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THEORETICAL BASIS OF CLASSIFICATION OF TERRAFORMING METHODS

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The article discusses the problem of finding theoretical foundations for terraforming. At the same time, the meaning of the concept of terraforming expands beyond its narrow understanding as environmental changes on other planets. The research aims to improve and unify the theory of ecosystem dynamics and increase the efficiency of reclamation methods and natural vegetation restoration. The purpose of the study is to develop theoretical foundations for various terraforming procedures. Following the goal, the following tasks are set: to give a general definition of the terraforming process from the standpoint of astroecology and to determine the theoretical basis for the classification of terraforming procedures. The research materials are standard geobotanical descriptions made in the place of restoration of vegetation after disturbances in the period from 2004 to 2024. Descriptions are made using route-expedition and stationary methods according to standard methods. The resulting standard geobotanical descriptions are classified according to the principles of the Brown Blanke ecological and floristic school. In the course of the research, the process of terraforming was considered for the first time in a broad context and its existing procedures were classified. The obtained results can be used during the development of reclamation algorithms, restoration of settlements after violations, and in the process of space exploration. As a result of the study, it was established that terraforming is a local or global change in the environment of the planet or an artificial structure, which shifts the indicators of environmental factors to the optimum of the human ecological spectrum. Terraforming corresponds to evolutionary and successional changes in ecosystems. Initially, it is an allogeneic succession that can, under favorable conditions, trigger autogenic and evolutionary processes. The basis for the classification of approaches to terraforming is the spatial characteristics of the territory where it occurs and the controllability of its processes by man. *Key words:* anthropogenic transformation, space expansion astroecology.

Теоретичні основи класифікації методів тераформування. Хом'як І.В., Онищук І.П., Василенко О.М.
У статті обговорюється проблема пошуку теоретичних основ для тераформування. При цьому, смисл поняття тераформування розширюється за межі його вузького розуміння, як зміни навколишнього середовища на інших планетах. Дослідження направлене на вдосконалення та уніфікацію теорії динаміки екосистем, а також на підвищення ефективності методів рекультивації та відновлення природної рослинності. Метою дослідження є розробка теоретичних основ для різних процедур тераформування. Відповідно до мети поставлені такі завдання: дати широке визначення процесу тераформування із позицій астроекології та визначити теоретичну основу для класифікації процедур тераформування. Матеріалами дослідження є стандартні геоботанічні описи зроблені в місці відновлення рослинності після порушень в період із 2004 по 2024 роки. Описи зроблено маршрутно-експедиційними та стаціонарними способами за стандартними методиками. Отримані стандартні геоботанічні описи класифіковано згідно із принципами еколого-флористиної школи Браун Бланке. У процесі дослідження вперше розглянуто процес тераформування в широкому контексті та здійснено класифікацію її існуючих процедур. Отримані результати можна буде використовувати під час розробки алгоритмів рекультивації, відновлення оселищ після порушень та в процесі освоєння космосу. У результаті дослідження встановлено що тераформування – це локальні або глобальні зміни середовища планети або штучної конструкції, які зміщують показники екологічних факторів до оптимуму екологічного спектру людини. Тераформування відповідає еволюційним та сукцесійним змінам в екосистемах. Спочатку воно є алогенною сукцесією, яка може за сприятливих умов запустити автогенні та еволюційні процеси. Основою для класифікації підходів до тераформування є просторові характеристики території, де воно відбувається та керованістю його процесів людиною. *Ключові слова:* антропогенна трансформація, космічна експансія, астроекологія.

Introduction. Statement of the problem. When we talk about the practice of terraforming, we often see it as a perspective of the distant future. However, this is the story of our past and present. Terraforming is often understood as the transformation of another planet into one that will be as close as possible to our home planet [1]. Already in this definition, it is laid down that we understand terraforming very closely. However, we will never get a copy of our planet, in which we will have a combination of a complete set of biogeocenous ecosystems or biomes of the Earth. We will have new ecosystems, some of which will only slightly resemble the ones we are used to. There will be areas that have not terraformed and completely new ecosystems that have no analogues on our planet. The main thing that we will achieve is a functional exobiosphere, which will allow us to function relatively comfortably and safely in the natural environment of the planet. So, in a broad sense, the concept of terraforming is a change in the environment with the approximation of the indicators of its factors to the optimum of the human organism [2].

