Biosystems Diversity

ISSN 2519-8513 (Print)
ISSN 2520-2529 (Online)
Biosyst. Divers.

The impact of strike UAV explosions on soil acidity and vegetation dynamics

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Article info

Received 14.03.2025
Received in revised form 03.04.2025
Accepted 09.05.2025

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Khomiak, I. V., Onyshchuk. I. P., Kychkyruk, O. Y., Vakerych, M. M., Hasynets, Y. S., & Schwartau, V. V. (2025). The impact of strike UAV explosions on soil acidity and vegetation dynamics. Biosystems Diversity, 33(2), e2530. doi:10.15421/012530

The article studies the predicted changes in vegetation self-regeneration vectors caused by soil acidity changes resulting from the explosion of unmanned aerial vehicles (UAVs). In the areas where the UAVs exploded, the pH range for active soil acidity is 6.62–7.41, with an average of 7.14; for exchangeable soil acidity, it is 6.68–7.28, with an average of 7.02. The decrease in acidity is likely due to the release of carbonate parent rocks from the blast crater. Within this range of acidity, communities of herbaceous, segetal, and ruderal vegetation in the early stages of autogenous succession exist. According to the Braun-Blanquet system from the "EcoDBase 5g" database, these communities belong to eight classes, nine orders, ten unions, and eleven associations of higher vascular plant communities. In most observed cases, synatropization of the flora in the affected area is high. This leads to the formation of several types of anthropotolerant plant communities. Areas where the upper fertile soil layer is partially or fully preserved are covered with *Stellarietea mediae* vegetation. *Poo compressae-Tussilaginetum farfarae* communities (class *Artemisietea vulgaris*) most often form at the bottom of deep sinkholes with exposed bedrock or transitional rocks. This occurs within one to two growing seasons after the explosion. The vegetation of the *Agropyretum repentis* association (class *Artemisietea vulgaris*) forms at sites of disturbance in the absence of an impermeable horizon. This is the most widespread variant. It occurs during primary tillage, spontaneous turf disturbance, overgrowth of fallow land, and mining operations. It also occurs in ecosystems that have been disturbed by military operations, such as the movement of heavy tracked vehicles, the construction of fortifications, and the formation of explosive craters. Once natural vegetation communities are established, their subsequent dynamics are less dependent on the impact of the explosion. This occurs due to biogenic and abiotic transformations of the edaphic environment, changes in microrelief caused by water and wind erosion, and structural transformations of ecosystems. If UAVs use thermobaric charges in areas where the seed bank is depleted, human intervention in the self-regeneration process is necessary. This intervention should involve planting trees, shrubs, and other flora typical of this stage of succession. If the level of nitrates and ammonium salts exceeds the threshold, vegetation dynamics shift towards forming nitrophilic phytocoenoses. Vegetation self-regeneration is an effective method of restoring disturbed ecosystems. However, the changes that occur in the edaphic environment due to explosions, along with the destruction of niches, create favorable conditions for invasive species to enter these areas. The presence of these species leads to dynamic changes in vegetation. Sometimes, this results in a catastrophic climax. Controlling invasive species during the self-regeneration of vegetation after disturbances is one of the main tasks of postwar reconstruction of natural ecosystems.

Keywords: autogenous succession; self-regeneration of vegetation; catastrophic climax.

Introduction

To ensure the long-term survival of humanity, the concept of sustainable development was developed at the end of the twentieth century. It calls for a balanced approach to economic, social and environmental development that will enable us to conserve natural resources, combat climate change, ensure social equity and strengthen economic resilience. Sustainable development is a balance between economic growth and improved environmental sustainability. Defining the characteristics and key parameters of this balance is an extremely complex theoretical and practical task. At the same time, without it, sustainable development programs will remain no more than nice declarations without practical consequences. We need reliable forecasting algorithms with a high probability of prediction for all human impacts on the environment without exception. Experience shows that we need to make these predictions both for intentions to exploit natural resources and for intentions to protect parts of the natural environment (Löfqvist et al., 2023).

The main obstacles to building effective predictive algorithms are the complexity of the systems for which they are designed and the lack of a developed theoretical framework (Usher, 2023). The central object of prediction is the ecosystem. It is a complex, multi-component object that connects many different components through numerous linkages. Moreover, ecosystems are open systems. There is a constant exchange of matter and energy between them and their environment. In addition, human behavior is difficult to predict and can act as an internal or external factor. This makes the behavior of the ecosystem stochastic and difficult to predict (Harbar et al., 2023). A shift in any of the environmental factors can cause noticeable and significant changes in ecosystems. Only by studying the mechanisms of self-regulation and self-organization can we establish at least some patterns that should form the basis of our predictions.

Despite the fact that the science of ecology has about 200 years of history, it has not yet developed a perfect system of theoretical models like those of mathematics, physics, or chemistry. The main problem is the complexity of its object of study. However, without such a theoretical framework, it is almost impossible to make predictions about changes in ecosystems. Only when we have universal, perfect, and mathematically harmonious models, verified by empirical experience of observations and experiments, will we be able to predict the impact of human activities on the environment with high probability and in the long term (Brudvig & Catano, 2024). The key ecological theory that integrates other theoretical models is the theory of ecosystem dynamics.

An ecosystem, in the modern definition of this concept, can be a full-fledged object of theoretical and applied research (Odum, 1971). According to this definition, it is not a dimensionless entity. Since its full functioning requires the combination of all valuable populations and their habitats, which ensure the circulation of substances and energy, its size can only be reduced to a certain threshold. The monocentric model of ecosystems has an undeniable advantage, since the producers pass through the entire flow of energy that is integrated into the circulation system. According to this model, the analysis of their structure and functions should be based on the characteristics of autotrophic units.

The most promising areas for the development of theoretical models of ecosystem dynamics are energy cycles in their main blocks (Didukh & Lysenko, 2009). First of all, we are talking about the biomass of producers (Khaurdinova & Moroz, 2013). It is assumed that changes in aboveground phytomass during autogenous succession can serve as a basis for modeling the natural dynamics of ecosystems. We assume that changes in the energy balance of ecosystems associated with autogenous succession will be opposite to those that occur during allogenic successions, including anthropogenic ones. This assumption is consistent with the Lotka-Odum-Pinkerton energy maximization principle and its development in the works of Margalef (1968).

