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Estimation of radiation non-regulatory stochastic risks for meadow plants of the semipalatinsk test site

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Abstract. An algorithm and formulas to estimate non-regulatory stochastic risks (for biota and humans) have been derived. These were used to assess radiation risks for meadow plants within the Semipalatinsk Test Site (STS). It has been shown that on small plots with relatively high radiation levels (~ 0.25 mGy/h) the radiation risks of death of radiosensitive plants (leguminous and coniferous shrubs) have a noticeable value ($> 2\%$). In the other STS area, radiation is not a danger to the vegetation.

1. INTRODUCTION

Over 1949–1989, at the Semipalatinsk Test Site (STS) 456 nuclear weapons tests were carried out resulting in a release to the environment of large amounts of long-lived radionuclides, including some $9 \cdot 10^{16}$ Bq ^{137}Cs, which is comparable with the amount of this radionuclide released after the Chernobyl accident [3]. A study into the radiation effects on the unique meadow vegetation of Kazakhstan is of great interest, since exactly this natural component that is responsible for the formation of cenosis over the whole STS area.

Radiation effects in plant populations are characterized by large uncertainty, due to the influence of many factors. In estimations of radiation effects, it is reasonable to make use of ecological risks as the integrated indices. These describe a ***probability*** of unfavorable outcome under the action for some time of a stressor [1, 2].

In general, both the acting factor and extent of a biological effect are random variables, which are described by density distributions (probability density). In this case, ***Risk*** is integral of distribution overlapping, which can be estimated without any assumptions of the limit values of the indices used. This provides a way to overcome uncertainty and subjectivity typical for estimations based on standard indices.

Hence, for stochastic risk computation the following components are necessary:

- distribution (form and parameters) of the acting factor (dose rate);
- distribution (form and parameters) of the value for biological effect as a function of dose rate;
- formula (relating these density distributions) for risk computation.

In the present paper, death rate of plants is taken as a biological effect criterion, since it is the most evident integral indicator of the radiation factor effects on biota.

2. MATERIALS AND METHODS

As STS sites for radiation risk assessment to meadow plants, pastures were considered located near the wintering ground « Atomic Lake » and a site with high radioactive contamination in close vicinity to Abnormal Pithole 1069 (site « Balapan »). The data on the content of the main dose-forming radionuclides in the soil of pastures near the « Atomic Lake » used to compute dose burdens were submitted by the National Nuclear Center (Kazakhstan).

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The radioactive contamination data for the site near Abnormal Pithole 1069 were taken from [3] using some data from [4] for reconstruction of ^{60}Co, ^{152}Eu and ^{154}Eu concentrations. Dose burdens to meadow plants were estimated with a dosimetric model devised on the basis of the multilayer model for aquatic ecosystems [5].

The information on plant radioresistance was taken from [6–8] using some data from the International radiation database Frederica-online.org.

All data were transformed to the same criterion: LD_{50} for 6 years of chronic exposure. To this end, transfer factors cited in [9] were used. Arbitrary LD_{50} values for the different living forms of the same plant group (family) where estimated as follows:

Living Form	**Annual herbs** (one season)	**Perennial herbs** (6 years)	**Shrubs & shrub-like plants** (6 years)
LD_{50}	100	∼25	∼16

All distributions, including LD_{50} distributions at the family levels, were described by the *Gamma*-distribution function, its probability density being expressed as follows:

$$P(\alpha, m, x) = \frac{\alpha}{m\Gamma(\alpha)} \left(x\frac{\alpha}{m}\right)^{\alpha-1} \exp\left(-x\frac{\alpha}{m}\right) \tag{1}$$

where m is the mean value of a random variable, α is the shape parameter: $\alpha = m^2/s^2$ (s is the standard deviation), $\Gamma(\alpha)$ is the normalizing coefficient (Euler gamma-function), x is the variable (dose rate).

