Assessment of Entry of ^{90}Sr into Plants in Case of a Heterogeneous Radiation Contamination of Ecosystems

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Introduction

Many places of the world are contaminated with radioactive isotopes. According to the recent report (Radiation 2013), there were 107,548 thousand m^2 of land contaminated with radionuclides in the adjoining areas of Rosatom enterprises, till the end of the year 2012. Besides, there were 11,312 settlements in the territory of Russia contaminated because of the Chernobyl accident. According to the State report "On the condition and protection of the environment of the Russian Federation in 2011" (On the condition 2011) a moderately dangerous contamination with metal complex was noted on 9% of examined lands and a dangerous contamination was noted on 3.5% of examined lands in 2011. Often polluted are suburban lands that are most suitable for a high-tech production of fresh vegetables, individual construction, gardening, and homesteading. Residents of settlements located outside the evacuation zone are under the necessity to grow potatoes and vegetables on contaminated soil of household plots or use the received land shares. For example, when the state farm "Bulzinsky" was liquidated, the former workers of the state farm obtained the ownership of land shares (9 ha each) in the territory adjacent to the East-Ural radioactive trace.

For hygienic regulation in radiation accident zone, the forecasting of the developmental programmes for radiation situation under different scenarios of environmental management and rehabilitation is necessary. Modern methods of forecasting are based on statistical analysis of historical data and methods of extrapolation of the discovered dependencies. However, in real conditions, conventional statistical analysis methods may not be suitable. This is connected, in particular, with the heterogeneity of the contamination of the territories.

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Problems of Entry Forecasting of ^{90}Sr and Other Radionuclides into Plants in Case of a Heterogeneous Contamination

The heterogeneity of radioactive contamination, a significant variation in soil and vegetation contamination levels was noted both in the territory of Belarus (Shchur et al. 2015) and in Trans Urals. An example of an area with a strongly heterogeneous radioactive contamination is the East-Ural radioactive trace, formed in 1957 as a result of the precipitation of a radioactive cloud, following the explosion of a waste container at a radiochemical enterprise producing weapons-grade plutonium, which is now known as the Production Association “Mayak.” Already at the first stage of research in the area contaminated as a result of activity of “Mayak” PA, it was noted that the distribution of values of radionuclide activity in natural objects and plant products do not comply with Gauss’ law (Shamov et al. 2012). During the radiation surveys and other studies, a lot of evidence of local features was obtained to ascertain the distribution of radioactive contamination density associated with the influence of meso and micro landscapes and other natural factors (Beacon 2005). The levels of soil contamination with radionuclides within one settlement can also vary greatly (Kazachonok 2015). In the survey of settlements in the area of influence of the “Mayak” PA, in most cases, the ^{90}Sr and ^{137}Cs activities was found, along with in about 10% samples of garden soil, potatoes showed much higher activity (Popova and Kazachonok 2015). In some cases, the heterogeneity of contamination of agricultural plants was even greater. Figure 1 shows a histogram of ^{90}Sr specific activity distribution in potatoes from the private farms of the town of Kasli in 1965.

When soil is contaminated with ^{137}Cs, a strong heterogeneity also appears. Chegerova (2000) showed that in the Mogilev region the activity of ^{137}Cs

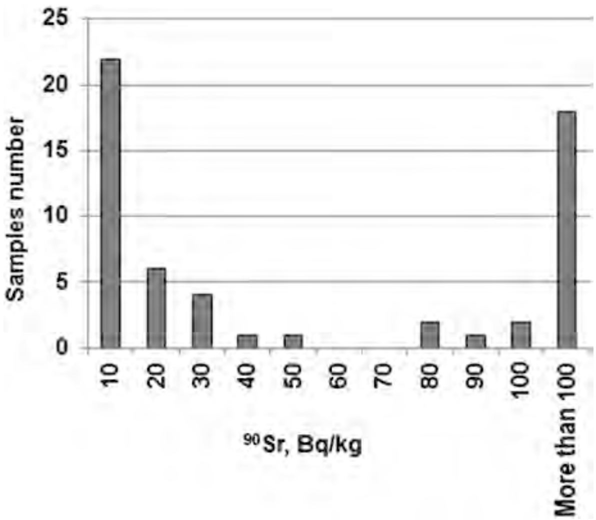

Fig. 1 Histogram of distribution of absolute values of ^{90}Sr specific activity in potatoes in the town of Kasli in 1965

