, their resistance to anthropogenic influences. A regulatory-functional scheme is presented that characterises the response of biota to external influences – the dynamics of changes in the environment of their existence. It has been proven that biotic potential is capable of reflecting the tendency of internal self-organisation, performing an adaptive function. A methodology has been proposed for assessing the effectiveness and reliability of the functioning of ecosystem self-regulation mechanisms under anthropogenic influences. It has been proven that in order to improve the ecological management of anthropogenically loaded ecosystems, application of phytotechnologies that ecosystems include in intra-ecosystem processes (to restore "damaged" components) as a reserve phytocomponent may be effective.

Originality. The dependence of the biotic potential of ecosystems on the influence of anthropogenic factors has been established, and mechanisms for managing anthropogenically loaded ecosystems through regulation of intra-ecosystem processes is proposed.

Practical value. The results obtained allow for the improvement of the ecological management of ecosystems under an increased risk of ecological imbalance. The developed methodology will allow the use of economically sound measures to increase the biotic potential of ecosystems, in particular phytotechnology.

Keywords: *environmental management, environmental sustainability, biotic potential, ecosystem regulation*

Introduction. Today, ecosystems are viewed as systems that, under the influence of anthropogenic loads, are capable of preserving their structural and functional properties in a spatial-temporal range. A distinctive feature of ecosystems is the presence of a significant number of structural elements and the existence of a complex network of interrelationships between them, which enable them to counteract negative anthropogenic impacts [1, 2].

Any ecological system has a hierarchical structure and is represented as a set of elements of different levels of integration, each of which performs a specific function. However, even under conditions of anthropogenic impact, ecosystems remain relatively balanced due to their emergent property, which acts as a kind of bifurcation point at the stage of formation of their regulatory mechanisms, in particular, mechanisms of ecological stability. Regulatory mechanisms are capable of providing ecosystems with a certain level of resistance to various stressful anthropogenic factors [2, 3]. Due to their emergent nature, ecosystems are capable of self-preservation, which is ensured by the functioning of their biotic components [4]. Living organisms, due to the importance of the functions they perform, occupy a leading place among other structural elements of ecosystems, directly influencing their ecological stability [5, 6].

Literature review. A number of authors [7, 8] conduct their research on the functioning of ecosystems and their energy-information transformations, relying on the laws of synergetics and thermodynamics. In the course of such research [9, 10], it has been proven that ecosystems, under stressful conditions, have the ability to recover. However, in modern conditions, due to intensive anthropogenic impact, ecosystems are unable to achieve a balanced, stable state of functioning, undergoing significant irreversible changes.

The ecological state of ecosystems is determined by their functioning regime [11, 12]. It has been proven that the number of probable states of ecosystems is limited and does not allow them to adopt arbitrary alternative

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states [13, 14]. This limitation of ecosystem alternatives is determined by their 'jerky' structural and functional reorganisations, which are caused by the characteristics of external influences and the levels of basic parameters. At the same time, such limitations of ecosystems do not affect their integration and, in particular, their hierarchical organisation [15, 16]. At extremely high levels of external anthropogenic influences, internal ecosystem recovery mechanisms are unable to maintain ecosystems in their original state. And due to radical restructuring in a new state, they may lose their ability to maintain their stable state [17, 18]. The transition of ecosystems to an alternative state usually occurs when they enter an 'acute' mode of functioning, which occurs after their structural and functional restructuring, 'forcing' ecosystems to activate mechanisms for selecting an alternative mode of functioning [18, 19]. Such internal ecosystem restructuring rarely leads to a positive alternative scenario for ecosystem development; on the contrary, it often manifests itself in the form of crises, cataclysms and environmental disasters [20, 21].

Unsolved aspects of the problem. Thanks to biotic and abiotic components connected by material, energy, and information flows, ecosystems are 'separated' from similar ecosystems by a certain degree of closed-loop material circulation and form the dynamics of intra-ecosystem processes [22, 23]. At the same time, when exposed to exogenous anthropogenic factors, ecosystems are brought out of a state of dynamic equilibrium and their biotic renewal processes are disrupted. If this external influence is not too strong, the disturbed intra-ecosystem mechanisms are almost completely restored or replaced by others, and the process of transferring matter, energy and information continues. From this point of view, succession, which is a process of sequential changes in ecosystems accompanied by changes in the states and properties of all their components, should be considered in the context of the ability of ecosystems to preserve their natural recovery mechanisms [3, 6].

Some authors note [7, 21] that the law of tolerance shows that the balanced functioning of ecosystems is determined by the magnitude of the deviation of the factors influencing them from the optimum. It is the tolerance range between the levels of deviation and optimum that determines the stability (resilience, tolerance, survival) of ecosystems to the action of this factor. This state is determined by a set of tolerance ranges of all individuals in populations and is always wider than the range of individual tolerance. However, an unbalanced value of one factor narrows the tolerance ranges for other factors (cross-sensitivity) and reduces the level of ecological stability of ecosystems [1, 2]. In our opinion, the tolerance range can also be called the ontogenetic tolerance potential (OTP), since it reflects the possible values of tolerance fluctuations (resilience, viability) observed throughout ontogenesis and determined by the genome of an organism or the metagenome of a specific species population. We believe that from an evolutionary point of view of ecosystem development, we can also talk about the evolutionary potential of tolerance (EPT) as the potential for adaptability of a species/population due to genetic and/or epigenetic changes in a number of generations of a specific species population. Unlike OPT, which is more or less fully realised in ontogenesis, EPT will only mean an assessment of the direction of evolutionary changes. Accordingly, a change in EPT is possible, first of all, due to modifications (mutations) in individual genomes (microevolution), although shifts in EPT parameters due to epigenetic processes (genetic assimilation) are not excluded [21].

