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TECHNIQUE OF LAND RECULTIVATION OF PLACES OF AMMUNITION DISPOSAL AND DESTRUCTION

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Abstract

The relevance of the research and the need to develop methods that allow restoring the lands of the ammunition disposal and destruction sites during the application of measures for their recultivation are shown. The criteria for evaluating the safety level of the process of recultivation of the lands of the ammunition disposal and destruction sites based on the use of a regulatory approach and significant indicators were determined, namely: the probability of an explosion, the amount of excessive pressure in the air shock wave, and the level of degradation of the lands of the ammunition disposal and destruction sites.

For the first time the technique of land recultivation of places of ammunition disposal and destruction was developed. It includes three stages: Stage 1 – monitoring of land of places of ammunition disposal and destruction based on unmanned aviation monitoring system; Stage 2 – demining of land of ammunition disposal and destruction by specialized pyrotechnic units of the State Emergency Service of Ukraine using the results of the monitoring conducted at Stage 1; Stage 3 – biological treatment of land of the ammunition disposal and destruction using the phytoremediation method.

Key words: land recultivation, ammunition disposal and destruction, explosion hazard, monitoring, demining, phytoremediation.

Introduction

Multiple armed conflicts grow in the scale among the mankind history. Lands being the ground of such tragic events become objects of the massive negative impact on natural surrounding environment. Instead, such impact is not typical for regular regime of human society functioning.

With the widespread use of long-range artillery, attack and bomber aircrafts, as well as missile weapons, the area of lands negatively affected during armed conflicts increases significantly. The modern experience of Ukraine's repelling the military aggression of the russian federation demonstrates that even for the largest country in Europe, it is practically impossible to limit the territorial impact of the specified types of weapons, in particular, on the environment.

As a result, armed conflicts in the world lead to large-scale contamination with explosive objects of large territories of the states, which participate in the conflict. Report materials based on the results of studies of the ecological consequences of armed conflicts and the use of the indicated tactics of warfare demonstrate common features of the impact on the lands that were subjected to shelling.

The most famous anti-environmental war in the history of mankind is certainly the war in Vietnam (1962–1971). In specified period the local vegetation of the region was purposefully destroyed by chemicals. And the soil of the land was the simultaneously damaged by massive shelling and bombing damaged the [1].

In recent years, the impact of armed conflicts on the natural surrounding environment has become the object of assessment in the global context. In particular, such impacts were assessed on the territory of Lebanon [2], Iraq [3], Afghanistan [4], Congo [5], Croatia [6], the Gaza Strip [7], Syria [8], etc.

According to the results of a study conducted by the Regional Ecological Center of Central and Eastern Europe on the impact of the armed conflict in Yugoslavia (1999) [9], the presence of craters from explosions, as well as damage to the soil structure, resulting in land degradation and the subsequent death of flora and fauna, was established. The remains of organic explosives and heavy metals enter the soil. In particular, heavy metals are the most dangerous pollutants, which, due to their inorganic origin, cannot be neutralized naturally [10–13]. Registered consequences of soil contamination with heavy metals are suppression of vital activities of representatives of flora [14–17] and fauna [18–22].

Modern studies of the soils of the lands of Ukraine affected by the military aggression of russian federation demonstrate the same set of factors of negative influence [23].

Today, for Ukraine this problem is more relevant than ever. Soils are the most contaminated by explosions. The relevance of the task of ensuring the environmental safety of objects contaminated by explosive substances is undeniable for the world community [24]. The goal of activities in this direction should be to restore the lands of places contaminated by explosions, in particular, places of ammunition disposal and destruction.

Analysis of references and formulation of the problem

The impact on the soil at the place of disposal and subsequent destruction of ammunition is determined by the factors of the explosion and consists of the following physical and chemical components [25–30]:

– ammunition elements formed during explosions, which can fly to a sufficiently large distance and sink into the soil;

– change of relief in places of explosions with the formation of craters or sinkholes;

– compressive impact of the shock blast wave changing the soil density and structure;

– pollution with explosives or fuel being organic by nature,

– pollution with heavy metals;

– contamination with chemical substances being components of the ammunition charge.