in mushrooms, fresh vegetables, fruits, and berries in 80, 43, and 70% of the samples respectively fits into the first interval of the histogram (Fig. 1), whereas in some samples the activity can be ten times higher than in the first interval (Chegerova 2000).

The reason for the appearance of “dirty samples” is either heterogeneity of territory contamination with radionuclides, or violation of the conditions of protected sanitary zone by some residents of settlements. The violation of the conditions of protected sanitary zones can be episodic or systematic and its causes can be different. Thus, during the initial period of the Techa river pollution with the PA “Mayak” discharges, the reasons for the restrictions were not explained to residents and, above all, the clean water supply was not organized.

Depending on the weather conditions and the yield of herbaceous vegetation, the residents use hay from sites having contamination. As for example in 2010, due to drought conditions, some residents in Southern Urals harvested feed from contaminated areas, although they knew about the sites. Violations may also have economic causes. According to residents of the settlement of Bulzi, in the 1970s many families harvested hay in the territory of the EURT as “it was free” (Popova and Kazachonok 2015).

The heterogeneity of the conditions for the formation of an internal irradiation dose of the population depends also on social factors. For the population of Belarus the tendency is revealed—the smaller are the settlements, the more often the average internal irradiation dose of the surveyed residents exceeds 0.1 mSv. This is due to the fact that in small settlements the infrastructure is less developed, the degree of farming naturalization is more pronounced, the population eats more food products grown in their own garden and produce from the forest. In these settlements there is also a low employment of the population, there are no organized food service areas, trading networks and other conditions that exist in large settlements (Ageeva et al. 2010, 2011; Shchur and Vinogradov 2016).

In our opinion, the Gaussian distribution of the values characterizing the radioactive contamination level (density, specific activity, etc.) can only occur in areas within which the points with different contamination levels are randomly distributed. In real conditions, the heterogeneity of the territory contamination appears often in the form of spots having an epicentre and aureole zones different in terms of area, and their contamination level can vary relatively smoothly and consistently, whereas the area of aureole zones will increase in most cases with radius increasing. In both randomized and systematic sampling, the probability of selecting a sampling point from the spots epicentres will be significantly lower than from aureoles. Therefore, the frequency of soil and vegetation sampling from the least contaminated areas will be much higher than from the most contaminated areas. A multiyear research has shown that, depending on the way how the array is divided into intervals, it is possible to obtain a more or less approximate normal distribution for samples from aureoles and a long “tail” for samples from the epicentre (Popova and Kazachonok 2015). It can be assumed that the distribution in the form of a “springboard” indicates the pollution heterogeneity caused by the natural features of the landscape, and a bimodal or a poly modal distribution indicates the “organizational heterogeneity" associated with an irrational use of natural resources in contaminated landscapes (allocation of heavily contaminated plots for use, noncompliance with restrictions and prohibitions by the population, etc.).

This may lead to underestimation of the overall pollution level of the territory and vegetation. Theoretically, the level of soil contamination, even by a one-dimensional heterogeneity, must be described as the sum of the integrals of the functions of pollution densities reduction from epicentres to background values. In practice, this method is unreasonably labor-consuming.

Assessment of Possibility of Increased Accumulation of ^{90}Sr and Other Radionuclides in Case of a Homogeneous Radiation Contamination

To date, there are many recommendations on agricultural production in the contaminated territories. However, they are designed for largescale farms. In addition, when choosing measures to reduce the product pollution levels in a particular farm for a given period, it is necessary to take into account a large number of conditions that are usually not considered in general regulatory documents and recommendations: market conditions, energy prices, alternative possibilities of products usage etc. It should be taken into account that at the present time there is no legislative basis in Russia for compelling owners of agricultural enterprises to implement any recommendations. Thus, the head or management of a particular farm takes the final decision on the reasonability of applying certain protective measures.

