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RISK ASSESSMENT METHODOLOGY FOR AGROECOSYSTEMS IN THE CONDITIONS OF TECHNOGENIC POLLUTION

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Abstract

Currently, the world scientific community is faced with the task of identifying and minimizing environmental risks of the impact of anthropogenic factors on ecosystems, especially agricultural ones (A.A. Muzalevsky et al., 2011). The keystone of environmental risk assessment is estimated probability of the adverse effects of various nature (radiation, chemical and biological agents) and prevention of their negative impact. The most common sources of pollution of agroecosystems are precipitation from industrial and transport emissions, industrial wastewater, sewage sludge, organic and mineral fertilizers and plant protection products, dumps of ash, slag, ores and slime (S.C. Barman et al., 2000; Yu.N. Vodyanitsky et al., 2011; E.C. Rowe et al., 2015). Such risks are usually assessed situationally, and methods used are applicable for specific factor (agent) acting in analyzed case and object of its influence. The purpose of the presented theoretical research was to develop a unified methodology for assessing agroecological risks caused by anthropogenic pollutants. The developed methodology uses mathematical modeling methods and is based on the principles and criteria ensuring the safety of agricultural ecosystems in conditions of man-made pollution. Atmospheric pollutants are the main source of man-made impact. Temporal patterns of their impact vary from acute (e.g. upon accidents) to chronic that should be taken into account. Agroecosystem productivity, as an integral indicator, is a basic criterion for assessing agroecological risks. The methodology includes a four-step algorithm: i) hazard identification based on available agroecosystem data with identification of the sources and nature of the hazard and key affected components; ii) impact assessment by measuring or calculating its intensity, duration, and mode of exposure; iii) a dose-effect assessment by a relationship between the degree of the impact and the probability of its negative consequences; iv) risk characterization, including reliability analysis of the obtained data, estimates of risk from individual factors and their combinations, and calculation of a probability of adverse effect for each agroecosystem component. The choice of a method for assessing agroecological risks (deterministic, probabilistic of the 1st and 2nd type, and integral probabilistic) is substantiated based on the indicator pools, risk criteria and the degree of technogenic impact. Risk characterization includes its classification in terms of an environmentally acceptable level as per maximum allowed concentrations and semi-lethal doses (LD_{50}). For each step, risk uncertainties are accounted. Agroecological risk assessment algorithm includes i) database analysis and selection of agent-specific and exposure-specific values of the effects; ii) estimates of meteorological parameters of pollutant diffusion under specific release conditions; iii) calculated or experimental estimates of pollutant deposition on the ground depending on peculiarities of the impact; iv) calculation or experimental assessment of radionuclide or chemical toxicant contaminations; v) calculation or measurement of the effects of radionuclides or chemical pollutants on the agroecosystem components. The proposed approaches to assessing agroecological risk are applicable to a wide class of environmental problems.

Keywords: agroecosystem, agricultural products, heavy metals, radionuclides, technogenic factor, agroecosystem components, impact level, dose-response relationships, mathematical models

Present status and development of nuclear power industry, metallurgy, transport, chemical and other industries, the activities of which (including man-made accidents) lead to environmental pollution, poses the task to identify and minimize environmental risks associated with their impact on ecosystems, especially agricultural [1-3]. Currently, environmental risk is the main generalized indicator for making management decisions. This requires adequate calculation methods, which, in turn, necessitates understanding of the basic mechanisms of the organization and functioning of ecosystems [4-6]. Such methods can provide a quantitative assessment of environmental risk, significantly reduce its uncertainty, and help find ways to manage risks at all levels of ecosystems [7-9]. The main role of environmental risk assessment is to determine the likelihood of various effects in ecosystems as a result of the influence of technogenic (radiation, chemical, biological) factors for taking preventive measures [10-12].

Agroecosystems are communities of cultivated plants and animals and their habitats, artificially created by man to obtain foodstuff and row materials. Human health directly depends on the quality of food products [13-15]. This necessitates restriction and prediction of the possible negative impact of technogenic factors of different nature on agricultural land and products [16-18]. A balanced composition of trace elements (including heavy metals) in soils is important for the optimal growth of agricultural plants [19-21], while the increased concentrations of heavy metals negatively affect physiological processes [22-24]. Mostly, the sources of pollution of agroecosystems are aerial fallout from industrial and transport emissions, industrial wastewater, sewage sludge, organic and mineral fertilizers and plant protection products, heaps of ash, slag, ores, sludge [25-27].