It should be noted that radiation contamination in case of destruction of ammunition by explosion is possible only in the case of presence of radioactive substances in the ammunition composition, for example, depleted uranium. The result of the explosion may also be indirect, in particular, due to the ignition of grass or trees. Prevention of such danger is mandatory during the preparation of the explosion.

Previous studies conducted by various authors have shown the presence of air, water, and soil pollution in places where ammunition explosions occur [31–35]. In particular, they have registered the presence of heavy metals – chromium, nickel, lead, zinc, manganese – in the soil [36] and surface waters [37] of military shooting ranges in concentrations exceeding background values.

Nitroaromatic and nitramine explosives, in particular, 2,4,6-trinitrotoluene (trinitrotoluene), hexahydro-1,3,5-trinitro-1,3,5-triazine (hexogen) and octahydro- 1,3,5,7-tetranitro-1,3,5,7-tetrazocine (octogen) [38]. These substances are included in the list of “priority pollutants” by the American Environmental Protection Agency [39]. Their removal from contaminated areas is a priority.

It is also important that the impact of explosions on the natural surrounding environment is prolonged. Yet, it demonstrates cumulative effect. In particular, in previous studies by other scientists, facts of a significant spread of pollutants from the places of their direct influence (localized on the surface) to deep levels of soil and groundwater were proven [24, 39, 40]. The latter should be taken into account when choosing technologies for recultivation of land in places where explosions occur, in particular, in places of ammunition disposal and destruction.

The soil of military shooting ranges is also heavily contaminated with lead because due accumulation of bullets. It can change fundamental soil properties, including pH, cation exchange capacity, moisture content, etc. [41, 42]. In particular, a single fired bullet typically contains 97 % of lead, 2 % of antimony, 0.5 % of arsenic, 0.5 % of nickel, and 0.1 % of copper [43].

In certain cases, the soil of the military shooting range was diagnosed with a lead content of even more than 1000 mg/kg [44, 45]. To assess this value we should mention that the maximum allowable concentration of lead is 32 mg/kg only [46]. In the paper [43] it is indicated that the soil of military shooting ranges contains significant concentrations of Pb^{2+} and Cu^{2+} ions, which can enter the groundwater after dissolution, as well as the air in the form of a finely dispersed aerosol. Lead also tends to accumulate in topsoil because it is a non-mobile contaminant [42, 47, 48].

As a result of the analysis of the existing recultivation technologies for land of ammunition disposal and destruction [49], the authors found that there is currently no any technologies for such objects that would allow solving the entire set of tasks to ensure technogenic and environmental safety. The reason for this is, in particular, the lack of a single comprehensive criterion for assessing the safety of the recultivation process, which would simultaneously take into account the factors of explosion danger, which can be not only the remains of ammunition, but also the soil contaminated with explosive substances, and the factors of ecological danger associated with the entire spectrum of impacts on soil, in particular, compressive impact, contamination with heavy metals and other chemical substances, etc.

The following technologies can be used to restore soils contaminated after explosions [25]:

– civil construction technologies, in particular, the formation of covering or barrier structures on the territory of the place of destruction of ammunition or waste disposal sites;

– biotechnology, including soil bioremediation using microorganisms or fungi and soil phytoremediation using plants;

– chemical technologies, in particular, soil washing with the subsequent separation of dissolved components;

– physical technologies, which are also based on soil washing with mechanical separation of small fragments of ammunition;

– thermal technologies, in particular, thermal desorption of organic explosives.

First of all, it should be noted that the formation of cover structures for the sites of ammunition disposal and destruction is not advisable, because in this way the pollutants are preserved in the soil. At the same time, this approach does not prevent the further movement of pollutants in the soil layer and their further distribution. Therefore, the prospect of using this technology is mainly focused on the provision of temporary protection of the contaminated territory until removal of ammunition remains.