Quite often, the countermeasures can be effective according to one of the parameters, but in general, according to the integral estimation, their application is unreasonable. For example, the combined use of ameliorants (liming, elevated use of organic and phosphate-potassium fertilizers, on light soils—the placement of clay minerals) made it possible to reduce the content of ^{137}Cs in plants up to five times (Sanzharova et al. 2005). However, the placement of a fertilizer complex led to an increase in the yield of cereals and, as a result, to an increase in the collective dose, which nearly neutralized the decrease in the ^{137}Cs specific activity in grain. In addition, production costs increased significantly. Thus, the averted dose, normalized to costs, was only 0.01–0.03 man mSv/million rubles (Prices of the year 1996) Fesenko (1997).

One of the effective methods to reduce the level of pollution of agricultural products is the conversion of the farm (The application 2011). However, this measure requires even greater costs, including costs for a reconversion if it turns out to be unprofitable.

"Guidance on the application of countermeasures in agriculture in the event of an accidental radionuclides release into the environment" issued by the IAEA in 1994 indicates that "the main goal of introducing any countermeasure should be to reduce the population irradiation doses and, thereby reducing the human health risk". In practice, this means choosing such a countermeasure strategy that enables to produce such food products that have contamination levels below intervention levels, as economically as possible and with minimal side effects (The application 2011).

In modern economic conditions, agricultural production in a contaminated area is not always profitable. The increase in economic costs associated with the implementation of recommendations on the agriculture in the territory contaminated with radionuclides is unacceptable for most farms. Therefore, a need arises to assess the reasonability of involving contaminated lands in agricultural production while maintaining its profitability.

For this purpose, it is necessary to predict the entry levels of ^{90}Sr and ^{137}Cs in the marketable part of harvest on the lands affected by radioactive contamination and to estimate the probability of making products which meet modern standards of radiation safety.

Using the radiation pollution mapping data from previous years and the radionuclide half-life values, it is possible to roughly calculate the average contamination density of the territory and the expected level of product contamination. However, the calculation of economic risk of the cultivation of specific crops in specific fields requires more detailed studies. In the initial period after the accident, the pollution density of the territory can be assessed using a direct method. Since radionuclides are located on the surface of the soil, it is sufficient to collect the top layer with a sampler having a known capture area.

In the long term after radioactive fallout, the nature of radionuclide distribution in the soil profile changes. In the forest and virgin soils, the pollution level is determined by the activity of the upper 20 cm of soil. On cultivated soils the distribution pattern in the profile may be different. Thus, on the axis of the East Ural radioactive trace (EURT), 50 years after the accident, in the long-fallow black soil in the lowland, 15–20% of ^{90}Sr was in the 30–85 cm layer. When the soil is treated regularly, especially irrigated, the contamination of the ploughing and subsurface horizon can be almost the same. Thus, the ratio of the densities of contamination with ^{90}Sr of 20–40 cm and 0–20 cm layers of the grey forest heavy loamy soil of "Sovkhoz Beregovoy" LLC in 2007 without irrigation was 0.76 ± 0.21, and with irrigation—1.16 ± 0.29. For ^{137}Cs these ratios were 0.58 ± 0.20 and 0.88 ± 0.43 (Kazachonok and Popova 2014).

It is commonly believed that the bulk of the roots are located in the upper "root-inhabited" soil layer. However, absorption of water and ions occurs in the root fibrils at the root tips, which reach a depth of 2–3 m of agricultural plants. Therefore, to assess the contamination density of the cultivated soil, it is recommended to have data on the radionuclide specific activity in layers having total thickness of at least 40 cm.