Since all ecosystems on Earth are subject to anthropogenic pressure, it is an urgent task to determine its impact on natural dynamics. The definition of the anthropogenic factor by anthropotolerance is a development of the idea of hemerobia (Blume & Sukopp, 1976). It has been improved by integrating different activities and creating an 18-point scale (Khomiak et al., 2024). However, the process of determining the energetic properties of ecosystems and anthropogenic impacts on them is technologically complex and very costly. Therefore, an urgent task is to study the possibility of using certain indicator features that are easy to establish. Many authors point out that in relation to the peculiarities of natural and anthropogenic ecosystem dynamics, living organisms will react according to Shelford's law of tolerance . This will allow the use of synphytoindication methods to determine indicators of natural dynamics and anthropogenic transformation of ecosystems (Didukh, 2012; Khomiak et al., 2024). To do this, it is necessary to analyze the distribution of species and communities along the scales of indicators of dynamics and tolerance to anthropogenic impacts of different intensity.

Unfortunately, in addition to peaceful sustainable development challenges that need to be addressed immediately, there are also war-related challenges (Yutilova et al., 2025). These include the environmental impacts of various forms of armed conflict (Pereira et al., 2022). Today, it is still too early to draw final conclusions and predictions about the processes that will accompany the dynamics of post-military ecosystems. The military aggression of the Russian Federation and its terrorist attacks against Ukraine cause not only economic losses and human casualties, but also damage to the environment (Serhii et al., 2022). The extent of the damage goes beyond the local level and becomes a regional problem (Haralampiev & Panayotova, 2022). Military operations destroy large areas of natural ecosystems, critically reduce the volume of their ecosystem services, and pollute the environment with hazardous and undesirable substances. Ukrainian and global environmental science faces the challenge of comprehensively studying the impact of hostilities on the environment, predicting their consequences, and developing measures to reduce and overcome them (Eslami, 2022). Hostilities are accompanied by many types of anthropogenic pressures: shelling, mining, construction of fortifications, movement of people and equipment (Shumilova et al., 2023). Each type of anthropogenic pressure has its own characteristics of impact on specific habitat components.

Based on previous studies, we can conclude that the impact of hostilities shifts ecosystem dynamics in the opposite direction from the climatic attractor (Bezsonov, 2024). The time required for self-regeneration of vegetation depends on the severity of damage to the edaphotope and seed bank (Lewis, 2023). Slowing down the self-regeneration of natural vegetation can be caused by constant anthropogenic pressure, the resistance of the edaphotope to endoecogenesis, the absence of representatives of the next stages of autogenous succession in the seed bank, and the influence of invasive transformer species. The shift in the indicators of edaphic factors from the climax optimum due to explosions, fortification works, or the movement of military equipment slows down the process of vegetation recovery (Ford, 2021).

Considering that the restoration of natural ecosystems damaged by hostilities will take place in conditions of acute shortage of resources, the development of predictive algorithms for this process is an extremely urgent task today. Since the most widespread and frequent means of destruction on the territory of Ukraine is the use of large strike UAVs, the primary task is to study the impact on ecosystem dynamics of environmental factors changed by these strikes (Eslami, 2022).

The aim of the study is to investigate the impact of changes in soil acidity caused by Shahed UAV strikes on the dynamics of self-healing of natural ecosystems. In accordance with the objective, the following tasks were set:

1) Analyze changes in soil acidity in areas affected by Shahed UAV strikes;

2) Create a forecast that predicts the process of natural self-healing of ecosystems damaged by Shahed UAV strikes;

3) Determine the shift in the probability distribution of the prediction of natural ecosystem self-restoration following changes in soil acidity.

Materials and methods

The study materials are soil samples collected at the sites of UAV impact explosions (combined mixed soil samples from 13 craters were analyzed). Soil samples were collected from the surface layer of different areas of the craters and from a depth of 20 cm (a total of 65 mixed soil samples were analyzed). Three types of acidity were determined in the mixed samples: active, metabolic, and hydrolytic. Active acidity was determined by preparing an aqueous extract: a 6.00 g sample of air-dry soil was poured with 30 ml of distilled water, stirred in a shaker for 20 minutes, then a portion of the solution was taken from above the sediment and the pH was measured using a pH meter with a glass electrode (I-117) (Nabyvanets et al., 1996). Exchangeable acidity was determined by the saline extraction method using a 1 M KCl solution. A 20.00 g soil sample was poured with 50 ml of 1 M KCl solution, stirred for 15 minutes and then the pH in the extract was measured using a pH meter (pH800 Benchtop pH Meter, Apera, USA) (Nabyvanets et al., 1996). The hydrolytic acidity was determined from the saline extract prepared according to the method (Nabyvanets et al., 1996). For this, 40.00 g of air-dry soil sample was poured into 100 mL of 1 M sodium acetate solution, stirred in a shaker for 30 minutes, and then the resulting solution was passed through a paper filter. Fifty milliliters of the clear filtrate was titrated with 0.1 M NaOH solution in the presence of phenolphthalein until a pale pink color appeared. The soil's hydrolytic acidity (H_{hydr}) was calculated using the following formula: $H_{hydr} = C_{NaOH} * V_{NaOH} / V_{salt\ extract} \times 1.75$, where V_{NaOH} is the volume of the titration solution used for titrating 50 mL of soil extract, C_{NaOH} is the concentration of the titration solution, and 1.75 is the conversion factor for total hydrolytic acidity per kilogram of soil (Nabyvanets et al., 1996).

To predict the process of vegetation self-renewal under different environmental conditions, we additionally analyzed 3,160 standard geobotanical descriptions (Yakubenko et al., 2020) made between 2004 and 2024. Plant communities were classified according to the principles of Braun-Blanquet (Dubyna et al., 2019). Descriptions were entered into the database using the software package Turboveg for Windows and Simargl 1.12 (Hennekens, 2009). The EUNIS system and principles were used to classify ecosystems, combined with the authors' own edaphic-dynamic classification. Ecosystems were differentiated by phytocoenotic characteristics and edaphotope characteristics in the absence of established plant communities.