Biotechnologies can be applied to remove soil contaminants in the form of organic explosive and fuel substances or heavy metals [39, 50]. A mandatory condition for the effective use of biotechnology is the presence of pollutants in the form of sufficiently small particles. Instead, after the destruction of ammunition with a discrete filling (pellets, plates, etc.), biotechnologies require preliminary soil preparation in order to remove or reduce large pieces of polluting substance. Also, the consequences of the compressive effect of the shock blast wave, in particular, the compaction of the soil, worsen the working conditions of biotechnology including the inflow of moisture and oxygen deep into its surface.

Due to the high stability of explosive and fuel substances in the soil, bioremediation for them *in situ* (directly at the site of the explosion) is practically impossible. Instead, *in situ* bioremediation methods in the form of phytoremediation [51, 52] demonstrate sufficient efficiency, in particular, when removing heavy metals – lead, cadmium, arsenic, etc. *Ex situ* bioremediation (on a prepared site) using composting or biopiles is effective for organic substances [53].

We should also note the possibility of moving the contaminated soil to a landfill, but in this case, if there are explosive substances in the soil in a sufficiently large amount, its handling requires ensuring special requirements regarding the safety of transportation and storage.

Soil washing can be used both to remove pieces of pollutants and to dissolve and separate their small particles from the soil. However, with this approach the properties of the soil deteriorate significantly. Thus its use is appropriate only in the presence of large amounts of pollution. Instead, sieving the soil will remove large chunks of contaminants that pose a hazard.

The use of thermal desorption is based on the burning of pollutants from the treated soil and can be used both *in situ* and *ex situ*. A significant drawback of this technology is the release of large amounts of nitrogen oxides, which are products of combustion of organic explosives and fuels. Its practical use requires appropriate purification of the gases emitted into the atmosphere.

In some cases, the presence of explosive objects in the soil poses the task of their identification and removal before the soil restoration process begins. The search for such items is most expedient to be carried out using remote control methods. To neutralize them (or in certain cases to prove their absence) they can also use controlled explosion technology.

Based on the results of the analysis of the technologies mentioned above in comparison with the factors of negative impact on the soil of ammunition disposal and destruction sites, it can be concluded that there is currently no unified technology for recultivation of the lands of such objects, which would allow solving all the tasks that have arisen. So, it is necessary to create a unified set of environmental protection technologies and methods of their application in order to quickly and effectively remove all available pollutants from the soil, taking into account the factors of the explosion hazard, which can be not only the remains of ammunition, but also the soil contaminated with explosives.

The purpose and objectives of the study

The purpose of the study is to reduce the level of technogenic and ecological danger at the sites of ammunition disposal and destruction.

To achieve it the following tasks were set and solved:

– determination of the significant factors of technogenic and ecological danger in the process of recultivation of the lands of ammunition disposal and destruction sites;

– development of technique of land recultivation of places of ammunition disposal and destruction.

Materials and methods

The object of the study is the impact of ammunition disposal and destruction sites on the natural surrounding environment.

The subject of the study is the technique of land recultivation of places of ammunition disposal and destruction.

Methods of system analysis were used to determine the significant factors of technogenic and ecological danger in the process of recultivation of land at the sites of ammunition disposal and destruction.

The following methods were used during the development of the technique of land recultivation of places of ammunition disposal and destruction: the method of simulation modeling in assessing the safety level of the process of recultivation of the lands of the ammunition disposal and destruction sites; the method of operational monitoring of territories where an environmental emergency has occurred, using unmanned aerial systems (UAS) during the development of the stage of monitoring the lands of the sites of ammunition disposal and destruction; the method of remote demining during the development of the stage of demining the lands of ammunition disposal and destruction sites; the method of phytoremediation in the development of the stage of biological treatment of the lands of the ammunition disposal and destruction sites.