The density of soil contamination is defined as the product of the radionuclide specific activity and the weight of soil contaminated with it per unit of area. The soil weight is calculated as the product of its bulk weight, the fixed area and the thickness of the contaminated layer.

It is known that the bulk weight of soils depends on their type, the content of organic matter, the structure and the granulometric composition.

Despite the great variety of agrophysical characteristics of soils, it can be assumed that in most cases the bulk weight increases in the lower horizons, where the content of organic matter is small, the structural properties are less pronounced and the aeration porosity is minimal.

This regularity expresses itself more clearly if not absolute, but relative values of the soil bulk weight are used for the comparison. This method makes it possible to compare soils with different average bulk weight of a meter layer and to reveal the dependence of the soil bulk weight from the depth of sampling. We suggest describing the obtained dependences using monotonic functions, since grey forest soils and, in particular, black soils are characterized by smooth transitions between horizons.

Based on this, according to the values of the bulk weight for different soil layers of the Chelyabinsk region published by Kozachenko (1999) we calculated empiric equations that allow us to define approximately the value of the soil bulk weight at a given depth.

For grey forest soil:

$$Y_x = -4 \cdot 10^{-5}\,\mathrm{x}^2 + 6 \cdot 10^{-3}\,\mathrm{x} + 0.829$$
$$\left(R^2 = 0.986\right)$$

For black soil:

$$Y_x = -4 \cdot 10^{-5}\,\mathrm{x}^2 + 7.5 \cdot 10^{-3}\,\mathrm{x} + 0.747$$
$$\left(R^2 = 0.948\right),$$

where Y_x—relative value of the soil bulk weight at a given depth x,x—Sampling depth in cm.

Accordingly, the absolute value of the bulk weight (V_x) at this depth:

$$V_x = V \cdot Y_x,$$

where V is the average bulk weight of a meter-deep layer of the soil.

By comparing actual and calculated data, the deviation averaged 7 ± 3%, and the deviation is mainly connected with the inaccuracy of the actual data due to sampling layer by layer.

If there is information on the bulk weight of at least the upper layers of the studied soil, it is possible to use not the average tabulated values of V, but to calculate V for a given particular soil, and this will increase the accuracy of bulk weight calculation for all layers.

To do this, it is necessary to divide the actual value of the bulk weight (V_x) in the studied layer by its calculated relative value (Y_x), which can be obtained from Table 3 or, more precisely, calculated using the above formulas.

For calculation of radionuclide contamination density in a given soil layer (P_i) (Bq m^{-2}) the following formula can be used:

$$\mathrm{P}_i = 10 a_i \cdot V_i \cdot h_i,$$

where a_i—radionuclide specific activity (Bq kg^{-1}) in the studied layer i, V_i—soil bulk weight in this layer (g cm^{-3}), h_i—layer thickness (cm), 10—conversion coefficient for the transition from g cm^{-3} to Bq m^{-2}.

For calculation of radionuclide specific activity (a_i) (Bq kg^{-1}) in the soil layer i based on known contamination density the following formula is used:

$$a_i = \frac{P_i}{10V_i \cdot h_i}$$

For calculation of radionuclide contamination density in the whole soil profile (P_i) (Bq m^{-2}) this formula can be used:

$$P = \sum \left(10a_i \cdot V_i \cdot h_i\right),$$

Based on the dependencies, as found, we have created a program to automate calculations of the pollution density with ^{90}Sr and ^{137}Cs of black soil and grey forest soil of the forest-steppe zone of Trans Urals according to the specific activity values of these radionuclides in the soil layers.

For podzolic, sodic, solod, and other soils having stark differences of agrophysical properties in different horizons, the dependence of the bulk weight from the horizon and sampling depth will probably be described by more complicated functions. However, such soils are rarely found in the territory of EURT, assessment of their contamination is less important, therefore, making an on-the-fly approximate evaluation for contamination density of podzolic and malt soils is necessary, in our opinion the formula for grey forest soils, and for estimating contamination of sodic soils, the same formula for black soils can be used.