The degree of prosperity of a population/species depending on the characteristics of the acting factors (stressors) is represented by the Shelford curve, with the maximum values of the factors at which their optimal functioning is observed [1, 19]. There are obligate (mandatory), facultative (partially mandatory) and neutral types of factors. It should be noted that a neutral factor on the Shelford curve will resemble a dose-dependent relationship, where at zero value of the factor, the organism will not experience any effects. The study is devoted to investigating the influence of neutral factors on intra-ecosystem processes under conditions of anthropogenic impact on ecosystems.

The purpose of the study was to develop principles for managing biotic restoration processes in anthropogenically stressed ecosystems.

The task was to develop a methodology for studying the dynamics of intra-ecosystem processes that ensure the ecological stability of ecosystems; to introduce methods to strengthen the restorative natural mechanisms of self-regulation by enhancing the realisation of the biotic potential of anthropogenically loaded ecosystems.

Research methodology. The research is based on standardised methods using maximum permissible concentrations (MPC) approach [24, 25] and the requirements for establishing European water quality standards set out in Article 13 of Directive 2008/105/EC [26]. The methodological approaches for determining MPC (Ukraine) and/or limit values (LV) (the European Union) for establishing water quality standards are practically identical.

The research was conducted using a comprehensive analysis of the ecological state of ecosystems, their quantitative and qualitative assessment, including biodiversity, the state of soils, surface water bodies and factors of anthropogenic impact on them. The following formula was used to establish the biotic potential of anthropogenically loaded ecosystems

$$P = \sum_{i=1}^{n} \left[Kr_{bim} + I_{sam} + \frac{\left(C_1 \cdot K_s + C_2 \cdot K_s + C_n \cdot K_s\right)}{n} \right] \cdot K_z,$$

where Kr_{bim} is the biomass criterion characterising viability under changing environmental conditions; I_{sam} is the self-purification index; C_1, C_2, C_n are the concentrations of pollutants; n is the number of pollutants; K_s is total self-purification coefficient from pollutants, 0.7; K_z is river and wastewater mixing coefficient, 0.8 for medium-sized rivers.

During the research, standardised biotesting methods [27] were also used as sensors of the biotic potential of anthropogenically loaded ecosystems.

The self-purification capacity of an anthropogenically loaded river section was assessed using the following formula

$$I = \frac{R}{COD - BOD},$$

where *R* is the amount of substrate used for plastic purposes; *COD* is the chemical oxygen demand of river water at the initial site; *BOD* is the total biochemical oxygen demands of the river at the initial site.

The retrospective database was formed on the basis of personal research and official monitoring data.

To test the proposed methods of ecological management of renewable processes in anthropogenically loaded ecosystems, a 45 km section of the Irpin River, which is a medium-sized river and a right tributary of the Dnipro River, was selected as the object of study.

To study the state of intra-ecosystem processes that ensure ecological resistance to stressful anthropogenic factors the methodology was developed. In particular, a method to enhance the effectiveness of natural self-regulation mechanisms by stimulating a more complete realisation of the biotic potential for recovery in anthropogenically transformed ecosystems was proposed.

Statistical processing was carried out using the standard package of applied statistical programs "Microsoft Office Excel 2003" and "Statistica 5.0 for Windows". Student's t-test was used to assess the significance of the results.

The density of statistical correlation was assessed by calculating the Pearson linear correlation coefficients.

Results and discussion. The primary task of the study is to provide a theoretical justification for the processes within conditionally distinguished zones in the context of the law of tolerance using the concept of hyperadaptation developed by us:

Optimum zone. It is believed that adaptive mechanisms are disabled in this zone and energy is spent only on fundamental life processes, such as growth and reproduction. This statement contradicts the concept of modified biological adaptation that we are developing, according to which there are three types of adaptation: ordinal (compensatory), hypo- and hyperadaptation. Since organisms, while viable, are always in a certain state of adaptation (adaptability). It is this state that we call ordinary adaptation or adaptability, which is ensured by the functioning of multilevel constitutive mechanisms of recovery (ranging from molecular to ecosystemic). Obviously, there are combinations of factors that maximise biological potential and are called optimal. In this state, the ecosystem or organism is maximally adapted, and all recovery mechanisms are activated to maintain this state. *Stress zone*. In the stress zone range, there is a decrease in basic biological functions, which increases with the deviation of factor values from the optimum. It is obvious that ecosystems survive as a result of the activation of multi-level mechanisms of adaptation to stress factor values. Accordingly, in this range, there is an intensification of adaptation mechanisms. However, according to the authors, the intensity of these adaptive mechanisms is insufficient to bring the biological system out of this state, and therefore the biotic potential of the ecosystem is in a 'suppressed state'. This is evidenced by the negative practice of attempting to achieve a hormetic effect in biological systems that are in an optimal state of viability. In its initial state, i.e., before the onset of stress, a biosystem can be at any point on the tolerance range curve and, accordingly, its initial (current) level of adaptability may differ from the maximum level in the optimal zone. Thus, biological systems at a specific time, under a specific limiting factor, are within a certain range of the tolerance zone and have a certain level of stability, i.e., they are in a state of ordinary (current, initial) adaptability. And only additional influences can change the existing level of stability of ecosystems. If this happens closer to the edges of the tolerance range, it indicates hypoadaptation (viability decreases, decompensates); if closer to the optimum, it indicates hyperadaptation (viability increases, hypercompensates).