For the active factors of the operation of the ammunition disposal and destruction site, the safety level was assessed based on the indicators of the probability of explosion ρ, the striking power of the explosion – excessive pressure P in the air shock wave, as well as the level of land degradation of the ammunition disposal and destruction site s_d. Partial criteria for safety evaluation with mentioned parameters are presented in a formalized form with formulas (1)–(4):

$$\chi_\rho = \frac{\rho}{\left[\rho\right]} = \bar{\rho} \le 1\,, \tag{1}$$

where $\left[\rho\right]$ – the maximum allowable value of the considered parameter ρ selected according to the scale presented in Table 1 [54];

$$\chi_P = \frac{P}{\left[P\right]} = \bar{P} \le 1\,, \tag{2}$$

where $\left[P\right]$ – the maximum allowable value of the considered parameter P selected according to the scale presented in Table 2 [55];

$$\chi_s = \frac{s_d}{\left[s_d\right]} = \bar{s}_d \le 1\,, \tag{3}$$

where $\left[s_d\right]$ – the maximum allowable value of the considered parameter s_d selected according to the scale presented in Table 3.

An integral assessment of the level of safety was carried out according to the criterion of the assessment of the level of safety of recultivation process of the land of ammunition disposal and destruction site in the following formalized form

$$\chi : \begin{cases} \chi_{\rho} \le 1; \\ \chi_{P} \le 1; \\ \chi_{s} \le 1. \end{cases} \quad (4)$$

Using the above-mentioned list of criteria parameters, the method of assessing the level of safety of the recultivation process of the land of ammunition disposal and destruction site was used, which is based on a step-by-step verification of compliance with safety conditions in the *n*-dimensional space of factors $F_i \in \Phi$, $i = 1...n$, where *n* is the number of factors that change according to the recultivation process program, with the provision of a generalized conclusion on the level of safety [56].

Results and discussion

In general we define the technique as "a set of interrelated methods and techniques for expedient performance of any work", which must be performed to achieve the goal [57].

The algorithm of the technique of land recultivation of places of ammunition disposal and destruction is presented in Fig. 1. It is composed of three levels according to the hierarchical principle.

Level I – procedures for monitoring the lands of the sites of ammunition disposal and destruction. At this stage, sources of explosive danger are identified on the territory of ammunition disposal and destruction site and the initial level of safety of the recultivation process of its land is assessed using the integrated synergistic criterion for assessing the level of safety.

Level II – procedures for demining lands of ammunition disposal and destruction sites. At this stage, operations are performed by specialized pyrotechnic units.

Level III – procedures for biological treatment of lands of ammunition disposal and destruction sites. Phytoremediation operations are performed at this stage.

Let's formulate the main provisions of the technique of land recultivation of places of ammunition disposal and destruction step by step.

Stage 1. Monitoring of the lands of ammunition disposal and destruction site.

Stage 1 corresponds to the preparatory stage of recultivation and is implemented on the basis of the principles of operational monitoring of territories where an environmental emergency has occurred, using UAS [58]. The possibility of using the experience of developing similar systems for monitoring fire zones on the territory of large objects (solid waste landfills, etc.) [56] seems promising.

The technical basis of the UAS for monitoring the lands of the ammunition disposal and destruction sites is in the application of control of the state of danger of the territory with the help of unmanned aerial vehicles (UAV) in real time.

The improved functional scheme of the UAS is presented in Fig. 2.

The automated control device installed on the UAV must include a control and measurement unit with appropriate control sensors, a subsurface geolocation unit, a video surveillance unit, a location setting unit, a unit for transmitting information to the ground monitoring center, a power supply unit, and an antenna unit.

The ground monitoring center should include a computerized analytical system for determining the level of danger of the investigated area, a unit for determining the location of the ground monitoring center, a unit for controlling the movement of UAVs, a unit for receiving and analyzing information from UAVs, a unit for storing information, and an antenna unit.

The process of monitoring the lands of the ammunition disposal and destruction sites includes the following operations:

– UAV launch;
– UAV flight control from the monitoring center;
– control of UAV location through the global navigation satellite system;
– control of the level of danger with the block of control and measurement sensors of UAV;
– video surveillance from UAV;
– ground monitoring center receiving information about the state of the territory from UAV;
– analysis of received information;
– information storing.

The use of georadiolocation research allows to get a color image – radar chart. Different colors on the radar chart show different levels of the amplitude of the signal reflected from the soil layer at the appropriate depth, which allows to visually (or with the use of image analysis tools) find the position of dangerous explosive objects or their separate parts.