When predicting the level of product contamination in a given field for a planned culture, it is necessary to know the ratio of the radionuclide contamination level of the marketable part of harvest to the soil contamination density (transition coefficient (C_t)), or the ratio of the radionuclide specific activity in agricultural products to the average specific activity in the root-inhabited horizon (accumulation coefficient (C_a)).

Both C_a and C_t differ for different agricultural plants and varieties, depending on different types of soils and their kinds. It is noted that they decrease with time. Therefore, in order to improve the accuracy of the forecast, it is recommended to calculate their average values and standard deviations for specific farms in which a high probability of obtaining products not corresponding to hygienic standards is assumed.

According to the radiochemical analysis data of soil and production, the accumulation coefficients (C_a) for each sampling point are calculated:

$C_a = \frac{A_{pr}}{A_s}$,where A_{pr}—radionuclide specific activity in plant products, A_s—in soil.

Then, the value of $C_a(\bar{x})$, average for all points of the whole field and the standard deviation σ are calculated:

$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{(n-1)}}$, where x_i—each value of C_a, $\bar{x}$ —average value of C_a, n—measurements number.

The probability of non-exceedance of a given value of a (the maximum permissible radionuclide level in the production) will be equal to the value of the distribution function (Gelman 2003):

$$F(x)=\frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{x}e^{\frac{-(a-\bar{x})^2}{2\sigma^2}}$$

Table 1 represents as an example the values of the accumulation coefficients of ^{90}Sr and ^{137}Cs in the marketable part of agriculture sampled by us in "Sovkhoz Beregovoy" LLC, and Table 2, sampled in personal farms in settlements located on the periphery of the EURT and in the 30-km zone of "Mayak" PA.

It can be seen from the tables that the standard deviations are quite large and exceed in some cases $\bar{x}$. This may be due to a deviation from the normal distribution. For example, in the village of Bagaryak in the study of milk samples, the distribution turned out to be bimodal. This is since the pastures on the north-west were contaminated much more than on the south-east, that is, samples of milk from different pastures belonged to different populations. In this case $\bar{x}$, σ, and $F(x)$ are calculated separately for each population.

A lognormal distribution occurs quite often. In the case of a lognormal distribution, when calculating $F(x)$, a is replaced with $\ln(a)$, when calculating $\bar{x}$ and σ, x is replaced with $\ln(x)$.

When C_a for one of the crops and the radionuclide specific activity in soil (A_s) are known, but its standard deviation isn't known, we can calculate approximate products contamination level (A_{pr}) using the formula:

Table 1 Average values of the accumulation coefficients of ^{90}Sr and ^{137}Cs in the marketable part of agriculture in "Sovkhoz Beregovoy" LLC and their standard deviations (in brackets)

Crop	Product	^{90}Sr	^{137}Cs
Peas	Grains	0.084 (0.029)	0.062 (0.036)
Wheat	Grains	0.036 (0.014)	0.078 (0.060)
Oats	Grains	0.054 (0.031)	0.032 (0.018)
Barley	Grains	0.070 (0.062)	0.039 (0.040)
Onions	Bulb	0.026 (0.009)	0.016 (0.009)
Cabbage	Head	0.029 (0.005)	0.019 (0.008)
Carrots	Root plant	0.237 (0.222)	0.146 (0.165)
Beets	Root plant	0.026 (0.007)	0.016 (0.008)
Potatoes	Tubers	0.020 (0.012)	0.008 (0.003)
Corn	Grass	0.242 (0.189)	0.049 (0.041)
Sudan grass	Grass	0.175 (0.062)	0.083 (0.040)

Table 2 Average values of the accumulation coefficients of ^{137}Cs and ^{90}Sr in the marketable part of agriculture in private farms and their standard deviations (in brackets)

Crop	Product	^{90}Sr	^{137}Cs
Potatoes	Tubers	0.0083 (0.0067)	0.0128 (0.0120)
Carrots	Root plant	0.0193 (0.0140)	0.0379 (0.0786)
Beets	Root plant	0.0172 (0.0099)	0.0156 (0.0124)

$$A_{pr} = A_s \cdot C_a$$

And assume that the probability of non-exceedance of this level is 50% (in case of a normal distribution).