Stress zone. In the stress zone range, there is a decrease in basic biological functions, which increases with the deviation of factor values from the optimum. It is obvious that ecosystems survive as a result of the activation of multi-level mechanisms of adaptation to stress factor values. Accordingly, in this range, there is an intensification of adaptation mechanisms. However, the intensity of these adaptive mechanisms is insufficient to bring the biological system out of this state, and therefore the biotic potential of the ecosystem is in a 'suppressed state'.

Areas of intolerance. It is believed that in the process of individual development, the width of the tolerance range in a given zone may vary. However, the authors believe that based on the above-defined tolerance range, it is necessary to identify the species-specific, maximum tolerance range and the tolerance range for the current phase of ontogenesis. Accordingly, the acting factors can only change the current tolerance range, expanding or narrowing it, but not going beyond the genetically fixed species tolerance range. This statement is important and must be taken into account when the phenomenon of hormetic action of factors occurs. Indeed, from the standpoint of the concept of hyperadaptation that we are developing, hormesis is the key response to stressors, manifested in the stimulation of life activities at all levels of ecosystem organisation.

The results of the studies revealed the presence of a hormetic effect in anthropogenically stressed ecosystems in terms of plant growth indicators, as well as at elevated soil and air temperatures, excess carbon dioxide in the air, soil moisture deficiency and excess, and light intensity. Therefore, virtually any stress factor is capable of causing a hormetic effect under appropriate quantitative characteristics and modes of exposure (acute, chronic, prolonged, evenly or unevenly fractionated). However, hormetic-type stimulation cannot cause an increase in signs (e.g., growth and photosynthesis rates, photosynthetic pigment content, etc.) above the biological (genetic) potential of the biosystem, but only allows it to be realised to some extent.

Given the above, the next stage of research was to identify patterns of correlation between the hormetic effect and the tolerance range, i.e. the parameters of the Shelford curve. Since hormesis is closely related to the phenomenon of stress, and according to Hans Selye, stress is the sum of non-specific biological reactions to stimuli or events that are perceived as threatening and tend to disrupt biological equilibrium, it follows that homeostasis, in terms of the impact of stressors on the state of adaptability of ecosystems, should be considered as a set of changes in it that can either increase or decrease its stability. In this regard, the authors concluded that stressors that cause a hormetic effect moderately increase the activity of non-specific protective intrasystemic mechanisms. From the perspective of the concept of hyperadaptation developed by the authors, hormesis is considered as a reaction of the biotic component of ecosystems to stressors, which manifests itself in the positive stimulation of vital activity according to certain parameters. When studying the 'dose (concentration) – effect' relationship, the hormetic effect is observed either in the form of exceeding the control level for parameters characterising viability (e.g., growth, photosynthesis) or in the form of a decrease in the level of damage below the control level (e.g., mutagenesis frequency). At the same time, hormetic doses (concentrations) are considered as dose ranges that have a positive stimulating effect. The maximum value of the hormetic effect for anthropogenically loaded ecosystems is usually 130–160 % of the control value, starting from 110 % of the control level. The range of hormetic doses also depends on the selected parameter and the level of integration of the biotic component of the ecosystem; in particular, the higher it is, the higher the hormetic doses.

Increasing the viability of the biotic component of ecosystems gives hope for improving the resilience (adaptability) of ecosystems to anthropogenic influences, and the hormetic effect is, in fact, a shift in resilience (adaptability) towards optimality on the Shelford curve, where resilience is maximally expressed. Regardless of which factor causes the hormetic effect and the phenomenon of the ecosystem's hyperadaptive response to anthropogenic influences based on it, the mechanism of hormesis is quite paradoxical. First, the fact of a hyperadaptive response means that a biological object (organism, population, ecosystem) is less damaged by a higher total dose (hyperadaptive dose + test dose) than by a lower dose (test dose only) – a paradox of the discrepancy between the dose (concentration) and the magnitude of the damaging effect. We explain this paradoxical discrepancy by the fact that recovery processes are capable of hypercompensation, which subsequently ensures an increased level of stability. Secondly, as shown by the results of our previous studies [1], in order to bring a biological object (organism, population, ecosystem) to a state of increased stability, it is necessary for the adaptive dose to cause a certain level of modification of the object being affected. Usually, this is a damaging (inhibitory) type of modification. However, the research results have shown that the basis of the hormetic effect, i.e. positive stimulation, is the damaging effect of the adapting factor – the paradox of the damaging mechanism of the hormetic effect. We explain these paradoxes by the presence of inertial processes observed in recovery mechanisms at different levels of integration of biological objects (organism, population, ecosystem). Applying Le Chatelier-Brown's principle, it becomes clear that each ecosystem (or organism, or population) strives for changes that can minimise the effect of negative external influences, including anthropogenic ones. This is because all ecosystems, regardless of the conditions in which they function, and in particular under extreme anthropogenic stress, have an inherent tendency towards self-preservation, which they achieve through appropriate mechanisms of self-reproduction, self-restoration and self-regulation. The property of self-recovery implies the ability of ecosystems, due to their own biotic potential, to return to the original (initial) state of dynamic equilibrium in which they were before they were removed from it under the influence of negative factors, at a certain level of action, ecosystems retain their inherent characteristics, structure and functions. The self-regulating property of ecosystems also determines their ability to restore their structural and functional characteristics through their own biotic potential, but through feedback. It should be noted that, due to self-regulating mechanisms, ecosystems are capable of restoring their structural and functional properties only within a certain range of doses (concentrations) of external influences on them.

