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METHODS FOR CALCULATING THYROID DOSES TO THE RESIDENTS OF OZERSK DUE TO ^{131}I RELEASES FROM THE STACKS OF THE MAYAK PRODUCTION ASSOCIATION

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Project 1.4

Reconstruction of dose to the residents of Ozersk from Operation of the Mayak Production Association: 1948–2002

October 2009

Contents

Introduction

The Mayak Production Association (MPA) was established in the late 1940s in accordance with a special Decree of the USSR Government for the production of nuclear weapons. In early years of MPA operation, due to the lack of experience and absence of effective methods of RW management, the enterprise had extensive routine (designed) and non-routine (accidental) releases of gaseous radioactive wastes to the atmosphere. These practices resulted in additional technogenic radiation exposure of residents inhabiting populated areas near the MPA.

The primary objective of ongoing studies under JCCRER Project 1.4 is to estimate doses to the residents of Ozersk due to releases of radioactive substances from the stacks of MPA. Preliminary scoping studies have demonstrated that releases of radioactive iodine (^{131}I) from the stacks of the Mayak Radiochemical Plant represented the major contribution to the dose to residents of Ozersk and of other nearby populated areas. The behavior of ^{131}I in the environment and of ^{131}I migration through biological food chains (vegetation→cows→milk→humans) indicated a need for use of special mathematical models to perform the estimation of radiation doses to the population.

The goal of this work is to select an appropriate model of the iodine migration in biological food chains and to justify numerical values of the model parameters.

1 Summary

In general, the thyroid dose, *D,* due to the intake of ^{131}I into the human body, *P*, can be obtained using the amount (mass) of inhaled air, consumed foodstuffs, etc., *M*; the concentration of ^{131}I in the air inhaled, foodstuffs consumed, etc, *C;* and values of the corresponding dose conversion factor, *DF*:

$$D = P \cdot DF = M \cdot C \cdot DF. \tag{1.1}$$

1.1 Analysis of pathways of ^{131}I transfer from ground-level air to humans

It is assumed that, after being released from the MPA stacks, ^{131}I dispersing within the atmospheric boundary layer was in the form of a mixture of three fractions: iodine bound with aerosol particles, molecular iodine (I_2), and various gaseous iodine compounds, which are generally referenced in the literature under the heading of 'organic iodine compounds' and most frequently are associated with methyl iodide (CH_3I). Each of these fractions of iodine is characterized by its unique capability for deposition from air on different surfaces and for being scavenged by precipitation. Calculations of atmospheric transport should be performed for each of the three above mentioned radioiodine components. Differences between the iodine fractions are considered to be insignificant after ^{131}I is transferred into humans or animals, thus summation of the results by components can be performed at any stage of further calculations where it is convenient.

In order to perform retrospective evaluation of internal thyroid doses to the residents of Ozersk (due to the intake of radioiodine via ingestion and inhalation) and of external radiation doses (from the contaminated soil surface and radioactive plume), age-dependent dose factors should be applied, and the peculiarities of exposure patterns of critical population groups should be taken into account. For example, intake of radionuclides by Ozersk residents from inhalation occurred both outdoors and indoors during the entire period of the plume passage over the town.

For the ingestion component of intake, cows' milk was known to be a significant contributor of radioiodine intake even during periods of stabling. However, there were situations when, for some reason, an individual did not consume contaminated cows' milk and potentially some other contaminated foodstuffs. Therefore, there is a need to consider all possible pathways of radionuclide transport into humans.

The longest pathways for ^{131}I intake are associated with the local production of whole milk, milk products, meat, and chicken eggs. During the grazing period, in addition to the bulk of ^{131}I ingested with contaminated herbage, a certain amount of iodine could be consumed with contaminated water from the open stock tanks or via inhalation. Pasture grass (herbage) and soil, between which redistribution of ^{131}I activity could occur, should be considered separately as sources of radioiodine intake into animals.

Fodder (such as hay and silage) laid in for winter was kept under different conditions and could be additionally contaminated with 'fresh' fallout of ^{131}I. This could become a major source of iodine intake into animals during periods when animals are fed stored fodder.

Some of the transport pathway components in the chain 'air→man' are associated with leafy vegetables and other greens grown either outdoors or indoors (i.e., in hotbeds or greenhouses). Depending on the location of pastures, private plots of land, and pens for keeping livestock, radioactive contamination of fodder and, consequently, locally produced food products in relation to the wind direction, contamination could occur independently of inhalation intake of radionuclides or, vice versa, almost during the same periods of time. This fact must be considered while selecting calculation schemes accounting for the actual location of dairy and other farms.