Depending on the purpose of the production and the possibilities of its alternative use (forage, technical raw materials, planting material, etc.), the economic service of the farm determines the probability level of receiving agricultural products that do not meet the radiation and hygienic standards and decides on the introduction of the lands into agriculture.

Assessment of Possibility of Increased Accumulation of ^{90}Sr and Other Radionuclides by Plants in Case of an Inhomogeneous Radiation Contamination

It should be noted that the use of functions of normal distribution to predict the contamination level of agricultural products is permissible only in case of a relatively uniform contamination of agricultural areas. That is, the radionuclide activity values in soil samples or food product samples taken at the same time in one settlement can be referred to one general population. However, practice shows that even within one settlement, the values of the radionuclide specific activity in environmental objects cannot be always related to a single general population. This is especially important for the areas of settlements located on the periphery of the East Ural radioactive trace, where the fallout of radioactive aerosols was nonuniform. In this case, it is necessary to use other methods for analyzing data and predicting pollution of agricultural products.

In our opinion, when processing experimental data for nonuniform radioactive contamination, the application of Bayesian methods and fuzzy logic can be a promising direction. The principles of application of fuzzy logic methods for the analysis of radioactive contamination of soil and agricultural products were outlined by us in 2013 (Kazachonok 2013).

To assess the level of radioactive contamination of a natural or anthropogenic object, the sampling rate should be much greater than the rate of change in the essential characteristics of the object. The number of samples that can be analysed for a particular object during the sampling period is finite, and all these samples either meet or do not meet the specified criterion. The taken samples are not returned back. For example, an object is a group of cows in private farms in the settlement. Their number in the sampling period is finite; the number of milk samples that are taken during the period of research from each cow is determined by the research methodology and is also finite. Therefore, the results of the selection and examination of milk samples can be considered as dependent events.

A dependent event (the result of a sample study) is connected with the truth of one of the incompatible hypotheses H_1, H_2, H_3, …, H_n. For example, the settlement A is:

H_1—not contaminated;
H_2—contaminated.

It is necessary to calculate the probability of the truth of these hypotheses. Prior to the study of the settlement, the a priori probabilities of these hypotheses are defined, relying on the already available data. After receiving the analysis result of the taken sample (event X), the probabilities of the truth of the hypotheses are recounted. For example, if sample X is contaminated, the probability of hypothesis H_1 is increased, and of hypothesis H_2 is decreased.

For example, in a settlement there are 20 plots where potatoes are grown; one sample is taken from each plot at this stage of the study. We will define the settlement as contaminated if at least in one sample the MPL of the studied radionuclide is exceeded. If at least one sample is contaminated, the probability of obtaining a clean sample is 0.947 or less. Let's take the probability of obtaining a clean sample equal to 0.95 as a criterion of referring the settlement to not contaminated, 0.94-to contaminate.

The simplest case is the calculation of the belonging of the studied object to one of two categories, but the Bayesian method makes it possible to calculate the probabilities for more hypotheses.

There are some examples of an algorithm for calculating the probability of three hypotheses using the Bayesian method.

1. The range of values, the probability of which in the study is different from zero, is divided into subranges. The structuring criteria are chosen according to the objectives of the study. For example, the structuring into a subrange of values not exceeding the MPL and a subrange of values exceeding the MPL.
2. The categories of objects to which the studied object can be assigned and the matching criteria with the defined categories of the studied object are specified. For example: object A is classified as "safe" if the probability of taking a sample characterized by a value in the subrange "not exceeding the MPL" = 0.95; object A is classified as "medium dangerous" if the probability of taking a sample characterized by a value in the subrange "not exceeding the MPL" is 0.5; object A is classified as "dangerous" if the probability of taking a sample characterized by a value in the subrange "not exceeding the MPL" = 0.05.
3. The hypotheses of the belonging of the studied object to the specified categories are developed.