The human body evolved in certain environmental conditions and as a result, adapted to it. Its ecological tolerance is somewhat wider under the condition of the primary range, but not enough to explain the global settlement of humanity on the surface of the planet. This was

achieved by changing the conditions of the microenvironment. From clothing and the use of fire to housing and the manufacture of tools – all these changes in the environment are directed towards its optimal primary conditions. Thus, man from the beginning of his history chose expansion using local terraforming of the habitat as one of the main evolutionary advantages [3]. In our time, the practice of building housing, landscape design of settlements, changes in agricultural land, creation of objects of a nature reserve fund, or recreational infrastructure, like the construction of space stations outside our planet, is terraforming in the broadest sense of the word.

However, despite thousands of years of practice, we make mistakes all the time when doing terraforming. This, first of all, is connected with the pressure of earthly chauvinism, born from the frequent forgiveness of our mistakes in the short term from the side of earthly ecosystems. When we move on to more clearly defined tasks, such as the reclamation or restoration of ecosystems, the creation of space stations, or experiments like "Biosphere 2", we understand how superficial and incomplete our theoretical knowledge is. This leads to excessive irrational costs, on individual tasks of terraforming, and the inability to overcome environmental crises and risks during the development of outer space [4].

Research relevance. The study of the theoretical foundations of terraforming is relevant at the national and international levels. Due to the tough military confrontation with the terrorist country, Ukraine faced the difficult task of restoring the elements of the environment affected by hostilities. In the conditions of a critical shortage of finances and technical means, we are forced to carry out the procedures of restoration ecology as efficiently as possible [5]. Also, the high efficiency of such actions should be in the process of assimilation of outer space, which has become more active recently. It is impossible to achieve such efficiency without developing the basic theories of terraforming. In connection with this, the research carried out in this direction is extremely relevant.

The connection of the author's work with important scientific and practical tasks. Our research is aimed at improving and unifying the theory of ecosystem dynamics, as well as improving the effectiveness of methods of reclamation and restoration of natural vegetation.

Analysis of the latest research and publications. From the point of view of astroecology, terraforming is a type of allogenic dynamics of ecosystems [4]. However, it includes elements of the evolution of ecosystems, as a result of the transfer of invasive species of transformers beyond their ranges with the formation of new ecosystems. Also, during terraforming, there are autogenic processes, when transferred species independently transform econiche packages. In other words, we have a combination of allogenic and autogenic successional processes against the background of anthropogenically activated evolution of ecosystems. On the one hand, according to its energy-dynamic characteristics, this is a typical successional process, but in essence, each link of the successional chain is a new ecosystem that corresponds to the definition of evolution. When this process takes place within the boundaries of the Earth and involves aboriginal species, it will be a classical succession. When this occurs outside the terrestrial natural environment or the introduction of edifiers is used, then this is classic ecosystem evolution.

The process of terraforming combines syngenesis, when species coordinate coexistence within a certain ecosystem, and endoecogenesis, when their life activity changes the abiotic environment [6]. These changes will accumulate until a certain critical limit is reached, when the econiches will be restructured with the formation of another ecosystem.

The task of terraforming is such changes in the environment that shift it to the optimal values of most factors of the human ecological spectrum. Based on the evolutionary history of man, it will be the environmental conditions in tropical savannas immediately after the end of the rainy season. These conditions cannot be created even on the entire surface of our planet. That is, these changes will be local.

The fact that humman was able to go beyond the borders of his original area was realized thanks to local terraforming [7]. Humans began to make clothes, build houses, and use fire and hunting tools. These are all also examples of local terraforming. On a larger scale, man most often spontaneously changed his environment, which often led to the depletion of resources, and as a result, the extinction of certain tribes or the stimulation of their further migration. There are also examples of terraforming that is positive for hunting tribes. For example, in North America, certain tribes have struggled with reforestation because bison and other populations of animals are more numerous on the prairies.

Highlighting previously unsolved parts of the general problem, to which the specified article is devoted. Nowadays, local terraforming is carried out within premises or settlements, during the restoration of plant cover disturbed by production or natural disasters. Also, such a demand arises during space exploration. At the same time, there are risks for extraterrestrial aboriginal biota that may not withstand competition with terrestrial species and dangers for astronauts living on space stations [8].

Scientific novelty. For the first time, the process of terraforming in a broad context was considered and its existing procedures were classified.

Methodological or general scientific significance. The results of the research can be used during the development of reclamation algorithms, restoration of habitats after breaches, and in the process of space exploration.