The features of the current ecological situation in the agro-sphere are the simultaneous influence of a large number of factors of different (physical, chemical and biological) nature, their low impact and chronic character [28-30]. Increased concentration of pollutants negatively affects the productivity of agroecosystems, which largely determines their stability [31-33]. In this regard, it is necessary to assess the likelihood of reversible or irreversible changes in the structure of the agroecosystem and the functions of its components in response to technogenic impact [34-36].

The qualitative and quantitative indicators characterizing the likelihood of negative effects include environmental (agroecological) risks, which currently serve as priority generalized parameters of technogenic impact on agroecosystems [37-39]. Quantitative indicators can be standardized through the development of standards for risk (acceptable risks) and further used for a comprehensive assessment of the agroecosystem component states [40-42]. Two currently used indicators, MPC/TPC (maximum permissible concentration/tentative permissible concentration), have certain disadvantages, since they do not distinct the contributions of natural and technogenic components, and do not regard the climatic and geochemical features of the region [43-45].

Previously, we have developed the methodology for assessing radiation risks in agricultural ecosystems and used it to calculate the agroecological risk for crops at ^{137}Cs contamination from an accident at a radiation hazardous facility [9]. However, it should be noted that the existing methods for assessing agroecological risks make the results hardly comparable, which hinders to obtain reliable estimates of negative technogenic impact on the components of agroecosystems [46-48]. In addition, technogenic risk assessments are performed, as a rule, situationally for a specific case and by the methods applicable for a certain factor (agent) in specific conditions and for a certain object of the impact [10].

This theoretical study aims to develop a unified methodology for assessing agroecological risks from technogenic pollution.

Stages of assessing agroecological risks from technogenic pollution. Prediction and reduction of negative impact of a technogenic factor on the components of agroecosystems should be based on the risk assessment using generalized quantitative or qualitative criteria. These criteria should assess the probability of 50% death of plants and a decrease in yields under a certain degree of technogenic pollution. [49-51].

Assessment of agroecological risks to agriculture under man-made pollution usually includes four stages [52-54]. Let's consider these stages given the task of unifying the methodology of risk analysis, regardless of the nature of technogenic pollution.

I. Hazard identification. This stage includes the collection and generalization of available information in order to determine the sources and the nature of pollution (radiation, chemical, biological) and to evaluate the degree of the impact. Particular attention should be paid to the most susceptible components of the agroecosystem, i.e. the "critical" components [55, 56]. The criteria to choose such components are the sensitivity to one or another negative factor and the response to the impact. Plant sensitivity is the ability to respond to external irritation manifested in different forms.

When choosing a priority pollutant or a group of pollutants for agroecological risk quantitative assessment, it is necessary to focus on the criteria characterizing the concentration of pollutants in the "critical" components, the toxic properties of substances, the ability to migrate, and the likelihood of a negative effect due to various exposure conditions. All factors (physical, chemical, etc.) should be taken into account, in particular, the migration of the pollutant, its transformation, the time of exposure [58-60]. When identifying man-made risk factors for the components of an agricultural ecosystem, it is necessary to rely on the design documentation of the pollution source and the results of environmental monitoring or special studies.

1. Dose of γ-irradiation leading to a 50% decrease in the yield of various agricultural crops [57]

Crops	Absorbed radiation dose, Gy
Winter rye, horse beans	5-8
Winter and spring wheat, barley, oats, maize, peas, soy	10-20
Sunflower, rapeseed	20-30
Buckwheat, millet, rice	30-50
Cotton plant, tomatoes	50-80
Cabbage	80-120
Potato	120-150
Sugar and table beets	180-220
Carrot	250-300
Flax	300-400

2. Probable loss of grain yield (%) **upon exposure to ionizing radiation at different plant development stages** [57]

Stage	Total dose of γ- and β-irradiatin, Gy						
	5	10	20	30	50	100	200
			Winter rye				
Tillering	5	15	40	70	95	100	100
Stem extension	25	80	95	100	100	100	100
Heading—flowering	15	40	75	95	100	100	100
Milk ripening	5	6	8	10	15	30	50
			Winter and spring wheat, barley, oats				
Tillering	5	8	27	50	95	100	100
Stem extension	9	20	50	75	90	100	100
Heading—flowering	7	15	35	50	75	95	100
Milk ripening	4	5	7	10	15	30	50
			Maize				
6-8 leaves	15	25	40	55	85	100	100
Tasseling	30	45	55	70	95	100	100
Milk maturity	4	10	20	30	40	60	80

Hazard identification includes generation of a preliminary scenario of the influence of a technogenic factor on "critical" components which describes the physicochemical properties of the acting substance, the mode, intensity and duration of exposure. For each identified technogenic factor, a list of indicators (effects) is established, reflecting the violation of the functioning of the components of the agroecosystem. In this, reliable published research data on negative effects can be the information sources. The indicators widely used as the intensity of plant biomass gain (productivity) and the biomass at a certain point in time (yield). Under radiation impact on crops, these parameters are estimated most accurately (Tables 1, 2). For low technogenic impact, the significant indicators are those observed at lower levels of biological organization (organismic, cellular and subcellular) [61, 62].