   H_1—taken sample X will belong to object A_1 (A is "safe").
   H_2—taken sample X will belong to object A_2 (A is "medium dangerous").
   H_3—taken sample X will belong to object A_3 (A is "dangerous").

The probability that the sample *X* will be "not exceeding the MPL" for samples of A_1

$$P_{H1}(X) = 0.95$$
$$\text{for } \textit{samples of } A_2$$
$$P_{H2}(X) = 0.5$$
$$\text{for } \textit{samples of } A_3$$
$$P_{H3}(X) = 0.05.$$

The probability that the sample X' will be "exceeding the MPL" for samples of A_1

$$P_{H1}(X') = 0.05$$
$$\text{for } \textit{samples of } A_2$$
$$P_{H2}(X') = 0.5$$
$$\text{for } \textit{samples of } A_2$$
$$P_{H3}(X') = 0.95.$$

The a priori probabilities that the sample is taken from an object classified as "safe" ($P(H_1)$) or as "medium dangerous" ($P(H_2)$) or as "dangerous" ($P(H_3)$) are calculated using available research data. If studies were previously not conducted, then at the first stage the a priori probabilities can be assumed to be equal.

$$P(H_1) = P(H_2) = P(H_3) = 1/3$$

4. Taking and analysis of the sample are carried out.

Let the sample X be "not exceeding the MPL."

According to the formula of total probability, the probability that the sample X will be "not exceeding the MPL":

$$P(X) = P(H_1) \cdot P_{H1}(X) + P(H_2) \cdot P_{H2}(X) + P(H_3) \cdot P_{H3}(X)$$

In this case, according to the Bayesian formula, the a posteriori probabilities of the hypotheses are calculated:

$$P_X(H_1) = (P(H_1) \cdot P_{H1}(X)) / P(X)$$
$$P_X(H_2) = (P(H_2) \cdot P_{H2}(X)) / P(X)$$
$$P_X(H_3) = (P(H_3) \cdot P_{H3}(X)) / P(X)$$

Let the sample X' be "exceeding the MPL."
In this case, the probability that the sample X' will be "exceeding the MPL":
for samples of A_1

$$P_{H1}(X') = 0.05$$
for *samples of* A_2
$$P_{H2}(X') = 0.5$$
for *samples of* A_2
$$P_{H3}(X') = 0.95.$$

According to the formula of total probability:

$$P(X') = P(H_1) \cdot P_{H1}(X') + P(H_2) \cdot P_{H2}(X') + P(H_3) \cdot P_{H3}(X)$$

According to the Bayesian formula, the a posteriori probabilities of the hypotheses are calculated:

$$P_{X'}(H_1) = (P(H_1) \cdot P_{H1}(X')) / P(X')$$
$$P_{X'}(H_2) = (P(H_2) \cdot P_{H2}(X')) / P(X')$$
$$P_{X'}(H_3) = (P(H_3) \cdot P_{H3}(X')) / P(X')$$

5. The a posteriori probabilities are taken as new a priori ones and the step 4 is repeated.
6. After a certain number of iterations, the a posteriori probabilities corresponding to the study tasks are obtained.

Thus, if it is not possible to calculate the probability of obtaining a sample matching/not matching the given parameters, the Bayesian method makes it possible to calculate the probability that an object belongs to a category for which the probability of interest is characteristic. The Table 3 represents the results of probabilities calculation, according to the given example.

Probabilities of truth of hypotheses of an object's belonging to the specified categories deduced using the Bayesian method are equivalent to the functions of an object's belonging to these categories. Therefore, the results of calculations can be processed using fuzzy logic methods.

In our opinion, when processing experimental data for nonuniform radioactive contamination, the application of fuzzy logic methods can be a promising direction. The principles of application of these methods for the analysis of radioactive contamination of soil and agricultural products were outlined by us in 2013 (Kazachonok 2013).