The assessment of environmental factors was carried out using the methods of synphytoindication according to the principles laid down by J. P. Didukh and P. G. Pluta (Didukh, 2012). The hemerobicity of plant communities was used to determine the degree of anthropogenic transformation. The calculations were performed using the software package Simargl 1.12 and Simargl 10.20 based on the "EcoDBase 5g" database.

Results

The analysis of the collected soil samples shows that in the area where Shahed or Geranium-2 UAVs were detonated, the pH range for active soil acidity ranges from 6.62–7.41 with an average value of 7.14, and for exchangeable soil acidity – 6.68–7.28 with an average value of 7.02. The reference values for this type of soil range from 6.80–7.30 with an average value of 7.05. The deviation towards a decrease in acidity, especially noticeable for its exchangeable component, is, among other things, due to the rise of parent and transitional rocks saturated with calcium and magnesium carbonates into the air. In the A-horizon of the soil, these substances are destroyed as a result of interaction with acids released during bacterial or fungal decomposition of organic residues. Deeper horizons are partially protected from this effect and therefore have a lower acidity. During the explosion, substances from the B-horizon and the bedrock are released into the air and mixed with the fertile layer.

The main question is whether such changes are sufficient to significantly affect the dynamics of disturbed ecosystems. In this case, we are talking about fluctuations, succession, and evolution. Today, the only way to activate the process of ecosystem evolution is to transfer invasive transformer species as a result of seed bombardment or to transform the environment into one more favorable for their invasion. Fluctuating changes in ecosystems occur in all cases of impact by attack UAVs. The ecosystem is affected locally and returns to its previous state in a few years. In order for fluctuations to move to the level of succession or evolution, the complex of accompanying factors must exceed certain thresholds. To identify these thresholds and to predict the consequences of crossing them, we analyzed the array of phytocoenotheca descriptions of the "EcoDBase 5g" laboratory of ecosystem theory.

The soil acidity range, with a pH of 6.62 to 7.41, includes 10.5% of the descriptions in the database. From this list, only 0.4% belong to terrestrial ecosystems. Their syntaxonomic scheme includes 8 classes, 9 orders, 10 unions and 11 associations of higher vascular plant communities. The syntaxonomic scheme of the vegetation is as follows:

Asplenietea trichomanis (Br.-Bl. in Meier et Br.-Bl. 1934) Oberd. 1977: *Asplenietalia septentrionalo-cuneifolii* Mucina et Theurillat 2015: *Asplenion septentrionalis* Gams ex Oberdorfer 1938: *Arabidopsio thalianae-Polypodietum* Didukh et Kontar 1998.

Molinio-Arrhenatheretea R.Tx 1937: *Arrhenatheretalia elatioris* Tüxen 1931: *Arrhenatherion elatioris* Luquet 1926: *Pastinaco sativae-Arrhenatheretum elatioris* Passarge 1964

Trifolio-Geranietea Th.Müll 1962: *Origanetalia vulgaris* T. Müller 1962: *Trifolion medii* Th.Müll 1962: *Agrimonio eupatoriae-Trifolietum medii* (T. Müller 1962) Dengler et al. 2003,

Nardetea strictae Rivas Goday et Borja Carbonell in Rivas Goday et Mayor López. 1966: *Nardetalia* Preis. 1950: *Violion caninae* Schwickerath 1944: *Calluno-Nardetum* Hrync 1959,

Sedo-Scleranthetea BR.-BL. 1955: *Sedo-Scleranthetalia* Br.-Bl. 1955: *Hyperico perforati-Scleranthion perennis* Moravec 1967: *Thymo pulegioidis-Sedetum sexangularis* Didukh et Kontar 1998; *Sedo-Scleranthion* Br.-Bl. et Richard 1950: *Sedo acri-Dianthetum hypanici* Solomakha et al. 2006.

Artemisietea vulgaris Lohmeyer et al. ex von Rochow 1951: *Agropyretalia intermedio-repentis* T. Müller et Görs 1969: *Convolvulo arvensis-Agropyrion repentis* Görs 1967: *Agropyretum repentis* Felföldy 1942, *Poo compressae-Tussilaginetum farfarae* R. Tx. 1931;

Galio-Urticetea Passrge et Kopecký 1969: *Galio-Alliarietalia* Oberd. in Görs et T. Müller 1969: *Aegopodion podagrariae* R.Tx 1967: *Elytrigio repentis-Aegopodietum podagrariae* Tüxen 1967,

Stellarietea mediae R.Tx., Lohmaer et Preising 1950: *Aperetalia spicae-venti* J. Tx. & Tx. in Malato-Beliz et al. 1960: *Scleranthion annui* (Kruseman et Vlieger 1939) Sissingh in Westhoff et al. 1946: *Centaureo cyani-Aperetum spicae-venti* Solomakha 1989; *Eragrostietalia* J. Tx. ex Poli 1966: *Salsolion ruthenicae* Philippi ex Oberd. 1971: *Plantagini indicae-Digitarietum sanguinalis* Papucha 1991.

As we can see from the syntaxonomic scheme, this area contains mainly herbaceous vegetation communities. Occasionally, meadow and forest edge communities of the associations *Pastinaco sativae-Arrhenatheretum elatioris* and *Agrimonio eupatoriae-Trifolietum medii* are found here. The rock outcrops of *Arabidopsio thalianae-Polypodietum*, *Calluno-Nardetum* have significant phytocoenotic diversity, *Sedo acri-Dianthetum hypanici* and synanthropic communities *Agropyretum repentis*, *Poo compressae-Tussilaginetum farfarae*, *Elytrigio repentis-Aegopodietum podagrariae*, *Centaureo cyani-Aperetum spicae-venti* and *Plantagini indicae-Digitarietum sanguinalis*. This picture fits the hypothesis and the expected results of the study. On the one hand, we observe vegetation associated with natural and anthropogenic outcrops of carbonate rocks, and on the other hand, we see segetal vegetation of highly fertile soils. Since fertile soils in Ukraine are mostly plowed and rock outcrops are poorly covered with tree and shrub vegetation, our database contains virtually no descriptions of forest and shrub communities associated with this range of acidity. This makes it somewhat difficult to make predictions about later stages of vegetation recovery.