Plant death rate was taken as a parameter defining radioresistance of plant populations. Dependences of this parameter $\boldsymbol{F(D)}$ on dose rate were reconstructed using (1) probability densities of plant group LD_{50} and (2) mortality dependence on dose rate of naturally growing species. Considering that all species have near the same shape of dose-effect dependence, the following formula is correct:

$$\boldsymbol{F(D)} = \int_0^\infty P(\alpha, m, X) \cdot F(2.24, X \cdot 1.1685, D)\, dX \tag{2}$$

where $\boldsymbol{F(D)}$ is the plant group distribution function of mortality-dose rate dependence; $\boldsymbol{P}(\alpha, m, \boldsymbol{X})$ is the probability density value of LD_{50} at point $\boldsymbol{X}$ of dose rate (α and m are the parameters of *Gamma*-distribution); $\boldsymbol{F}(\alpha_0, m_0, \boldsymbol{D})$ is the species distribution function value at point $\boldsymbol{D}$ of dose rate (α_0 and m_0 are the parameters of *Gamma*-distribution; after data analysis constant $\alpha_0 = 2.24$; m_0 is the variable mean value of *Gamma*-distribution; integration variable $\boldsymbol{X}$ corresponds to median of distribution, and coefficient 1.1685 transforms $\boldsymbol{X}$ to the mean value m_0).

Probabilistic description of spatial heterogeneity of dose burdens to plants growing in the study area was also based on *Gamma*-distributions.

The mathematical parameters of distributions were optimized by the simplex-method based on the minimum of residual variance. For the optimization procedure the cumulative histograms of experimental data (without any grouping) where used and these were mathematically described by *Gamma*-distribution functions (or by a sum of such two functions).

Mathematical processing and computations used the « MATLAB » software (The MathWorks, Inc., 21 Eliot St., South Natick, MA 01760).

3. RESULTS AND DISCUSSION

3.1 Parameters of distributions of dose rates and mortality of plants

The unique STS flora contains some 200 plant species. However, no data are available on the radioresistance of these species. Therefore, the radioresistance analysis was made at the level of groups (families) of plants assuming approximately the same radioresistance heterogeneity for plant families from different regions of the Earth. The floristic analysis has revealed that within the experimental sites most common are perennial herbaceous families *Poaceae* and *Asteraceae*. These have practically the same radioresistance parameters and were analyzed collectively. The most radiosensitive meadow plants within the study sites are coniferous and leguminous shrubs (*Ephedra distachia*, *Ephedraceae*, and *Caragana pumila*, *Fabaceae*). Spatial heterogeneity of radioactive contamination of pastures and radioresistance (mortality) of plant groups are described as superposition of two *Gamma*-distributions: $P = P_1 \cdot C_1 + P_2 \cdot C_2$ (corresponding average $m = m_1 \cdot C_1 + m_2 \cdot C_2$). The distribution parameters are presented in Table 1. The corresponding probability densities (or distribution functions) are shown in Figs. 1 and 2.

Table 1. Parameters of *Gamma*-distributions for experimental data of objects used for stochastic ***Risks*** determination.

	Low dose part of distribution			**High dose part of distribution**			**Average**
Parameter / **Object**	m_1	α_1	C_1	m_2	α_2	C_2	m
	µGy/h	–	%	µGy/h	–	%	µGy/h
Dose rate near Abnormal Pithole 1069	250	2.60	100	–	–	–	250
DR on Pastures around «Atomic Lake»	0.12	0.72	97.8	2.69	1.58	2.2	1.74
Fabaceae shrubs mortality (*Caragana pumila*)	1000	1.84	44	2640	1.77	56	1920
Coniferaceae shrubs mortality (*Ephedra distachia*)	1190	2.16	47	2370	2.15	53	1810
Poaceae & *Asteraceae* perennial herbs mortality	9090	1.55	44	26920	1.50	56	19070

3.2 Equations for the stochastic *Risk* calculation

At point X (Fig. 1 insertion) the probability of dose rate $W_1(X) = P_1(X)\,dX$, and corresponding semistochastic *Risk* (probability of plant death) is the left part of radioresistance distribution ($D \leq X$):

$$W_2(X) = \int_0^X P_2(D)\,dD \tag{3}$$

Because of the independence of the stochastic variables used, a subsequent differential ***Risk*** value is the production of the corresponding probabilities (***I*** is the non-normalized probability density of ***Risks***):

$$d\boldsymbol{Risk}_1(X) = \boldsymbol{I}_1(X)dX = W_2(X) \cdot W_1(X) = W_2(X) \cdot P_1(X)\,dX \tag{4}$$

Alternatively, the probability of plant mortality at point X is $W_2(X) = P_2(X)\,dX$; corresponding semistochastic *Risk* is the right part of dose rate distribution ($DR > X$), and subsequent

$$d\boldsymbol{Risk}_2(X) = \boldsymbol{I}_2(X)dX = W_2(X) \cdot W_1(X) \ldots etc.$$

The more obvious presentation of differential form of *Risk* is complete overlapping of factor and object distributions as a Sum of partial overlapping functions $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$: $\boldsymbol{I} = \boldsymbol{I}_1 + \boldsymbol{I}_2$. This variable smoothly fills all space between the P_1 and P_2 density functions (Fig. 1 insertion).