In fact, we are dealing with the combination of at least two subsets of data: the analysis results of samples obtained in the farms of "law-abiding citizens" (A) and in the farms of "violators" (B). Such a combined set AB will have either a polymodal distribution or a distribution similar to a lognormal. We assume that if the subset A has a symmetric distribution, then the subset of the values x of the set AB for x > M has the function of membership in A equal to $\mu_A(x) = y(2M - x)/y(x)$, and the function

Table 3 An example of probability calculation of the truth of three hypotheses using the Bayesian method

Sample no.	Measurement result	H_1 (object is "safe")		H_2 (object is "medium dangerous")		H_3 (object is "dangerous")	
		$P_{H1}(X)$	$P_X(H_1)$	$P_{H2}(X)$	$P_X(H_2)$	$P_{H3}(X)$	$P_X(H_3)$
	Before the experiment	0.95	0.333333	0.5	0.333333	0.05	0.333333
1	<MPL	0.95	0.633333	0.5	0.333333	0.05	0.033333
2	<MPL	0.95	0.781385	0.5	0.21645	0.05	0.002165
3	>MPL	0.05	0.261594	0.5	0.724638	0.95	0.013768
4	<MPL	0.95	0.406387	0.5	0.592487	0.05	0.001126
5	<MPL	0.95	0.565777	0.5	0.434141	0.05	8.25E-05
6	<MPL	0.95	0.712317	0.5	0.287677	0.05	5.47E-06
7	<MPL	0.95	0.824702	0.5	0.175297	0.05	3.33E-07
8	<MPL	0.95	0.899383	0.5	0.100617	0.05	1.91E-08
9	>MPL	0.05	0.471981	0.5	0.528019	0.95	1.91E-07
10	<MPL	0.95	0.629404	0.5	0.370596	0.05	1.34E-08
11	<MPL	0.95	0.763419	0.5	0.236581	0.05	8.54E-10
12	<MPL	0.95	0.859769	0.5	0.140231	0.05	5.06E-11
13	>MPL	0.05	0.380078	0.5	0.619922	0.95	4.25E-10
14	>MPL	0.05	0.057769	0.5	0.942231	0.95	1.23E-09
15	<MPL	0.95	0.104336	0.5	0.895664	0.05	1.17E-10
16	<MPL	0.95	0.181221	0.5	0.818779	0.05	1.07E-11
17	<MPL	0.95	0.296037	0.5	0.703963	0.05	9.17E-13
18	>MPL	0.05	0.040356	0.5	0.959644	0.95	2.38E-12
19	<MPL	0.95	0.073989	0.5	0.926011	0.05	2.29E-13
20	<MPL	0.95	0.131802	0.5	0.868198	0.05	2.15E-14

of membership in B equal to $\mu_B(x) = (y(x) - y(2M - x))/y(x)$, where M—mode (in case of the polymodal distribution, the first mode), $y(x)$—frequency x, $y(2M - x)$—frequency of a value that is symmetric to x with respect to M (Coffman 1982).

It should be noted that the use of fuzzy models is suggested by other researchers too. In particular, this approach is mentioned in the review paper of Tikhonova and Rylova (2014).

Such an approach, in our opinion, will allow justifying the identification of "violators," as well as conducting a more correct analysis of the dynamics of contamination levels of environmental components in the long term after emergency fallouts.

Conclusions

1. The heterogeneity of radioactive contamination of soil and vegetation causes problems for predicting the probability of increased pollution of plant products with ^{90}Sr and other radionuclides.

2. In case of a homogeneous radioactive contamination, the possibility of non-exceedance of maximum permissible accumulation levels of ^{90}Sr and other radionuclides in plants can be calculated using the function of normal or lognormal distribution.
3. In case of a heterogeneous radioactive contamination, the possibility of non-exceedance of maximum permissible accumulation levels of ^{90}Sr and other radionuclides in plants can be calculated using the Bayesian formula and fuzzy logic methods.

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