Such phytocoenotic diversity allows us to predict the main directions of vegetation development after disturbance in the first years after UAV strikes. Their formation will be influenced by the force of the impact, the structure of the affected soil, the preservation of the seed bank, the potential for the introduction of seed diaspora and the level of its synanthropization. The more powerful the charge and the closer it is to the soil surface, the more the soil horizons will be mixed. Sometimes the depth of the crater exceeds one meter and the bedrock is completely exposed. Even more important is the ratio of the blast force to the structure of the upper soil layers. The thinner the A and B soil horizons are, the lower the blast force required to destroy and mix them. If the synatropization of the damaged area is low, extremophile communities (vegetation classes *Asplenietea trichomanis*, *Nardetea strictae*, *Sedo-Scleranthetea*) can form. At the same time, fern communities (*Asplenietea trichomanis*) are formed where there are outcrops of crystalline rocks, lichen-moss psammophyte communities (*Nardetea strictae*) on loose rocks, and sedge communities (*Sedo-Scleranthetea*) on mixtures of hard fragments and loose sedimentary rocks, as well as in crevices filled with them.

In most of the observed cases, the synatropization of the flora of the affected area is quite high. This leads to the formation of several types of anthropotolerant plant communities. Areas where the upper fertile soil layer is at least partially preserved are covered with *Stellarietea mediae* vegetation. This happens extremely quickly, and already in the first growing season, in the absence of additional human intervention, we can observe segetal phytocoenoses with a full set of diagnostic features. Depending on the conditions of the environment that formed after the explosion, these may be different associations of this class.

With the exception of nitrogenized forest edges (*Elytrigio repentis-Aegopodietum podagrariae* association), all possible variants have very low indicators of natural dynamics. Their average values are 4.63 points and the minimum is 3.31 points. Nitrophilized forest edges due to shading by phanerophytes have an indicator of about 9.11 points. Thus, we can predict with high accuracy the process of self-regeneration of vegetation in the early (cereal and shrub-cereal) stages of autogenous succession. At the same time, the process of vegetation change will be unequal in different parts of the affected area (Fig. 1).

If the thickness of the soil horizons is not large and the explosive power is significant, it is possible to expose bedrock at the bottom of the crater. These can be loose or crystalline rocks of different chemical composition. Acidic igneous rocks at the bottom of craters are found locally only in the area of their approach to the bottom surface. Most often, acidic and neutral loose sedimentary rocks are exposed (northern part of Ukraine) or slightly alkaline loose or gravelly sedimentary rocks (most of Ukraine is covered with black soil or gray forest soils on a forest base).

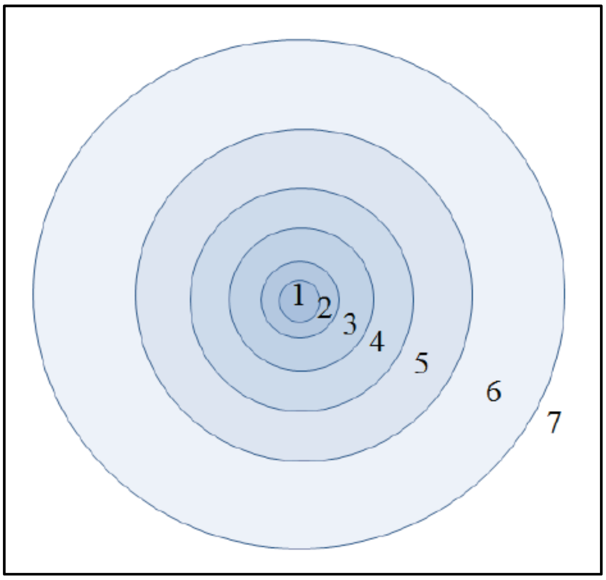

Fig. 1. Zoning of the area affected by the UAV strike explosion: *1* – crater bottom with bedrock, *2* – crater slope formed by bedrock, *3* – crater slope formed by loose sedimentary rocks transitioning to bedrock, *4* – crater slope formed by fertile soil layer, *5* – the side of the crater is formed by the ejection of rocks from the center of the crater, *6* – the area affected by explosive fragments and fragments of soil and rock, *7* – the area affected by the blast wave and contamination by explosive combustion products

The walls of such a crater consist mainly of transitional rocks to the parent rock. If the explosion is of low power or occurs above the surface, such rocks will form the bottom of the crater. For even smaller explosions, the entire crater will consist of a fertile layer of soil. Around the perimeter of the crater is a low berm of rocks and soil thrown from the epicenter of the explosion. Beyond this berm, the area will be affected by thermal, acoustic, blast, chemical, and debris impacts. The most noticeable changes will be in the chemical composition of the soil. Each site described above will differ in terms of chemical and mechanical composition of the substrate, blast force, and orography. This will determine the direction and rate of autogenous succession during the first few years of vegetation recovery (Fig. 2).

Poo compressae-Tussilaginetum farfarae communities (class *Artemisietea vulgaris*) are most often formed at the bottom of deep sinkholes with exposed bedrock or transitional rocks. This occurs within 1–2 growing seasons after the explosion. Vegetation of this association is very often observed on disturbed substrates of mining sites, so its presence at the bottom of craters corresponds to its ecological spectrum. It is described in the range of long-term moisture regime 11.21–12.35 points, moisture variability 6.83–8.25 points, acidity 7.68–8.25 points, total salinity 7.35–7.94 points, carbonate content 7.75–8.77 points, nitrate content 5.86–6.54 points and with soil aeration 6.71–7.50 points. Although we often observe this community at the bottom of ditches and gullies, it can form in a narrow range of light conditions 7.37–7.55 points. The dominant species in such communities is *Tussilago farfara* L. It is a fairly hardy and undemanding plant that is able to adapt to the conditions of disturbed substrates. Because individuals of this species are connected by a network of rhizomes, they find relatively rich sites for water and nutrients, which become a common property. This allows them to dominate disturbed substrates. The most common limiting factors are competition from other species and a long-term moisture regime below 11.2 points. At the same time, they can grow on well exposed slopes with southern exposure.