The integral risk for the components of the agrarian ecosystem should be assessed on the basis of generalized information, including data on the impact of each risk factor. Already at this stage, preliminary decisions on agroecological risk management can be made, including the termination of further analysis due to the insignificant danger or the sufficiency of the initial assessments, a more detailed hazard analysis and risk assessment, and the development of preliminary recommendations to reduce the hazards [9].

II. Impact assessment. The assessment includes measurement and/or calculation of the intensity, duration, and the ways of the impact on the agroecosystem components. The intensity of the radiation factor means the dose of irradiation, for a chemical factor it is the concentration or dose of a chemical substance, for a biological factor it is the number of biological agents entering the body per unit of time. The source of information on the intensity of the technogenic factor is the accumulated scientific data obtained both for the previous period and as a result of the experiments, as well as data from published scientific works and reports. The atmospheric route of spreading radionuclides, chemicals and biological agents is one of the main sources of technogenic impact. In assessing exposure loads, the radiation exposure for less than 2 weeks is identified as acute, up to 7 years as subacute, more than 7 years as chronic [10].

Assessment of the technogenic impact includes a sequence of actions, i.e. i) analysis of generalized information on the impact levels, including the values of the response of agroecosystem components at different levels of technogenic impact; ii) determination of meteorological parameters of the model for the behavior of air impurities for specific conditions of their release (atmosphere stability class, wind speed at the height of release, aerodynamic roughness of the underlying surface as per MU 2.6.5.010-2016) [63]; iii) quantitation of the impurities deposited on the earth surface, depending on specificity of pollution; iv) assessment of the pollution of the aboveground plant biomass and soil with priority substances; v) calculation or measurement of the degree of impact of priority substances on agricultural plants.

The second stage results in a quantitative description of the intensity, frequency and nature of the technogenic impact on the components of the agroecosystem.

III. Assessment of the dose-effect relationship. This reflects the quantitative relationship between the level of technogenic impact on the components of agrarian ecosystem and the likelihood of occurring negative effects of different severity [9].

The dose-effect relationship assessment is based on accumulated scientific data, mathematical models and agroecological safety criteria. This information should characterize the dependence of negative effects towards the agroecosystem components on the specific extend of the technogenic factor impact. The degree of impact should be chosen given negative effects from minimal impact, as well as different duration of exposure (acute, subacute, chronic). The response of biotic components above the acceptable environmental risk is characterized by a median lethal dose (LD_{50}) justified by survivability or by maximum permissible concentration (MPC) [9, 10].

This stage results in the models of dose-effect relationship which contain quantitative parameters and descriptions of the "critical" components and allow us to assess the likelihood of negative effects of the established technogenic factors.

The choice of methods for agroecological risk models is determined primarily by the level of information support (a set of risk assessment criteria, levels of anthropogenic impact). Deterministic, probabilistic and integral probabilistic methods are mostly used in assessing risk [9]. By deterministic method, the risk indices are assessed, which are the ratio of the dose load to the risk criterion value (the level of acceptable environmental risk). The advantages of the method are relative simplicity and a small amount of input data (only two indicators are required). The disadvantages are the lack of accounting for uncertainties of indicators and, as a consequence, rough estimates [4]. Probabilistic methods are of the 1st and 2nd type. The 1st type method uses a point estimate as a risk criterion. The probabilistic method of the 2nd type is advisable to apply when the identification of the technogenic factor distribution is difficult due to lack of data or the need for a quick assessment [4, 10]. The integral probabilistic method takes into account the uncertainties of the parameters inherent in the object and the environment, which determine the intensity of the impact [9].

IV. Risk characterization. The stage includes an analysis of the hazard data reliability obtained at the previous stages. Based on the calculated quantitative indicators of the dose-effect relationship and comparison with the data of similar studies, a conclusion is made about the degree and probability of environmental risk for the "critical" component or the agroecosystem as a whole. At this stage, the risk is classified and its compliance with the acceptable environmental level is assessed (the use of MPC and LD_{50} values) [9, 10].