Risk value is an integral of either $\boldsymbol{I}_1$, or $\boldsymbol{I}_2$ (or of the complete $\boldsymbol{I}$ function with coefficient 1/2):

$$\boldsymbol{Risk} = \int_0^\infty P_1(X)\left[\int_0^X P_2(D)dD\right]dX = \int_0^\infty P_2(X)\left[\int_X^\infty P_1(D)dD\right]dX = \frac{1}{2}\int_0^\infty I(X)\,dX \quad (5)$$

The derived expressions have several simple consequences. Let M_1 be a mean value of *DR*, M_2 is the mean value of plant radioresistance, S_1 and S_2 are the corresponding standard deviations.

1. $|(M_2 - M_1)| \gg S_1 + S_2$(distributions of dose rate and radioresistance are located in different dose domains and are not overlapped):
   $\boldsymbol{Risk} \approx 0\,(M_2 > M_1 - \textit{usual case})$ or
   $\boldsymbol{Risk} \approx 1(M_2 < M_1 - \textit{very dangerous case})$.
2. $S_1 \ll S_2$ or $S_1 \gg S_2$, the cases of usual semistochastic $\boldsymbol{Risks}$: (6)
   $\boldsymbol{Risk} = \int_0^{M_1} P_2(D)dD$, or $\boldsymbol{Risk} = \int_{M_2}^{\infty} P_1(D)\,dD$
3). $M_2 \approx M_1$ and $S_1 \approx S_2$ (distributions of dose rate and radioresistance coincide):
   $\boldsymbol{Risk} \approx 1/2 = 50\%$.