In the absence of the aforementioned waterproof horizon, the *Agropyretum repentis* association (class *Artemisietea vulgaris*) will form vegetation. This is the most widespread form of vegetation regeneration in the first stage after soil disturbance. This occurs during primary tillage, spontaneous turf disturbance, overgrowth of fallow land, mining operations, and in ecosystems disturbed by military operations, such as the movement of heavy tracked vehicles, the construction of fortifications, and explosive craters. These communities are usually dominated by *Elymus repens* (L.) Gould, *Elytrigia intermedia* (Host) Nevski, and *Carex hirta* L. *Elymus repens* dominance is most often observed in mesophytic conditions on poorly lit slopes or placers. The variant *Agropyretum repentis* var. *Elymus repens* often occurs during mechanical disturbance of the topsoil and turf. It also almost always accompanies the first years of restoring natural vegetation after the cessation of arable farming. If an area subjected to UAV strikes is taken out of agricultural use for a period of time, this variant of the association will persist for five to ten years.

On well insolated slopes of the southern exposure, *Elytrigia intermedia* most often dominates. It forms a variant of the association of plant communities *Agropyretum repentis* var. *Elytrigia intermedia*. Very often the projective cover of such plant communities is low (less than 75%). In addition to *Elytrigia intermedia*, species of mesocerophytic meadows and meadow steppes are found here. In the north, *Agrostis vinealis* Schreb., *Bromus tectorum* (L). Nevski, *Festuca ovina* L., *Potentilla argentea* L. and *Poa angustifolia* L become codominant. Further to the south, *Festuca valesiaca* Gaud., *Agropyron cristatum* (L.) Gaertn., *Melica transsilvanica* Schur, *Potentilla recta* L., *Stipa lessingiana* Trin. et Rupr. are more common.

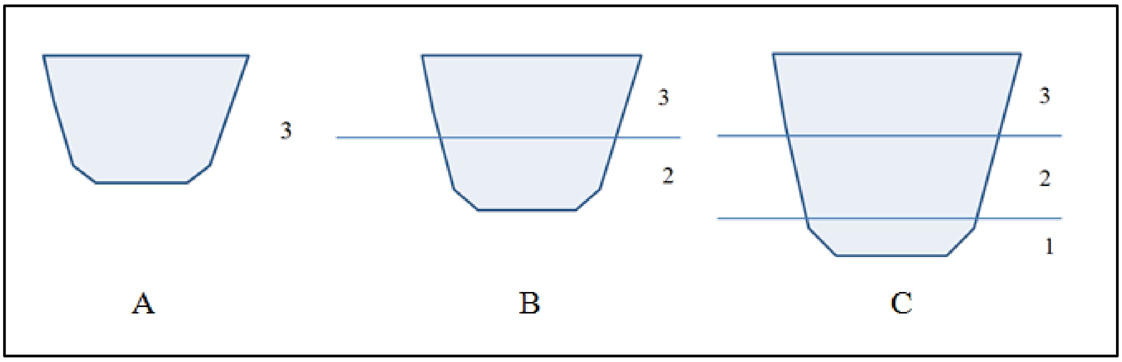

Fig. 2. Types of craters caused by UAV strike impacts based on their reflection of the soil profile: *A* – crater with disturbance of fertile soil horizon, *B* – crater with disturbance of fertile and transitional soil horizons, *C* – crater with exposure of bedrock; *1* – bedrock, *2* – transitional rocks, *3* – fertile soil layer

Carex hirta is a co-dominant species on disturbed substrates with low humus content, in the ecotone with meadows, and under increased recreational load. It forms the *Agropyretum repens* var. *C. hirta* association. The above-mentioned plant and *Agrostis capillaris* L., *Elymus repens*, *Elytrigia intermedia*, *Equisetum arvense* L., and *Veronica persica* Poir. are found here. These plant communities are more resistant to competitors from meadow phytocoenoses and often form ecotones with them.

The ability of variants of the *Poo compressae-Tussilaginetum farfarae* and *Agropyretum repentis* associations to adapt to disturbed substrates is associated with cloned, dominant plants connected by a network of rhizomes. These rhizomes serve as a means of reproduction during turf disturbance and are the basis of their adaptation strategy. Some of the cloned organism spreads onto undisturbed soil where there is enough moisture and mineral nutrients. However, they face competition for solar energy in such places. At the same time, such competition is much lower in disturbed areas. The second part of the cloned organisms of the typical species of the order *Agropyretalia intermedio-repentis* is located here. They can freely photosynthesize without interference from competing phototrophs. Thus, the clone in the disturbed area produces most of the total glucose through photosynthesis, while the clone in the undisturbed soil receives most of the minerals and moisture.

Fern communities of the class *Asplenietea trichomanis* can form here under low anthropogenic pressure if the outcrops of parent rocks at the bottom of the sinkhole are at an angle close to 90° and their exposed layer is at least 30–50 cm thick. One of the most widespread variants is the *Arabidopsio thalianae-Polypodietum association* vegetation. However, other *Asplenion septentrionalis* associations are also possible. The flora of such communities often contains other elements. For example: *Poa bulbosa*, *Potentilla argentea*, *Sedum acre*, *Sedum reflexum*, and *Thymus serpyllum*. This variant of restoring disturbed vegetation is similar to communities in the *Sedo-Scleranthetea* class.

The presence of vegetation in the *Sedo-Scleranthetea* class indicates a slowdown in the succession process leading to the formation of a temporary catastrophic climax. This slowdown in ecosystem dynamics occurs due to the substrate's resistance to endoecogenesis. Typically, this involves a humus-poor substrate with numerous crystalline inclusions on a well-salted and drained slope. Here, we observe two lines. The first is formed by various stonecrop species, such as *Sedum acre* L., *S. reflexum* L., and *S. sexangulare* L. This usually occurs in areas with fragmented crystalline rock or coarse sand. This is usually the *Sedo acri-Dianthetum hypanici* association (*Sedo-Scleranthion alliance*). The second line is associated with the dominance of thyme (*Thymus pulegioides* L., *Thymus serpyllum* L., and *Thymus marschallianus* Willd.). This lineage can be found on both fine sand and loess as well as on formed, humus-poor soils. This is the *Thymus pulegioides-Sedum sexangulare* association (*Hyperico perforati-Scleranthion perennis* alliance).