Table 1 – Scale for selection of the maximum allowable value of the probability of an explosion

Probability level	Maximum allowable value $[\rho]$
Very high	0.9
High	0.7
Average	0.5
Low	0.3
Very low	0.1

Table 2 – Scale for selection of the maximum allowable value of the excessive pressure in the air shock wave

Level of lesions	Maximum allowable value $[P]$, kPa
Extremely heavy	> 100
Heavy	100
Medium severity	60
Light	40
Insignificant	20

Table 3 – Scale for selection of the maximum allowable value of the level of land degradation of the ammunition disposal and destruction site

Level of land degradation	Maximum allowable value $[s_d]$
Very high	0.9
High	0.7
Average	0.5
Low	0.3
Very low	0.1

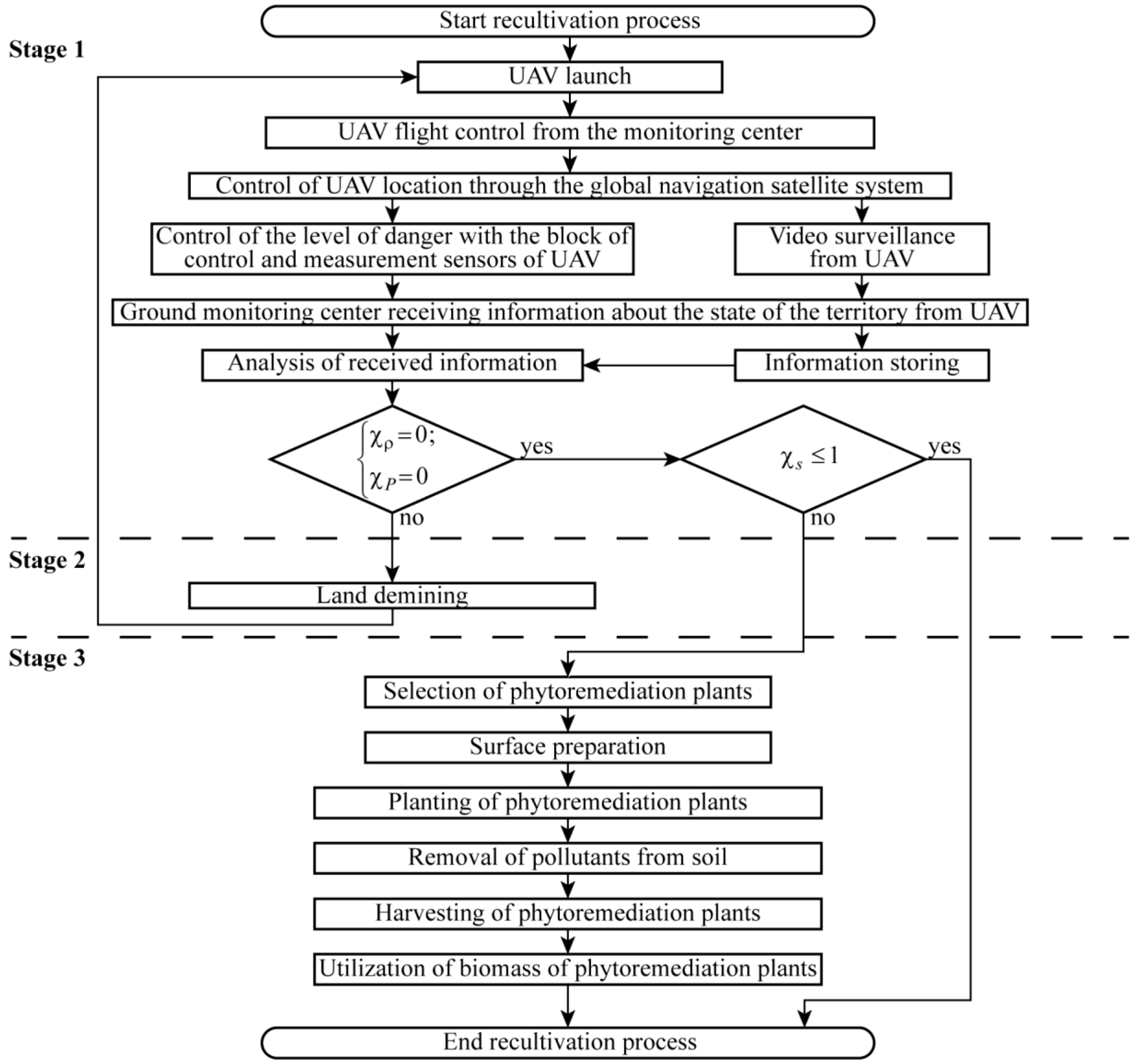

Figure 1 – Control algorithm of the technique of land recultivation of the sites of ammunition disposal and destruction

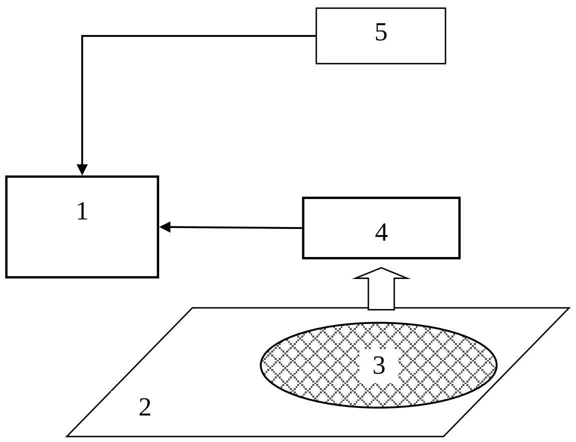

Figure 2 – An improved functional diagram of the UAS for monitoring the lands of ammunition disposal and destruction sites:
1 – ground monitoring center; 2 – territory under investigation; 3 – directly affected lands; 4 – UAV; 5 – global navigation satellite system

Subsequently, the level of danger of the surveyed territory is determined in a partial (for each dangerous explosive object) and integral (for the entire surveyed territory) form using the method and criteria for assessing the level of danger of ammunition disposal and destruction sites presented in section 4.

The result of Stage 1 implementation is a map of the location of the sources of danger to be used by specialized units during demining supported with the specified values of following parameters:

– criteria for assessing the level of explosion danger for each dangerous explosive object, determined with formulas (1) and (2), as well as for the entire territory as a whole;

– the criterion for assessing the level of ecological safety for the studied territory, determined with formula (3);

– the integral criterion for assessing the level of danger determined with formula (4).