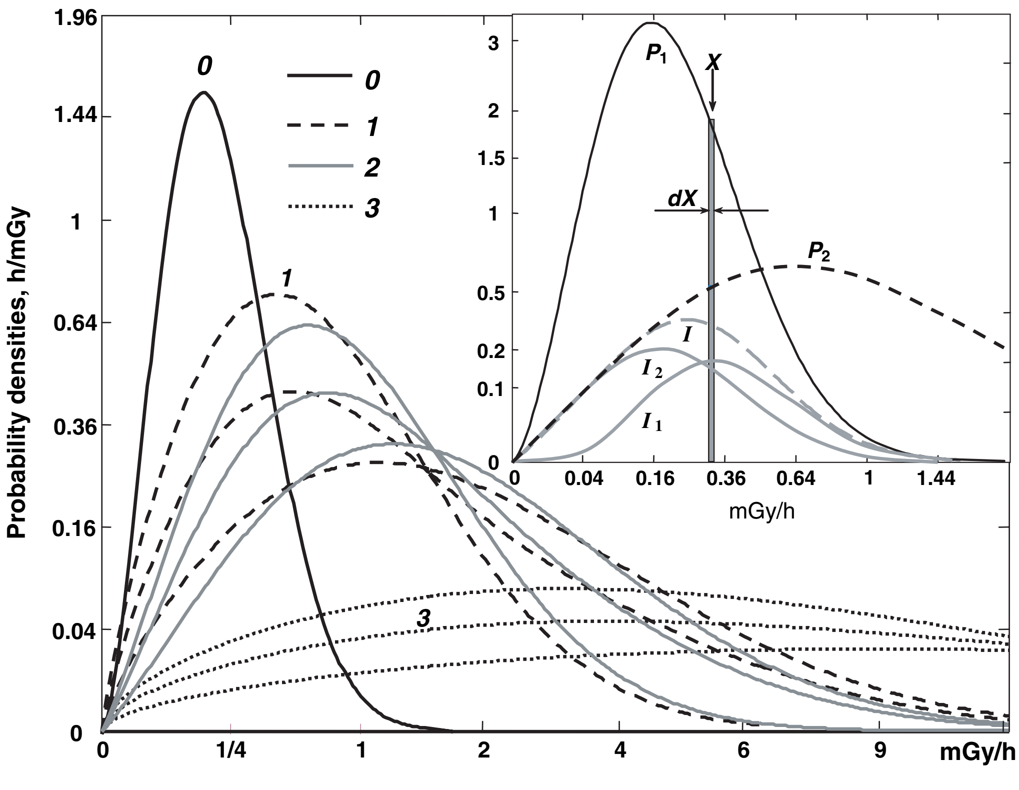

Figure 1. Probability densities of dose rate distribution near the Abnormal Pithole 1069 and radioresistance (mortality) of some meadow plants (for the best visualization both scales are nonlinear and proportional to square roots of corresponding values). Probability densities of mortality are shown for the mean values (middle curves), for the low dose part (upper left at *max*; $C_1 = 100\%$) and for the high dose part of resistance (lower right at *max*; $C_2 = 100\%$). Parameters of low dose and high dose parts are presented in Table 1. 0 – two fold diminished dose rate distribution ($P_1/2$); 1 – leguminous shrubs; 2 – coniferous shrubs; 3 – common meadow perennial grasses (*Poaceae* & *Asteraceae*); <u>*Insertion*</u>: probability densities of dose rate distribution (P_1), mortality of leguminous shrubs (P_2) and distribution overlapping ($\boldsymbol{I_1}, \boldsymbol{I_2}$ and $\boldsymbol{I} = \boldsymbol{I_1} + \boldsymbol{I_2}$).