In some cases, psammophytic plant communities belonging to the *Nardetea strictae* class form on sandy substrates. These are different variants of the *Calluno-Nardetum* association. In addition to *Nardus stricta* L., these communities are characterized by the presence of relatively large areas of mosses (e.g., *Dicranum polysetum* Swartz, *Polytrichum commune* Hedw) and ground lichens (e.g., *Cladonia alpestris* (L.) Rabenh., *Cladonia coccifera* (L.) Willd., *Cladonia gracilis* (L.) Willd., *Cladonia rangiferina* (L.) F. H. Wigg.). Such communities are usually found in neutral or slightly acidic environments, so it is unlikely that they will form in areas where the main parent rocks have been removed from the surface.

Since most areas affected by UAV strikes are highly synanthropic, the soil almost always contains a seed bank of ruderal and segetal plants. Combined with soil integrity violations, this leads to the formation of *Stellarietea mediae* communities. Under these conditions, various associations of this class form. Most often, these are *Centaureo cyani-Aperetum spicae-venti* (*Scleranthion annui* alliance) and *Plantagini indicae-Digitarietum sanguinalis* (*Salsolion ruthenicae* alliance) associations, whose acidity values correspond to changes after the main parent rocks were removed by explosions. *Portulaca oleracea* L. often acts as a co-dominant species, forming variants of the *Centaureo cyani-Aperetum spicae-venti* var. *Portulaca oleracea* and *Plantagini indicae-Digitarietum sanguinalis* var. *Portulaca oleracea* associations.

A meadow community of the *Molinio-Arrhenatheretea* class can form within a year if a slight disturbance of the soil occurs in the middle of a hayfield or pasture. The *Pastinaco sativae-Arrhenatheretum elatioris* association (union *Arrhenatherion elatioris* of the *Arrhenatheretalia elatioris* order) falls within the range of acidity values obtained. However, observations in Polissia and the Forest-Steppe indicate that the following communities fall within this range: *Koelerio-Agrostietum vinealis* (Sipaylova et al., 1985; Shelyag et al., 1987); *Agrostietum vinealis-Calamagrostietum epigei* Shelyag-Sosonko et al., ex Shelyag-Sosonko et al., 1985; and *Agrostietum vinealis-tenuis* (Shelyag et al.,1985); *Carici praecox-Alopecuretum pratensis* Mirkin in Denisova et al., 1986; *Poëtum angustifoliae* (Shelag-Sosonko et al., 1986); *Bromopsietum inermis* (Shvergunova et al., 1984); and *Achillea submillefolium-Dactyletum glomeratae* Smetana, Derpoluk, Krasova, 1997 (*Agrostion vinealis* union of the order *Galietalia vera*). This phenomenon occurs because meadow vegetation forms at later stages of autogenous succession. It displaces segetal and ruderal communities that appear in the first years after disturbance. During this time, endogenous changes in the edaphic landscape occur, increasing soil acidity. This is due to the transfer of fragments of parent and transition rocks, as well as the interaction of their basic chemicals with organic residues.

When vegetation regeneration reaches the formation of phanerophyte cones, we can observe the forest edge plant communities of the *Trifolio-Geranietea* class along their perimeter. Most often, this is the *Agrimonio eupatoriae-Trifolietum medii* association. These associations are mainly identified by the presence of *Agrimonia eupatoria* L., alongside the flora of mesocerophytic meadows belonging to the *Galietalia vera* order (*Molinio-Arrhenatheretea* class). The lowest dynamics indicators for this association are 4.89 points. Over time, these values rise, reaching 7.93 points.

If an explosion occurs near or in the middle of tree and shrub vegetation, communities of nitrophilized forest edges of the *Elytrigio repentis-Aegopodietum podagrariae* association (class *Galio-Urticetea*) often form here. This is facilitated by the numerous plant residues and nitrogen-containing compounds released by the explosion, which are the basis for most types of explosives. The most common variants are *Elytrigio repentis-Aegopodietum podagrariae* var. *Urtica dioica* and *Elytrigio repentis-Aegopodietum podagrariae* var. *Elymus repens*. The association is dominated by *Urtica dioica* L., *Rubus caesius* L., *Aegopodium podagraria* L., and *Elymus repens* (L.) Gould.

Within a certain range of acidity, we can predict which plant communities will emerge in the first years following a disturbance and how they will transform as the acidity reverts to its original level due to endoecogenesis (Fig. 3). At the same time, certain community types can begin to form on the primary substrate or become links in the autogenic succession that accompanies the self-regeneration of vegetation.

Once natural vegetation communities are established, subsequent changes in their dynamics will be less dependent on the impact of the explosion. This occurs due to biogenic and abiotic changes in the edaphic environment, changes in microrelief caused by water and wind erosion, and structural transformations of ecosystems. In the early stages of succession, phytoplots of dominant species cover small areas. Thus, the pioneer plant community can function as an autotrophic ecosystem unit within a portion of the blast vortex. For instance, the full functional area of communities formed by mosses or lichens may be less than one square decimeter. For grassland ecosystems, the minimum area is 1–4 m². We only observe differences in the dynamics of vegetation self-regeneration at the level of associations for sinkholes exposing bedrock and transitional rocks. Small sinkholes differ only at the level of co-dominants, i.e., variants of associations or subassociations of plant communities. Once autogenous succession reaches the formation of phanerophyte communities, differences caused by the funnel's presence manifest only at the variant level, and then only during tree-shrub cone formation. Subsequently, the differences caused by sinkholes in forest ecosystems are classified as sinusia (Fig. 4).

Discussion

Changes in soil acidity combined with mechanical impacts on the soil have a direct effect on succession processes that unfold after a UAV strike explosion, but they are not the only influence. There are also a number of remote impacts that can have noticeable consequences. These impacts spark discussions about approaches to mitigating the consequences of these strikes.