Peculiarities of prenatal thyroid exposure and of transfer of radioiodine from mother's milk to the baby should also be considered separately.

Absorption of radioiodine from contaminated skin surface to the individual's blood and transfer of radioiodine from the contaminated hands to the digestive tract during eating or smoking are of relatively small importance, and, hence, they are not taken into account in our analyses.

The main points of the model under consideration were taken from Snyder et al. (1994), while Mokrov et al. (2003; 2007) were used for selecting the model parameters.

1.2 Temporal factors and determination of basic integrated parameters

The major overall objective of JCCRER Project 1.4 is to perform retrospective evaluation of thyroid doses to Ozersk residents for the period from the MPA start-up in 1949 to the mid 1960s (when releases of radioiodine significantly decreased). Therefore, the primary requirement to the level of detail of dosimetry estimates here is that excessive extension of the time periods under consideration should not result in a dramatic increase in errors of these estimates of thyroid doses, which are explicitly dependent on the age of an individual at the moment of the intake of radioiodine into the body.

For location in the vicinity of Ozersk, it is legitimate to talk about some integrated (formed over a prolonged period of time) ground surface concentration of ^{131}I. This value is the outcome of 'averaging' maximum concentration values (occurring during the ^{131}I plume passage towards Ozersk) and almost zero concentration values (occurring when the plume was spreading in other directions). In other words, peak values of air concentration were interrupted by periods of zero concentration, when objects in the environment were not additionally contaminated; consideration of this pattern is important for an adequate interpretation of the results of actual measurements. For example, information on the actual rate of radioactive fallout of each of the three fractions of radioiodine under consideration is vitally necessary for appropriate processing of the results of field measurements of ^{131}I in pasture grass. However, for calculating the total internal thyroid dose, it is sufficient to know only the absolute amount of the radionuclide taken into the body and the route of its intake to the body (ingestion or inhalation). The same holds true for ^{131}I intake into cattle, considering the time-integrated concentration of the radionuclide in grass and milk.

In order to calculate the migration of ^{131}I through trophic chains and to determine the radiation exposure, values of ground surface volumetric activities, $\chi(l,t)$, and surface contamination densities, $I(l,t)$, (summed up for all iodine forms) integrated over day t were obtained for each calculation point l of the model domain using the RATCHET code (Ramsdell et al. 1994).

1.3 Selection of age groups

For identical levels of radioactive contamination of air and foodstuffs there is a significant dependence of the internal dose on age of the exposed individual. All guidelines issued by the International Commission on Radiological Protection (ICRP) over the last few decades are generally applied to six age groups (V):

3 months,	$0 < V \leq 1$ year;
1 year,	$1 < V \leq 2$ years;
5 years,	$2 < V \leq 7$ years;
10 years,	$7 < V \leq 12$ years;
15 years,	$12 < V \leq 17$ years;
adults,	$V > 17$ years.

2 Main points of the ^{131}I migration model in the chain 'air $\rightarrow$ vegetation $\rightarrow$ soil $\rightarrow$ animals $\rightarrow$ man'

Initial parameters of the model under consideration include (Snyder et al. 1994):

- Time-integrated surface air concentrations (volumetric activities) of ^{131}I due to releases from the enterprise stacks, χ, (Ci·s)/(m^3 day);
- ^{131}I deposition rates (flux densities) from the atmospheric surface layer on surfaces of soil/vegetation, I, Ci/(m^2 day).

Values of these parameters were obtained for each calendar day t of the time interval under consideration (starting from January 1) for each node of the calculation spatial grid, l, in which the atmospheric transport model is implemented.

A generalized diagram of primary ^{131}I sources in the biological model in the chain 'atmosphere $\rightarrow$ soil/vegetation' is given in Fig. 2.1. The model assumes four major compartments in which accumulation and redistribution of ^{131}I deposited from the atmosphere on soil and vegetation surfaces occur:

- upper soil layer, Q_{usl};
- root zone, Q_{rz};
- outer part of vegetation, Q_{ov};
- inner part of vegetation, Q_{iv}.