The next important stage of research was to identify patterns of how ecosystem components are able to function in interaction with each other and under what conditions changes (reversible or irreversible) can occur that can lead to the failure of their basic functions and essential properties such as resilience, stability and vitality. The main focus was on studying the mechanisms of regulation of ecosystem processes through research into direct and reverse links between ecosystem elements and the duplication of reverse links that ensure an increase in biotic potential and, accordingly, the stability of ecosystems to external influences. Living organisms directly influence the ability of ecosystems to counteract damaging anthropogenic influences and self-regenerate in the event of a return to 'normal conditions,' as well as to return to a state close to 'original.' After all, in the process of forming and realising the biotic potential of any ecosystem, the leading role belongs to the system of living organisms, which refers to negative feedback loops, the effectiveness of which contributes to the integration of ecosystems. The authors have come to the conclusion that the speed of restoration of ecosystem processes is proportional to the coordination between direct and reverse links (Fig. 1).

It is under these conditions that it is appropriate to present the regulatory-functional scheme developed by the authors, which characterises the response of biota to external influences – the dynamics of changes in their environment (the principle of negative feedback). This is because any deviation from ecological equilibrium – the optimum for biota – causes changes in ecosystems that are compensated for by the mechanism of biotic self-regulation.

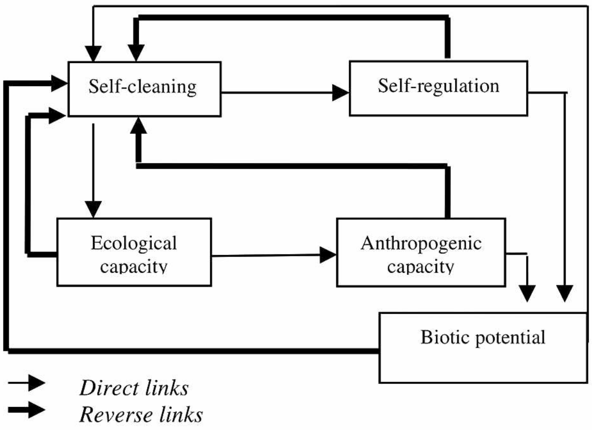

Fig. 1. Regulatory and functional diagram of ecosystem self-organisation

The figure shows that ecosystem self-regulation mechanisms are associated with the formation of intra-ecosystem processes, the intensity of which correlates with changes in ecological capacity and anthropogenic capacity and indicates that one of the main driving forces of the natural mechanism of ecosystem self-regulation is the realisation of their biotic potential, which indicates the level of the totality of material, energy and information exchange and adaptive reactions of biota to these ecosystem endosins.

In addition, patterns have been established for coordinating the interaction of changes in intra-ecosystem processes and anthropogenic influences, as well as patterns for the formation of the process (mechanism) of ecosystem stability to external and internal changes. At the same time, a decrease in the intensity of the functioning of the ecosystem self-regulation mechanism over a certain period of time can be observed, while the biotic potential is an indicator of the intensity of the self-regulation process. In addition, biotic potential is capable of reflecting the trend of internal self-organisation, performing an adaptive function in self-regulation, as shown schematically in Fig. 2.

Thus, according to the theory of self-organisation, biotic potential is a kind of bifurcation point, as it can become a 'cornerstone' for the ecosystem when its development becomes extremely unstable and further development may follow a scenario in which minor deviations in the life activity of the biotic component can lead to extremely undesirable, drastic consequences for it as a whole. That is, the biotic component of the ecosystem directly influences the formation of its critically unstable state and creates uncertainty about the likely paths of its further development: the ecosystem will develop according to a chaotic scenario, leading to its 'decline,' or, conversely, it will transition to a more highly organised level of self-organisation. That is why the authors recommend that the assessment of the state of the biotic component of the ecosystem be considered as an applied tool for assessing its ecological stability.

If the biota is sufficiently productive, it is capable of preserving and maintaining its numbers, as well as accumulating and retaining biomass, which allows it, through these functions, to ensure the ecological stability of ecosystem processes as a whole. The performance of these functions by the biota allows the ecosystem, even under stressful and critically unstable conditions (intensive anthropogenic pressure on it), to ensure the 'conditioning' of the habitat of the system of living organisms. It is under such conditions that the ecosystem is capable of self-regulation, and its biotic potential is maximally capable of resisting destructive anthropogenic pressure, even under conditions where the biotic component is under constant influence of ecological and anthropogenic stress factors.