The analysis of sources of uncertainty is an integral part of the agroecological risk assessment, which significantly increases the reliability of the obtained results. Uncertainty may be due to i) lack of information about the problem as a whole; ii) the absence or inaccuracy of the data necessary to determine the level of risk; iii) lack of research and theoretical knowledge for an appropriate conceptual or calculation model; iv) lack of knowledge on the true statistical distribution of data [9].

Probable uncertainties of hazard identification include i) an insufficient information about the studied components of the agroecosystem; ii) incorrect parameters of the established risk factors; iii) lack of data on negative response of the agroecosystem components; iv) incorrect formation of the original data set. The main sources of uncertainty in "impact assessment" include i) inappropriate choice of exposure models or input parameters; ii) errors in the choice of ways of exposure. Errors in determining "critical" components and the reliability of negative effects can be sources of uncertainty at the stage of dose-effect assessing [9].

The assessment of the uncertainty of agroecological risk makes it possible to make decisions without constraints (first level), decisions aimed at minimizing risk, or specific decisions on risk management (second level), or provides evaluative data that are used to simulate the situation (third level) [9, 10].

The final results of all stages are the basis for making decisions on the management of agroecological risks from man-made pollution.

Algorithm for assessing agroecological risks from technogenic pollution. The generalized algorithm for assessing agroecological risks is as follows.

The first step is the database (DB) analysis to sample quantitative parameters characterizing the considered negative effects depending on degrees of technogenic impact.

The second step includes determination of meteorological parameters of the air pollutant behavior model for specific emission conditions (atmospheric stability class, wind speed at the emission height, the aerodynamic roughness of the underlying surface) as per MU 2.6.5.010-2016 [63]. The atmosphere stability class is determined according to Pasquill [64].

The third step includes quantitation of pollutant deposition on the earth surface (by calculation or experimentally), depending on the character of the technogenic impact. It should be noted that at present, the assessment of the inflow of radioactive and chemical substances to the earth surface is most fully developed [65, 66].

The density of the fallout of radioactive or chemical substances is determined by the formula:

$$As_n(x) = Q \cdot (V_g \cdot G(x)), \tag{1}$$

where Q is integral release of radioactive or chemical substances, g or Bq; V_g is the rate of gravitational settling of radioactive or chemical substances, m/s; G(x) is meteorological dispersion factor at a distance of x meters from the emission source, s/m^3 [65].

The parameter of meteorological dispersion at different distances x from the emission source is calculated at the underlying surface level (z = 0) on the axis of the fallout trace (y = 0) [65]:

$$G(x) = \frac{f_d(x) \cdot f_s(x) \cdot f_w(x)}{\pi \cdot \sigma_y(x) \cdot \sigma_z(x) \cdot U} \cdot \exp^{\left(-\frac{H_g^2}{2 \cdot \sigma_z(x)}\right)}, \tag{2}$$

where x is distance to the source of emission, m; U is the wind speed at the emission height, m/s; Hg is the height of the discharge above the ground, m; σ_z, σ_y are standard deviations of the pollutant dispersion of in the ejection cloud to the direction of corresponding coordinate axes, m [67]; f_d or f_{tr}, f_s, f_w are corrections for decay or chemical transformation, deposition and washing out of pollutants from the atmosphere by precipitation.

The expression for the correction for a radionuclide decay or a toxicant chemical transformation is as follows:

$$f_d(x) = \exp(-\lambda \cdot x/u), \tag{3}$$

where λ is the constant of radioactive decay for a specific radionuclide or constant of chemical transformation, 1/s; x/u is the time of cloud movement to the point with a distance x from the ejection site [65].

The correction for gravity settling is calculated as

$$f_s(x) = \exp\left[-\sqrt{\frac{2}{\pi}} \cdot \frac{V_g}{u} \int_0^x \left(\frac{1}{\sigma_z(x) \cdot \exp(0.5 \cdot h^2 \cdot \sigma_z^{-2}(x))}\right) dx\right], \tag{4}$$

where vg is the gravitational settling velocity, m/s (0.001 for aerosols, 0.02 for elemental iodine, 0.0005 for organic iodine, 0 for inert gases) [65].