Purpose and objectives of the study. The purpose of the study is to develop theoretical foundations for various terraforming procedures. Following the goal, the following tasks are set:

Give a broad definition of the terraforming process from the standpoint of astroecology

Determine the theoretical basis for the classification of terraforming procedures

Create a preliminary classification of terraforming procedures

Materials and methods of research. The research materials are standard geobotanical descriptions made in the place of restoration of vegetation after disturbances in the period from 2004 to 2024. Descriptions are made using route-expedition and stationary methods according to standard methods [9]. The resulting standard geobotanical descriptions are classified according to the principles of the ecological and floristic school of Braun Blanke using the «Turboweg» program [10]. Indicators of environmental factors were determined by the synphytoindication methods using the «Simargl» software package [11].

Presentation of the main material. Scientific classification of natural objects or functions is not a simple sorting of them by a set of features. Classification is still a research and forecasting tool. A well-made classification can overtake scientific theories that existed at the time of its creation. A great example is the Mendeleev-Meier classification of chemical elements. Thanks to her, it was possible not only to predict the existence of unknown elements but also to reconcile the position with the quantum theory of the placement of electrons, which was discovered half a century later.

The classification of different types of terraforming is difficult to build based on a minimum of fundamental features. Therefore, in order to cover all varieties of terraforming in the broad sense of the word, we are forced to choose several signs. They are related, first of all, to the spatial characteristics of the territory where terraforming takes place, and the controllability of the processes by humans. As for the latter, we should divide all its types into two groups: spontaneous and planned processes. Life is ubiquitous and resilient enough for extreme travel. Within the limits of our planet, all its surface everything is saturated with its representatives, so as soon as the edaphic and climatic conditions allow it, life quickly settles on its own in unoccupied territory. To keep its resettlement under control, you need to constantly spend a lot of resources. The same thing happens outside the natural part of the biosphere. Despite our best efforts to sterilize spacecraft, terrestrial organisms constantly penetrate them and spread through space. This is especially noticeable in manned spaceships and stations. Therefore, regardless of where we are going to carry out terraforming and how we will do it, its spontaneous processes will act in parallel.

The presence and possibilities of spontaneous terraforming processes allow us to plan our actions taking this into account. In this regard, we can only change the abiotic conditions without deliberately settling selected groups of living organisms on the territory; to populate the biota and not interfere in the course of its settlement, syngenesis and endoechogenesis; combine changes in the abiotic environment with the cultivation of certain groups of biota.

Terraforming can be carried out both in individual local areas or in a conditionally closed space, and in open spaces, even on the scale of the entire planet. In this regard, we can distinguish a number of localities according to their scale and area (table 1).

Table 1

Examples of localities were selected for terraforming, which were classified using features of area and scale

Type of localities	Examples of localities were selected for terraforming
Environment of one organism.	Clothes, space suit
Group environment	Earth vehicle, spacecraft, space station compartment
Local	A house, a residential area, a space station, or a fragment of a natural tract.
Tract.	Quarry, natural tract, local biocenous ecosystem
Landscape	Several tracts are interconnected, such as the headwaters of a river with the catchment basin of the source from which it begins
Biome	A large, relatively uniform area of the planet's surface
All-planetary	The whole planet.

When we talk about different approaches to terraforming, which differ among themselves in terms of spatial characteristics, we must understand that their isolation is conditional, relative, and incomplete. Even from the space station, representatives of the biota will penetrate into the environment. And we have to admit that there is a non-zero probability that they will find a breeding ground for themselves. This probability depends on two factors – the proximity to the optimum indicators of the factors of this environment and the amount of biota that goes beyond the zone for terraforming. In our planet's conditions, this regularity is perfectly illustrated by the use of invasive species of transformers (for example, *Robinia pseudoacacia*) for reclamation or other hydromelioration works. That is why, when using any terraforming method, we must take these risks into account and reduce their probability [12].

On the other hand, the principle of interpenetration of biota and abiotic components between neighboring ecosystems is a guarantee of their more sustainable existence. For example, these are forest strips around agroecosystems, green areas in urban development, or swamps surrounded by forests near the source of the river. Therefore, when carrying out terraforming in order to obtain the necessary environmental conditions in a certain local area, it is desirable to influence the neighboring areas connected with it ([13]).

Main conclusions. Terraforming is a local or global change in the environment of the planet or an artificial structure, which shifts the indicators of environmental factors to the optimum of the human ecological spectrum.

Terraforming corresponds to evolutionary and successional changes in ecosystems. Initially, it is an allogeneic succession that can, under favorable conditions, trigger autogenic and evolutionary processes.

The basis for the classification of approaches to terraforming is the spatial characteristics of the territory where it occurs and the controllability of its processes by man.

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