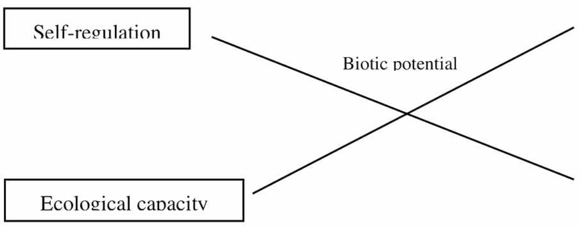

Fig. 2. Structural and functional features of ecosystem self-organisation

The results obtained allow improving methods of ecological management of ecosystems under stressful pressure from anthropogenic factors. In particular, the authors propose a practically sound methodology for assessing the effectiveness and reliability of ecosystem self-regulation mechanisms under conditions of high anthropogenic impact. This is because any ecosystem that has been 'damaged' or thrown out of balance by anthropogenic influence can be 'repaired' through its own biotic potential, i.e. by activating natural mechanisms of biotic self-regulation to restore its structural and functional properties [6], while creating conditions for the ecosystem that promote the maximum realisation of its biotic potential.

To this end, the authors propose introducing a reserve, excess, additional element into the structure of ecosystems damaged by anthropogenic impact, which should be biotic in nature. In particular, populations of plant or animal organisms can be used as such an element.

The authors' previous experience shows that phytotechnologies should be used to restore anthropogenically disturbed ecosystems, whose phytocomponents are 'perceived' by anthropogenically disturbed ecosystems as a redundant, reserve element capable of contributing to the restoration of ecosystem parameters and their biotic potential and triggering intra-ecosystem mechanisms of biotic self-regulation.

To improve the system of environmental management of anthropogenically transformed ecosystems, the advantages of using phytocomponents (in technological systems) to restore 'damaged' ecosystem elements are obvious and boil down to the fact that phytotechnologies are designed by humans and belong to natural – anthropogenic systems, which are predicted at the design stage and are given clear parameters, allowing them to be easily managed, unlike the biotic elements of natural ecosystems, which, in particular, the authors have covered in detail in publications [3, 6], which are based on experimental research on the patterns of the biotic component's response to changes in the physical and chemical composition of its environment caused by intense anthropogenic impact.

Empirical verification of the developed methodology for studying the dynamics of intra-ecosystem processes was carried out on a 45 km section of the middle Irpin River and in laboratory conditions where a pilot phytoengineering system was tested.

To design the phytotechnology, the authors included the following species of higher aquatic plants as a reserve component of the anthropogenically loaded ecosystem, which have a wide range of ecological valence, high growth rate and high ability to clean the environment.

As a result of the screening (over 120 combinations), the following species of higher aquatic plants were selected for inclusion in the phytotechnological system:

- common reed (*Phalaroides arundinacea*);
- water sedge (*Cárex aquátilis*);
- narrow-leaved cattail (*Typha angustifolia*);
- broadleaf cattail (*Typha latifolia*);
- common reed (*Phragmites australis*);
- lake reed (*Schoenoplēctus lacūstris*);
- yellow iris (*Iris pseudacorus*);

- reed grass (*Glyceria* family);
- salvinia (*Salvinia natans All.*);
- Canadian waterweed (*Elodea canadensis*);
- Hornwort (*Ceratophyllum*).

On the experimental site of the Irpin River (Fig. 3), the studies have shown that the optimal density of common reed (*Phragmites australis*) and lake reed (*Schoenoplectus lacustris*) stands to achieve effective purification and restoration of the intensity of intra-ecosystem processes is 11–14 plants per m^2.

The optimal density of broadleaf cattail (*Typha latifolia*) and narrowleaf cattail (*Typha angustifolia*) is 8–11 plants per m^2, depending on the level of damage to the natural mechanisms of biotic self-regulation.

The results showed that it is possible to restore an ecosystem damaged by anthropogenic impact, especially in the summer period, when, within a few weeks, by introducing phytocomponents from eurybionts of various species of higher aquatic plants, anthropogenically loaded ecosystems are capable of intensive self-recovery.

In addition to introducing a reserve component in the form of a phytoengineering system into an anthropogenically loaded ecosystem, the authors consider it expedient to apply methods of forming additional biofilters that will take on the function of an additional phytoblock and enhance the destruction of anthropogenic pollutants.

The authors have proposed for the first time a method for constructing additional biofilters using terrestrial plants adapted to germinate in aquaculture conditions. A series of experiments showed that the following terrestrial plants, which are capable of growing on an artificial substrate without soil, proved to be the most effective as biofilters:

- creeping wheatgrass (*Agropyron repens P.B.*);
- couch grass (*Agropyron junceum*);
- water sedge (*Carex aquátilis*);
- slender sedge; (*Carex gracilis*);
- marsh bluegrass (*Poa palustris*);
- meadow bluegrass (*Poa pratensis L.*);
- timothy grass (*Phleum pratense*);
- meadow foxtail (*Alopecurus pratensis L.*);
- red fescue (*Festuca rubra*);
- red fescue (*Deschampsia cespitosa*);
- creeping bentgrass (*Agrostis stolonifera*);
- common beckmannia (*Bromus inermis Leyss*);
- common beckmannia (*Beckmannia eruciformis Host*);
- marsh pea (*Lathyrus palustris*).

The terrestrial plants selected are capable of growing in aquatic environments such as aquaculture, demonstrating high absorption properties and the ability to 'integrate' into aquatic ecosystems as an additional biofilter. Fig. 4 shows a roll biofilter made of terrestrial plants, which was successfully 'accepted' by the hydroecosystem as an additional reserve unit, thereby increasing its biotic potential and ecological stability.