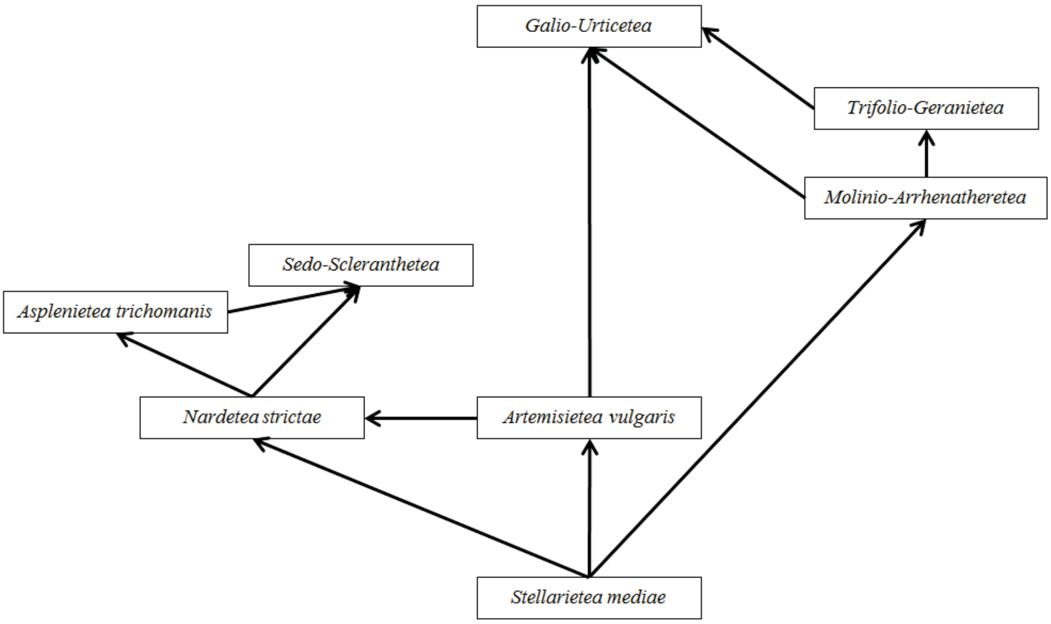

Fig. 3. The main lines of autogenous succession at the class level in the first years after the UAV strike explosion

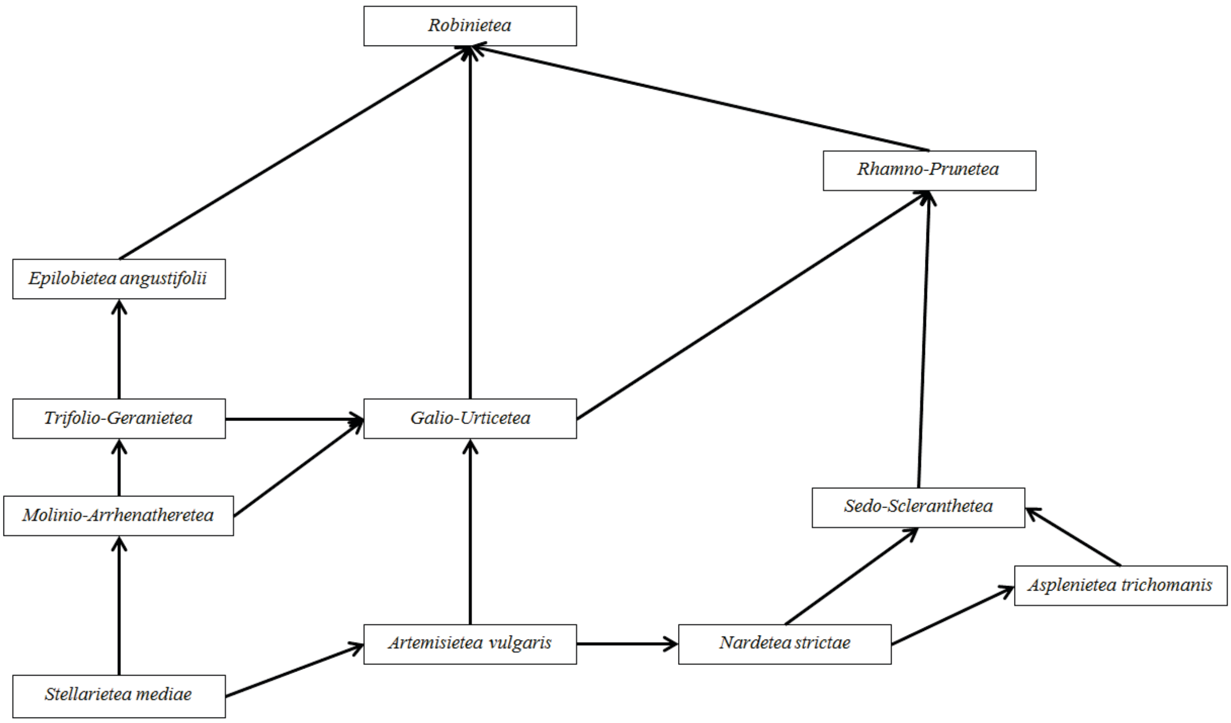

Fig. 4. Main lines of autogenous succession at the class level during the formation of woody and shrubby vegetation after a UAV explosion

One of the important factors that arise during an explosion is a sharp short-term temperature rise. This became especially relevant when, starting in 2024, UAVs carrying a thermobaric charge appeared en masse (Eslami, 2022). The sharp rise in temperature during an explosion changes the structure of the seed bank stored in the soil. Some seeds are sensitive to this temperature increase and die. In this case, there may be a slowdown in the self-regeneration of vegetation up to the onset of a catastrophic climax or deviation of its development vectors (Khomiak et al., 2024). The seeds of certain plant species not only tolerate temporary temperature increases well, but also perceive them as a positive factor (Meunier et al., 2021). These are mainly seeds of the flora of pyrogenic ecosystems. The most striking example is *Calamagrostis epigeios* (L.) Roth. It is the unifier and diagnostic species of the association *Calamagrostietum epigei* Juraszek 1928 (union *Epilobion angustifolii* Oberd. 1957, order *Galeopsio-Senecionetalia sylvatici* Passarge 1981, class *Epilobietea angustifolii* Tx. et Preising ex von Rochow 1951). Seeds and rhizomes of this species tolerate high temperatures well, and due to the loss of competitors, they easily form monodominant coenoses in areas affected by fire. Researchers have been recording areas occupied by this small-species community where thermobaric charges have been applied since 2022. In some cases, especially in the context of climate change, such cenoses suspend vegetation recovery for a long time (Ali et al., 2023). This happens for several reasons. First, high temperatures destroy the seed germs of species from the next stages of autogenous succession. Secondly, due to snowless winters, a thick layer of undecomposed *Calamagrostietum epigei* remains forms over the soil, blocking the seed diaspora from entering the soil. Thirdly, *Calamagrostietum epigei* is a highly competitive species and even after the formation of a continuous forest canopy, it prevents the formation of a typical forest flora in its grass cover. Therefore, in the case of the use of thermobaric charges by UAVs or in the presence of signs of depletion of the seed bank in the soil, human intervention in the process of self-regeneration of vegetation is necessary. It will be associated with the planting of trees, shrubs, and representatives of forest flora typical for this stage of succession (Luong, 2022).