The correction for the washing out of chemical toxicants or radioactive substances from the atmosphere is as follows:

$$f_w(x) = \exp(-\Lambda \cdot x/u), \tag{5}$$

where Λ is the average annual constant for the removal of impurities from the atmosphere by precipitation, averaged over the year given the type and duration of precipitation during the year, 1/s [65].

At the fourth stage, the content of pollutants in the agroecosystem components is calculation or determined experimentally. The concentration of radionuclides (Bq) or chemical toxicants (g) in the aboveground biomass for any day after the release q(t) is calculated as follows:

$$q(t) = \frac{K_z(t_o) \cdot \exp^{[-(\lambda+\lambda_{ec})(t-t_o)]}}{a \cdot (t - t_{bg}) \cdot 4} \cdot As_n(x), \tag{6}$$

where λ is the decay constant of radionuclides or chemical transformation constant of toxicants, 1/day; λ_{ec} is the rate constant for the loss of radionuclides or chemical toxicants from the aboveground biomass, 1/day; t_0 is the number of days from the beginning of the year to the fallout date; t is the number of days from the beginning of the year to the date to determine the main parameters of the agroecosystem components (e.g. plant height and biomass, the pollutant concentration in the main components, dose characteristics for the aboveground biomass); 4 is the conversion factor to change from air-dry mass to native mass.

The coefficient of initial retention of radionuclides or chemical toxicants by the aboveground plant biomass is calculated as

$$K_z(t_0) = 1 - \exp^{(-\mu \cdot \rho(t_0))}, \tag{7}$$

where μ is an empirical constant of the retention of radionuclides or chemical toxicants by vegetation cover (2.8 m^2/kg air-dry mass), $\rho(t_0)$ is the aboveground biomass at the fallout time t_0, kg/m^2.

The plant aboveground biomass at the fallout time is calculated as given in [67]:

$$\rho(t_0) = a \cdot (t_o - t_{bg}), \tag{8}$$

where a is the rate of biomass growth per unit of crop area, kg/(m · day) (Table 3); t_{bg} is the number of days from the beginning of the growing season of certain agricultural plant species (see Table 3).

3. Growing season parameters and the rate of biomass growth for some crops [10]

Crop	Start of vegetation season	Time form the beginning of growth (t_{bg}), days	Rate of biomass gain, kg/(m^2 · day)
Spring wheat	May 15	135	6×10^{-3}
Spring rye	May 15	135	6×10^{-3}
Barley	May 15	135	3×10^{-3}
Oats	May 15	135	3×10^{-3}
Potato	May 25	145	9×10^{-4}
Beet	June 5	155	6.4×10^{-4}
Cabbage	May 20	140	6.4×10^{-4}
Hayfield grass	April 15	105	6.4×10^{-4}

The fifth step of the suggested algorithm includes calculation or measurement of the pollutant impact on the agroecosystem components. In the release of chemicals, the calculated concentration of toxicants (6) is deemed the starting point to determine the effect of pollutants on plants. To assess the effect of radionuclides on agricultural plants, it is necessary to consider two main sources of radiation [68, 69], an infinite source of finite thickness equal to the plant height with a uniform distribution of activity (the source consists of plants contaminated with radionuclides and atmospheric air between plants as a single environment) and an endless source of radiation with a mass thickness of 0.5 g/cm^2 [68] from radionuclides deposited on the soil due to incomplete retention by the aboveground plant parts.

In more detail, methods for assessing the impact of radionuclides from various sources on agricultural plants are described by Perevolotskaya et al. [9].

To conclude, it should be noted that, given the world trends in industry and industrial agriculture, the probability of complex technogenic pollution [11, 14], including potentially hazardous to human health [15, 18, 20], objectively increases. To control the threats of technogenic impact, it is not enough to have a set of methods suitable for analysis of a particular case. The methodology we propose establishes criteria and approaches that provide assessment of agroecological risks from technogenic pollution, regardless of their nature [70, 71]. The described methods for creating assessment models are applicable to a wide range of environmental challenges, including human health protection [72, 73], and can be the basis for managing man-made risks in the agro-industrial complex, environmental protection, control and forecasting environmental pollution.

Thus, we suggest a unified methodology of assessing risks of various technogenic pollution for agricultural ecosystems. The methodology is based on the principles and criteria for minimizing threats and ensuring the safety of agroecosystems subjected to technogenic impact. Mathematical modeling is used as an analytical tool. The methodology defines approaches and criteria for agroecological risk assessing. A methodological framework is proposed that allows one to study the dynamics of dose-dependent effects of various factors towards each component of the system and to undertake management decisions to minimize agroecological risks.

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