During the experiment, an excess bio-component from higher aquatic plants and higher terrestrial plants was introduced into the structure of the aquatic ecosystem with a high level of anthropogenic load – the Irpin River section, and the hydroecosystem 'accepted' both phytocomponents as its own reserve element capable of promoting the intensification of internal water self-recovery mechanisms and included it in internal ecosystem processes aimed at levelling anthropogenic pollutants to a level that did not interfere with its optimal functioning.

Quantitative confirmation of the inclusion of the phytoengineering system we designed into the internal ecosystem processes of the Irpin River is presented in the Table.

Analysis of the data presented in the table indicates effective intra-ecosystem transformations of the anthropogenically loaded reservoir due to the application of the phytoengineering system we designed, which it incorporated into its structure as a reserve phytoelement. Thus, due to the introduction of an artificially designed system, the degree of restoration of ecological capacity according to BOD$_5$ indicators is 28.0 %, COD – 29.0 %, toxic metal contents – 57.1–94.0 %, and petroleum hydrocarbon content – 81.3 %. Accordingly, the introduction of a plant component into an anthropogenically loaded ecosystem is perceived by it as a natural reserve element that allows it to increase its barrier function and restore ecosystem parameters. This was made possible by the fact that the natural filters of the ecosystem increased their potential thanks to the introduced phytocomponent, which is perceived by the ecosystem not as a foreign element, but as a reserve component of its own self-regulation mechanism. Thus, the proposed principle of managing restoration processes in anthropogenically loaded ecosystems through the use of additional phytoelements can become an effective applied tool in the context of improving the environmental management system through the management of the intra-ecosystem restoration mechanism. It allows for the rapid restoration of the ecological capacity of anthropogenically modified ecosystems through their own biotic potential.

Fig. 3. Fragment of a bioengineering system in natural conditions

Fig. 4. Fragment of a biofilter in natural conditions

Table

Degree of purification of surface water in the Irpin River section due to the introduction of a biotic component from higher terrestrial and aquatic plants ($M \pm m$, $n = 5$)

Indicator	Before application of the reserve biocomponent	After application of the reserve biocomponent	Purification, %
BOD_5, MgO_2/dm^3	5.0 ± 0.1	3.6 ± 0.7	28.0
COD, MgO_2/dm^3	27.2 ± 1.3	19.3 ± 1.0*	29.0
Cu^{2+}, mg/dm^3	1.5 ± 0.07	0.09 ± 0.001*	94.0
Zn^{2+}, mg/dm^3	1.4 ± 0.04	0.6 ± 0.07*	57.1
Petroleum hydrocarbons, mg/dm^3	1.6 ± 0.09	0.3 ± 0.03*	81.3

* $p < 0.01$ compared to pre-treatment values

This approach can be based on a cybernetic interpretation of direct and reverse connections (Fig. 5).

In the environmental management system proposed by the authors, a direct link is understood as a destructive anthropogenic impact on ecosystems (for example, excessive discharge of return water into a surface water body – the internal self-regulation mechanisms of the water body began to operate in extreme mode). Feedback is understood as the dependence of the control mechanism on the biotic potential of the ecosystem (for example, the biotic component of the reservoir affects the internal self-regulation mechanisms and, consequently, its ecological capacity and anthropogenic capacity). Thus, feedback in the ecological management system should be considered as an element of ecosystem management, taking into account its ecological capacity. Based on the above, the authors concluded that feedback loops in ecosystems perform an extremely important function – suppressing deviations in the management process.

Thus, feedback loops stimulate ecosystems to enter a structural and functional state in which their previously established mechanisms and interrelationships, which are no longer relevant to them under stressful conditions, are destroyed. The biotic component of ecosystems plays a decisive role in this process, since it is through this component, namely through biotic potential, that alternative modes of ecosystem functioning are triggered and new properties are acquired. And then, feedback loops in the context of ecological management of ecosystems acquire an important management function, as they ensure the stability of functioning in ecosystems in each of the modes into which they gradually enter and ensure the consistency of structural and functional properties (in the process of ecosystems transitioning to different modes of functioning, in the process of their adaptation to anthropogenic influences on them). Under such conditions, a certain range of gradual changes in the physiological and biochemical reactions of living organisms in ecosystems is aimed at restoring their damaged structural and functional properties.

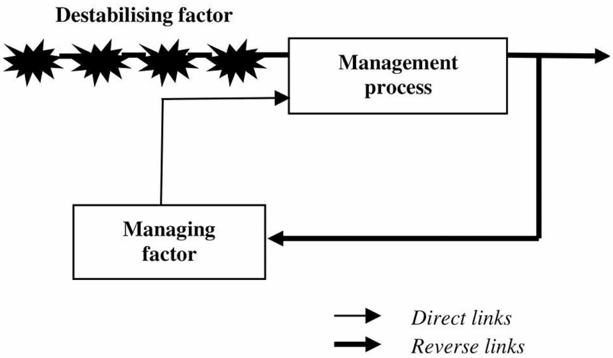

Fig. 5. Schematic representation of the control influence of feedback loops on intra-ecosystem recovery mechanisms

Conclusions. It has been established that biotic potential of ecosystems is capable of reflecting the trend of internal self-organisation, performing an adaptive function. Empirical evidence has shown that the biotic component of ecosystems directly influences the formation of intra-ecosystem mechanisms of self-regeneration. The results of experiments show that the use of phytotechnologies as a reserve phytoblock in anthropogenically loaded ecosystems allows them to self-regenerate, immobilising the potential of ecological capacity. The results of experimental studies have shown that by introducing an artificially constructed bioengineering system into an anthropogenically loaded ecosystem, the degree of restoration of ecological capacity according to BOD_5 indicators is 28 %, by COD – 29 %, by toxic metal content – over 57 %, and by petroleum hydrocarbon content – 81.3 %.