Stage 2. Demining of the lands of the ammunition disposal and destruction sites.

Stage 2 corresponds to the mining and technical stage of recultivation and is implemented by the specialized pyrotechnic units of the State Emergency Service of Ukraine using the results of the monitoring carried out in Stage 1. The most important problem that significantly slows down the process of land recovery at the sites of ammunition disposal and destruction is the slow speed of surveying and demining of territories, contaminated with explosive objects. To solve this problem, it is proposed to use specialized equipment for remote demining at Stage 2 [59, 60].

The use of equipment for remote demining makes it possible to significantly increase the level of safety for pyrotechnic units and the speed of processing the territory without losing the quality of demining. These systems are effective in removing anti-personnel mines, and can be equipped with a cultivator that carries out secondary soil treatment. This leads to better soil preparation for the implementation of Stage 3.

After demining operations accomplished the Stage I operations are to be repeated, after which a reassessment of the level of safety of the ammunition disposal and destruction sites is carried out.

As a result of Stage 2 operations, the territory of the ammunition disposal and destruction site is prepared for recultivation, for which the values of the criteria for assessing the level of safety in the direction of the explosion hazard for the entire territory as a whole are equal to zero.

Stage 3. Biological treatment of the lands of ammunition disposal and destruction sites.

Stage 3 is the longest of all stages. The implementation of Stage 3 can be started immediately after the successful completion of Stage 2.

Stage 3 is based on the method of phytoremediation. It consists in the planting and subsequent cultivation of special plants that accumulate heavy metals and organic explosives on contaminated land.