Current (by time) surface (per unit area) activity of ^{131}I in each of these compartments is expressed in the units of Ci/m^2. Redistribution of activity between the compartments is described by the following system of differential equations:

$$\begin{cases} \dfrac{dQ_{usl}}{dt} = I \cdot f_s - Q_{usl} \cdot \left(\lambda_{perc} + \lambda_{rad}\right) + Q_{ov} \cdot \lambda_{weath} - R_{resus} + R_{senc,iv} + R_{senc,ov}; & (2.1) \\ \dfrac{dQ_{rz}}{dt} = Q_{usl} \cdot \lambda_{perc} - Q_{rz} \cdot \left(\lambda_{leach} + \lambda_{rad}\right) - R_{root}; & (2.2) \\ \dfrac{dQ_{ov}}{dt} = I \cdot f_v - Q_{ov} \cdot \left(\lambda_{weath} + \lambda_{rad} + \lambda_{trans}\right) + R_{resus} - R_{senc,ov}; & (2.3) \\ \dfrac{dQ_{iv}}{dt} = Q_{ov} \cdot \lambda_{trans} - Q_{iv} \cdot \lambda_{rad} + R_{root} - R_{senc,iv}. & (2.4) \end{cases}$$

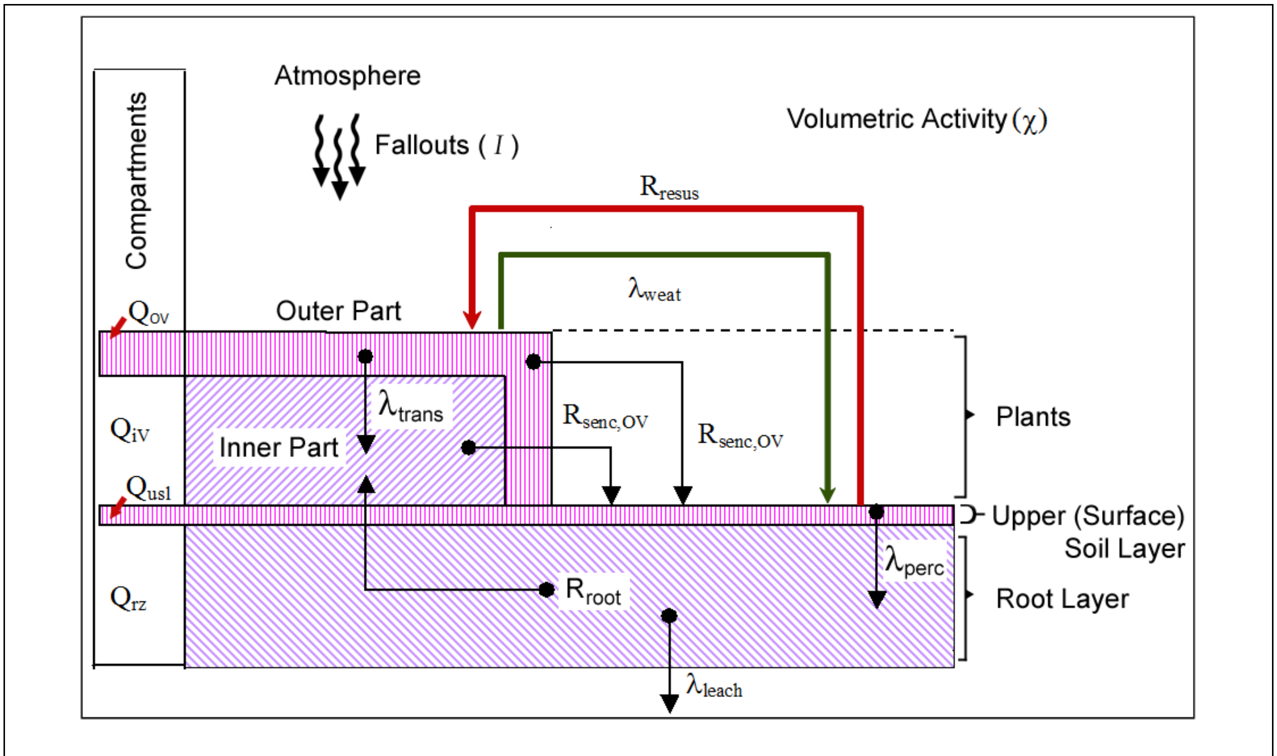

Figure 2.1. Diagram of primary flows in the ^{131}I transport model in the chain 'atmosphere $\rightarrow$ vegetation $\rightarrow$ soil'.