The tests of phytotechnology, which included a phytocomponent from higher aquatic plants (those with a wide range of ecological valence, high growth rate, and high habitat purification capacity) and terrestrial plants (adapted to germination in aquaculture conditions) showed that the ecosystem 'accepted' both phytocomponents as its own reserve element capable of promoting the intensification of self-recovery mechanisms and included it in internal ecosystem processes.

The experiments have shown that common reed and water sedge with a density of 11–14 units per m^2, as well as broad-leaved and narrow-leaved cattail, with a planting density of 8–11 units per m^2 are optimal for biotic self-regulation in natural surface water.

When designing additional biofilters from terrestrial plants, the highest level of absorption properties and the ability to 'integrate' into aquatic ecosystems as an additional biofilter were demonstrated by such terrestrial plants as creeping and sedge-like wheatgrass, water sedge and slender sedge, marsh and meadow bent grass, timothy grass and meadow foxtail, red fescue and turf grass.

Therefore, the proposed approach of managing restoration processes in anthropogenically loaded ecosystems through the use of additional phytoelements can become an effective practical tool for improving the environmental management through the activation of the internal ecosystem restoration mechanism. This allows a rapid restoration of the ecological capacity of anthropogenically loaded ecosystems through their own biotic potential.

References

1. Madzhd, S., Yakymenko, I., & Nychyk, O. (2025). Environmental sustainability as an indicator of ecosystem reliability. *Selected papers VII International conference European dimensions of sustainable development, 2025*, 62-67. Retrieved from https://dspace.nuft.edu.ua/items/6c81a52b-300c-4904-9754-42f602a67031

2. Mikheev, A. N. (2025). The connection between Shelford's law of tolerance and the concepts of hormesis and hyperadaptation. The evolutionary aspect. *Factors of experimental evolution of organisms, 36*, 174-179. https://doi.org/10.7124/FEEO.v36.1733

3. Madzhd, S., Nychyk, O., Togachynska, O., Lunova, O., & Maksymenko, O. (2025). Environmental management: Assessing the reliability of ecosystems to ensure their environmental sustainability. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (2), 164-171. https://doi.org/10.33271/nvngu/2025-2/164

4. Rev, A. (2022). The Concept of Adaptation. *The Annual Review of Environment and Resources*, (17), 535-552. https://doi.org/10.1146/annurev-environ-112320-095719

5. Ekins, P., & Zenghelis, D. (2021). The costs and benefits of environmental sustainability. *Sustainability Science*, (16), 949-965 https://doi.org/10.1007/s11625-021-00910-5

6. Isaenko, V., & Cherniak, L. (2019). Development of a procedure for determining the basic parameter of aquatic ecosystems functioning – environmental capacity. *Eastern-European Journal of Enterprise Technologies, 1/10*(97), 21-28. https://doi.org/10.15587/1729-4061.2019.157089

7. Ashok, K., Rupesh, K., & Deepak, B. (2024). Emerging drifts big data analytics and environment sustainability (EBAES). *Environmental Science and pollution*. Retrieved from https://springer.com/article/10.1007/s11356-024-35876-1

8. Yarema, L. V., & Zamora, O. I. (2021). Management of the region's resource potential. *Bulletin of the V. V. Dokuchaev Kharkiv National Agricultural University*, (1), 364-376. Retrieved from https://journal-met.kh.ua/visn2021_t1.html

9. Dong, J., Zhou, Q., Gao, Y., Gu, Q., Li, G., & Song, L. (2018). Long-term effects of temperature and nutrient concentrations on the phytoplankton biomass in three lakes with differing trophic statuses on the Yungui Plateau, China. *Annales de Limnologie – International Journal of Limnology, 54*, 9. https://doi.org/10.1051/limn/2017031

10. Makota, L., & Novitska, N. (2014). Hygienic aspects of cleaning and reagent-free disinfection of domestic wastewater using the 'bioplat' phytotechnology. *Scientific and technical collection*, (112), 88-94.

11. Peiyue, Li, Karunanidhi, D., Subramani, T., & Srinivasamoorthy, K. (2021). Sources and Consequences of Groundwater Contamination. *Archives of Environmental Contamination and Toxicology*, *80*, 1-10. https://doi.org/10.1007/s00244-020-00805-z

12. Aronson, J., Blignaut, J. N., & Milton, S. J. (2010). Are socioeconomic benefits of restoration adequately quantified? *Restoration Ecology, 18*(2), 143-154. https://doi.org/10.1111/j.1526-100X.2009.00651.x

13. Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997). Human domination of Earth's ecosystems. *Science, 277*(5325), 494-499. https://doi.org/10.1126/science.277.5325.494

14. Chapman, E. J., & Byron, C. J. (2018). The flexible application of carrying capacity in ecology. *Global Ecology and Conservation, 13*, 1-12. https://doi.org/10.1016/j.gecco.2017.e0 0365

15. Masikevych, A. Yu., Heretsun, H. M., Masikevych, Yu. G., Kolotylo, M. P., & Yaremchuk, V. M. (2018). Atmospheric protection as a composition of environmental safety of the region. (Part 1). *East European Scientific Journal*, *12*(40), 30-34.