After pollutants accumulation, the biomass of the plant cover must be collected and disposed at specially adapted sites. Accordingly, the duration of the biological treatment stage is determined by the duration of the biological cycle of development and growth of plants accumulating pollutants.

The advantages of the phytoremediation method are low cost and safe use for the natural surrounding environment. As it was noted biological purification should be made simultaneously for removal of heavy metals and organic explosive substances.

For removal of heavy metals, it is proposed to use the technology of biological purification [61] based on the extraction of heavy metals from technogenically polluted soil through their phytoextraction by curly parsley plants. Under certain conditions, the process of sowing curly parsley may be made during Stage 2 remote demining operation by means of remote demining systems equipped with planters.

Phytoextraction method is not suitable for removal of organic explosive substances, since these substances must be split to ensure absorption by the plant. Based on this, it is proposed to use the method of biodegradation, where colonies of microorganisms capable of breaking down explosives are formed on the roots of plants. The use of grass crops in this case is not appropriate, as their root system does not provide enough space for a colony of microorganisms. Thus it is proposed to use the technology [62] based on the use of transgenic poplar and aspen trees. The advantages of the proposed plants are their adaptability to the natural conditions of Ukraine, which will allow the implementation of the proposed method to solve the problem of restoring the lands of the territory of our country, disturbed as a result of the military aggression of the russian federation. After cleaning the soil, the biomass of curly parsley and transgenic trees of the poplar and aspen species must be collected and disposed as biofuel.

After carrying out operations on biological treatment of land, a re-evaluation of the level of safety of the ammunition disposal and destruction site is carried out with the definition of:

– the criterion for assessing the level of safety on environmental safety of the studied territory, determined with formula (3);

– the integral criterion for assessing the level of safety, determined with formula (4).

The result of the Stage 3 operations is the territory of the ammunition disposal and destruction site prepared for economic use. Thus the values of the criteria for assessing the level of safety on the explosion hazard for the entire territory as a whole are to be equal to zero, and the values of the criteria for assessing the level of safety on environmental safety of the studied territory and integral of the safety level assessment criterion are to be less than or equal to one.

Conclusion

For the first time the technique of land recultivation of places of ammunition disposal and destruction was developed. It includes three stages:

– Stage 1 – monitoring of land of places of ammunition disposal and destruction based on unmanned aviation monitoring system;

– Stage 2 – demining of land of ammunition disposal and destruction by specialized pyrotechnic units of the State Emergency Service of Ukraine using the results of the monitoring conducted at Stage 1;

– Stage 3 – biological treatment of land of the ammunition disposal and destruction using the phytoremediation method.

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МЕТОДИКА РЕКУЛЬТИВАЦІЇ ЗЕМЕЛЬ МІСЦЬ ЗНЕШКОДЖЕННЯ ТА ЗНИЩЕННЯ БОЄПРИПАСІВ

Показано актуальність дослідження й необхідність розробки методів, що дозволяють відновлювати землі місць знешкодження та знищення боєприпасів при застосуванні заходів з їх рекультивації. Визначено критерії оцінювання рівня безпеки процесу рекультивації земель місць знешкодження та знищення боєприпасів на основі використання нормативного підходу та значущі показники, а саме: ймовірність вибуху, величина надмірного тиску у повітряній ударній хвилі та рівень деградації земель місця знешкодження та знищення боєприпасів.

Вперше розроблено методику рекультивації земель місць утилізації та знищення боєприпасів, яка включає три етапи: 1 етап – моніторинг території місць утилізації та знищення боєприпасів на основі безпілотної авіаційної системи моніторингу; 2 етап – розмінування території утилізації та знищення боєприпасів спеціалізованими піротехнічними підрозділами ДСНС України за результатами моніторингу, проведеного на 1 етапі; 3 етап – біологічна очистка землі утилізації та знищення боєприпасів методом фіторемедіації.

Ключові слова: рекультивація земель, знешкодження та знищення боєприпасів, небезпека вибуху, моніторинг, розмінування, фіторемедіація.

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