The availability of the seeds necessary for self-renewal may be affected by the blast wave, as it destroys the surrounding vegetation. After a UAV strike, trees and bushes within a radius of several meters are destroyed. If the explosion occurs in a mature forest, only a few trees are affected, and this does not significantly impact the supply of seeds to the affected area. However, when an explosion occurs in a young forest, an area up to 10 meters in diameter is created where all the trees are destroyed. In this case, there is a shortage of the seeds needed for the forest to renew itself. This is particularly true for tree species unable to disperse seeds long distances from their parent trees (Nathan et al., 2020).

At the same time, the need to level the land and reclaim the soil is debatable. On the one hand, there is a need for this within agricultural lands and exploited forest plantations due to the technical conditions of using this site. In this case, the question of feasibility arises. After all, the soil becomes contaminated with various chemicals during the explosion, which affects the quality and safety of products obtained here (Alpatova et al., 2022). Therefore, we can assume the reclamation and normal use of single craters (Roberts et al., 2024). In areas of massive shelling where hazardous substance concentrations will be high, we should consider decommissioning the area and restoring natural vegetation. In natural areas, explosive craters lead to the formation of sinusia, significantly increasing species and landscape diversity. Therefore, it seems reasonable to restore the natural vegetation, which will ultimately provide a wide range of ecosystem services.

Another important factor to consider is how the products of the chemical reactions that accompany the explosion can nitrify the environment. Most explosives do not burn; rather, they spray and evaporate. Because they contain a high concentration of nitro compounds, they cause local nitrification of the environment. This is often observed at quarries where blasting is used in the mining process. When the levels of nitrates and ammonium salts exceed a certain threshold, the vectors of vegetation dynamics shift towards the formation of nitrophilic phytocoenoses. For instance, the *Poo compressae-Tussilaginetum farfarae* association's typical pioneer community is often formed by the *Poo compressae-Tussilaginetum farfarae* var. *Bidens tripartita* variant. As a result of succession, it passes to the *Polygonetum hydropiperis* Passarge, 1965 or *Bidentetum tripartitae* Miljan 1933 associations (union *Bidention tripartitae* Nordhagen ex Klika et Hadač, 1944 order. Bl. et Tx. ex Klika and Hadač, 1944; order *Bidentetalia* Br.-Bl. et Tx. ex Klika et Hadač 1944; and class *Bidentetea tripartiti* Tx. et al. ex von Rochow 1951.

Self-regeneration of vegetation is an effective method of restoring disturbed ecosystems. However, the changes that occur in the edaphic environment due to explosions, along with the destruction of ecosystems, create favorable conditions for invasive species to take hold in these areas. A decrease in acidity, coupled with an increase in nitric compounds, facilitates the establishment of *Acer negundo* L., *Ambrosia artemisiifolia* L., *Bidens frondosa* L., *Heracleum sosnowskyi* Manden., *Parthenocissus quinquefolia* (L.) Planch., *Robinia pseudoacacia* L., and other species (Khomiak et al., 2024). The penetration of these species leads to changes in vegetation dynamics. Sometimes, this results in a catastrophic climax and a decrease in phytodiversity (Nerlekar et al., 2024). Controlling invasive species while promoting self-regenerating vegetation after disturbances is one of the main tasks of post-war reconstruction of natural ecosystems.

Conclusions

In the area where the UAVs were blown up, the pH range for active soil acidity is 6.62–7.41, with an average of 7.14; for exchangeable soil, it is 6.68–7.28, with an average of 7.02. The decrease in acidity is likely due to the release of carbonate parent rocks from the blast crater. Within this range of acidity, communities of herbaceous, segetal, and ruderal vegetation are in the early stages of autogenous succession. According to the Braun-Blanquet system from the "EcoDBase 5g" database, these communities belong to eight classes, nine orders, ten unions, and eleven associations of higher vascular plant communities.

In most observed cases, synathropization of the flora in the affected area is high. This leads to the formation of several types of anthropotolerant plant communities. Areas where the upper fertile soil layer is partially or fully preserved are covered with *Stellarietea mediae* vegetation.

Poo compressae-Tussilaginetum farfarae communities (class *Artemisietea vulgaris*) most often form at the bottom of deep sinkholes with exposed bedrock or transitional rocks. This occurs within one to two growing seasons.

The vegetation of the *Agropyretum repens* association (class *Artemisietea vulgaris*) forms at sites of disturbance where there is no impermeable horizon. It is the most widespread variant of the initial stage of vegetation regeneration following soil disturbance. This process occurs during primary tillage, spontaneous turf disturbance, overgrowth of fallow land, mining operations, and in ecosystems affected by military activities such as the movement of heavy tracked vehicles, the construction of fortifications, and the formation of explosive craters.

Once natural vegetation communities are established, their subsequent dynamics are less dependent on explosive impacts. This is due to biogenic and abiotic changes in the edaphic environment, changes in microrelief caused by water and wind erosion, and structural transformations of ecosystems.

If there are signs of depletion of the seed bank in the soil due to the use of thermobaric charges by attack UAVs, human intervention in the self-regeneration process of vegetation is necessary. This intervention should involve planting trees, shrubs, and other flora typical of this stage of succession.

When the concentration of nitrates and ammonium salts surpasses the threshold level, the dynamics of vegetation shift towards the formation of nitrophilic phytocoenoses.

Vegetation self-regeneration is an effective method of restoring disturbed ecosystems. However, changes in the edaphic environment resulting from an explosion, together with the destruction of ecosystems, create favorable conditions for invasive species to enter these areas. The presence of these species leads to changes in vegetation dynamics. Sometimes, this results in a catastrophic climax. Controlling invasive species during vegetation self-regeneration after disturbances is one of the main tasks of post-war reconstruction of natural ecosystems.

The authors declared no conflicting interests.

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