16. Turevych, A., Madzhd, S., & Ojeh, V. (2021). Modern means of assessing the impact of emergencies on the environmental condition of the ground layer of atmosphere. *Web of Conferences*, *280*, 1-10. https://doi.org/10.1051/e3sconf/202128009017

17. Nezbrytskaya, I. N., & Kureyshevich, A. V. (2015). Changes in the Content of Photosynthetic Pigments in Representatives of Chlorophyta and Cyanoprokaryota at a High Temperature. *Hydrobiological journal, 51*(4), 46-56.

18. Matveeva, I. V. (2011). Investigation and assessment of the reliability of radionuclide transport systems in the local agroecosystem. *Bulletin of the National Aviation University, 2*(47), 148-154.

19. Azarov, S., & Zadunay, O. (2020). Analysis of methodological approaches to assessing ecosystem sustainability. *Ecological safety and environmental management, 34*(2), 99-110. https://doi.org/10.32347/2411-4049.2020.2.99-110

20 Azarov, S., & Zadunay, O. (2019). Analysis of ecosystem sustainability. *Ecological safety and environmental management*, 3, 46-56.

21. Azarov, S., & Zadunay, O. (2018). Modelling the sustainability of ecosystems. *Ecological Sciences, 4*(23), 5-9. https://doi.org/10.32347/2411-4049.2019.2.18-29

22. War in Ukraine: An overview of environmental impacts and consequences for human health (2024). *Frontiers in Sustainable Resource Management*. Retrieved from https://www.frontiersin.org

23. Musikevich, Yu. G., Shestopalov, O. V., & Negadaylo, A. A. (2015). Systems Theory in Ecology. *Sumy State University, 330*. Retrieved from https://essuir.sumdu.edu.ua/bitstream-download/123456789/41329/1/ecology.pdf;jsessionid=0090696E66DE848987DD881952BA5FFB

24. Sarkis, J., & Zhu, Q. (2017). Environmental sustainability and production: taking the road less travelled. *International Journal of Production Research*, *56*, 743-759. https://doi.org/10.1080/00207543.2017.1365182

25. *DSanPiN 2.2.4-171-10. Hygienic requirements for drinking water intended for human consumption*. (n.d.). Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=27272

26. *Directive 2008/105/EC on the establishment of environmental quality standards in the field of water policy*. (n.d.). Retrieved from https://compass27.info/vodna-ramkova-dyrektyva-2000-60-yes-2/

27. *DSTU 4173:2003 Water quality. Determination of acute lethal toxicity to Daphnia magna Straus and Ceriodaphnia affinis Lilljeborg (Cladosera, Crustacea) (ISO 6341:1996, MOD)*. (n.d.). Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=72858

Екологічне управління: відновлювання біотичної складової антропогенно навантажених екосистем

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Мета. Розроблення принципів управління відновлювальними процесами в антропогенно навантажених екосистемах.

Методика. Застосовані стандартизовані методи лабораторних і польових досліджень, а також методи статистичного опрацювання експериментальних результатів. Для оцінки стану антропогенного навантаження застосовані стандартизовані методики, що ґрунтуються на гранично-допустимих концентрацій речовин. Динаміка внутрішньоекосистемних процесів досліджувалась із застосуванням методів кількісної й якісної оцінки, включаючи оцінку біорізноманіття, стану ґрунтів, поверхневих водойм і чинників антропогенного впливу. Статистичний аналіз проводився за допомогою статистичного пакету Corel Quatro Pro 7.

Результати. Сформульовані основні теоретично-методологічні положення розробленої концепції гіперадаптації екосистем. Встановлені закономірності взаємозв'язку гормезисного ефекту з діапазоном толерантності й доведено, що гормезисний ефект для екосистем є зсувом стійкості (адаптованості) у бік оптимальності. Вивчені механізми регуляції екосистемних процесів шляхом дослідження прямих і зворотних зав'язків. Доведено, що зворотні зв'язки зберігають інтегрованість структури та функцій антропогенно навантажених екосистем, а дублювання зворотних зв'язків забезпечує підвищення їхнього біотичного потенціалу, а отже й стійкість до дії антропогенних впливів. Представлена регуляторно-функціональна схема, що характеризує відповідь біоти на динаміку змін середовища свого існування. Доведено, що біотичний потенціал здатний відображати тенденцію внутрішньої самоорганізації, виконуючи адаптивну функцію. Запропонована методика оцінки ефективності й надійності функціонування механізмів саморегуляції екосистем в умовах антропогенних впливів. Доведено, що для удосконалення системи екологічного управління антропогенно навантаженими екосистемами доцільно застосовувати фітотехнології, які екосистеми включають до внутрішньоекосистемних процесів (для відновлення «пошкоджених» елементів), як резервний фітокомпонент.

Наукова новизна. Встановлена залежність біотичного потенціалу екосистем від впливу антропогенних чинників і запропоновані механізми управління антропогенно навантаженими екосистемами через регулювання їх внутрішньоекосистемних процесів.

Практична значимість. Отримані результати дозволяють удосконалити систему екологічного управління екосистемами із підвищеним рівнем екологічної небезпеки. Розроблена методика дозволяє використовувати економічно обґрунтовані заходи підвищення біотичного потенціалу екосистем, зокрема, фітотехнології.

Ключові слова: *екологічне управління, екологічна стійкість, біотичний потенціал, регуляція екосистем*

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