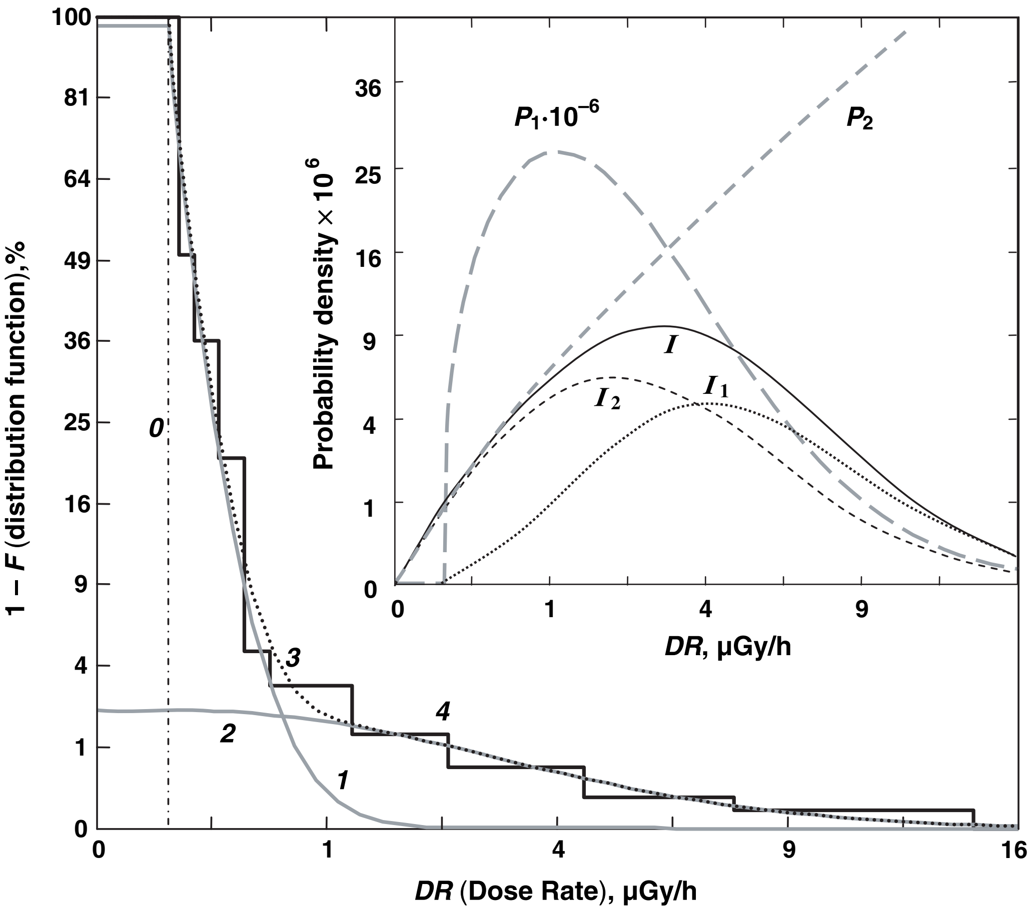

Figure 2. Spatial distribution of radioactivity on STS meadow pastures around « Atomic Lake » (for the best visualization both scales are nonlinear and proportional to square roots of corresponding values). 0 – background *DR* value (0.1 μGy/h); 1, 2 – calculated components of *DR* distribution; 3 – sum of components 1 and 2; 4 – experimental cumulative histogram of radiation distribution. Parameters of calculated components (over the background value of radiation) are given on Table 1. *Insertion*: probability densities of dose rate distribution (P_1) of component 2, mortality of leguminous shrubs (P_2) and distribution overlapping ($\boldsymbol{I_1}$, $\boldsymbol{I_2}$ and $\boldsymbol{I} = \boldsymbol{I_1} + \boldsymbol{I_2}$).

3.3 Assessment of radiation risk for meadow STS vegetation

Using Eq. (5) and mathematical descriptions of density distributions of radioactivity and radioresistance (Table 1), radiation risks for some STS meadow plants have been estimated. Results of Risk estimation are summarized in Table 2.

The *Min*, *Mean* and *Max* risk values belong to the high dose part, mean values and low dose part of plant group radioresistance, respectively (Table 1, Fig. 1).

As is evident from the table 2, the risk values for meadow plants of pastures are negligible, less than 10^{-5} (the derived values are actually beyond the probable accuracy limits, about 10^{-3}, of the method for assessment of stochastic risks described in this paper). On pastures in the vicinity of « Ground Zero » radioactive contamination and, consequently, risk values are much less (data are not presented).

Table 2. Stochastic Risks of plant mortality for different STS areas.

Territory	Plant group	Risk values *Min*	*Mean*	*Max*
Pastures around « Atomic Lake » (STS, « Balapan »)	*Fabaceae* shrubs	$3.8 \cdot 10^{-7}$	$8.8 \cdot 10^{-7}$	$15.2 \cdot 10^{-7}$
	Coniferaceae shrubs	$0.5 \cdot 10^{-7}$	$1.2 \cdot 10^{-7}$	$2.1 \cdot 10^{-7}$
	Perennial herbs	$0.7 \cdot 10^{-7}$	$1.5 \cdot 10^{-7}$	$2.5 \cdot 10^{-7}$
Dirty part of Pastures around « Atomic Lake »	*Fabaceae* shrubs	$1.2 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$	$5.2 \cdot 10^{-5}$
	Coniferaceae shrubs	$2.0 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$	$8.5 \cdot 10^{-6}$
	Perennial herbs	$1.7 \cdot 10^{-6}$	$3.7 \cdot 10^{-6}$	$6.3 \cdot 10^{-6}$
Abnormal Pithole (Slit) 1069 (« Balapan »)	*Fabaceae* shrubs	2.7%	6.5%	11.3%
	Coniferaceae shrubs	2.0%	4.4%	7.0%
	Perennial herbs	0.1%	0.3%	0.6%

The site with relatively high level of radioactive contamination in close vicinity to Abnormal Pithole 1069 (« Balapan ») is a small spot, only about 30 m in diameter. Such spots probably exist near the epicenters of surface bursts within the STS experimental site « Ground Zero ».

As is seen from the table, on spots with relatively high radiation levels, there is noticeable death hazard (more than 2%) for radiosensitive plant groups. In these conditions radiosensitive plants cannot possibly propagate by seeds, since seed production is much more sensitive to radiation than plant vitality [4].

It should be noted that dose rate value within these spots (∼0.25 m Gy/h) is lower than the permissible level of dose rate (∼0.40 m Gy/h) recommended for terrestrial plants [10]. This standard seems to be overestimated and needs to be revised.

On the other hand, the ***Risk*** values for vegetation on pastures are neglected, even in the most affected part of the area. Evidently, radiation risks for vegetation are lacking on pastures, which is in agreement with the results of investigations into the composition of meadow phytocenoses.

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