The factors f_s and f_v characterize the fraction of atmospheric fallout that is deposited directly upon soil or upon vegetation surfaces, respectively, where:

$$f_S + f_v = 1; \quad f_v = 1 - e^{-\alpha \cdot B(t,l)}; \quad f_S = e^{-\alpha \cdot B(t,l)}, \tag{2.5}$$

where *B(t,l)* is the surface density of the plant biomass at time *t* in the node *l* under consideration of the spatial calculation grid, kg/m^2 (dry weight);

α is an empirical constant considering the deposition of ^{131}I retained by plants, m^2/kg (dry weight).

(All parameters used in the equations given in this report are described, and default values are supplied, in Appendix A. Only those of particular interest or importance are discussed in more detail in this section)

The constant parameters λ (with corresponding subscripts), d^{-1}, characterize the rate of activity redistribution between the compartments. Physical interpretation of these constant parameters and recommended numerical values are given in Appendix A.

The parameter R (with corresponding indexes), Ci/(m^2 day) designates activity transfers between compartments that take into account the following physical processes:

- ^{131}I resuspension from the soil surface layer, R_{resus}

$$R_{resus} = \frac{Q_{usl} \cdot ML \cdot V_d}{\rho_{usl}}; \tag{2.6}$$

- activity transfer to plants from the root soil layer, R_{root}

$$R_{root} = Q_{rz} \cdot \frac{CR}{\rho_{rz}} \cdot \left(\frac{dB(t,l)}{dt} \right). \tag{2.7}$$

The function $\frac{dB}{dt}$ describes the variation of above-ground biomass per time unit during the vegetation period of the current year. Based on the proposed form of the equation for herbaceous vegetation biomass dynamics $B(t,l)$ (Appendix C), equation (2.7) takes into account periods of biomass growth or senescence. The loss via senescence of surface (external), $R_{senc,ov}$, and internal $R_{senc,iv}$, parts of vegetation is given as:

$$R_{senc,iv} = \frac{Q_{iv}}{B(t,l)} \cdot k_S \cdot \left(B(t,l) - B_{\min}\left(\tilde{T},l\right) \right) = C_{p,iv} \cdot k_S \cdot \left(B(t,l) - B_{\min}\left(\tilde{T},l\right) \right) \tag{2.8}$$

$$R_{senc,ov} = \frac{Q_{ov}}{B(t,l)} \cdot k_S \cdot \left(B(t,l) - B_{\min}\left(\tilde{T},l\right) \right) = C_{p,ov} \cdot k_S \cdot \left(B(t,l) - B_{\min}\left(\tilde{T},l\right) \right) \tag{2.9}$$

where $\tilde{T}$ is the duration of vegetation season; the default $B_{\min}\left(\tilde{T},l\right)$ value is equal to zero. When $\tilde{T}$ is the duration of the grazing period, strictly speaking, $B_{\min}\left(\tilde{T},l\right)$ differs from zero (at the end of $\tilde{T}$) (Appendix C).

Senescence processes are taken into account during the period after achieving maximum biomass of herbaceous vegetation (by default from July 1 to the end of the vegetation period of the model year).

Parameters $C_{p,iv}$ and $C_{p,ov}$ are the specific activities of the internal and external parts of biomass of vegetation of type p. Their sum provides the total specific activity of vegetation biomass C_p

$$C_{p,ov} = \frac{Q_{ov}}{B(t,l)}; \quad C_{p,iv} = \frac{Q_{iv}}{B(t,l)}; \quad C_p = C_{p,ov} + C_{p,iv}. \tag{2.10}$$

The amount $A_{const}(t,l)$ of ^{131}I transferred to the animal at location l on day t is calculated as:

$$A_{cons}(t,l) = \sum_{v=1}^{v} R_v \cdot C_v \cdot (h_v, l) \cdot e^{-\lambda_{rad} \cdot th_s} \text{ , (Ci/day),} \tag{2.11}$$

where R_v is the amount of food of type v, including water from stock tanks and ponds consumed by an animal during the day, kg/day (dry weight) or m^3/day (for water);

h_v is the day, since the beginning of the year, on which the fodder of type v was gathered (harvested or consumed), where v – grain, green grass, hay, silage, etc.;

$C_v(h_v,l)$ is the ^{131}I concentration in foodstuff v (including water in stock tanks and ponds) consumed on day h_v at location l, Ci/kg (dry weight) or Ci/m^3 (for water);

During the grazing season (period with no ice cover), ^{131}I concentration in water of a stock tank, swamp, ditch, pond, lake, $C_v \cdot (h_v, l)\big|_{v=water}$ can be estimated as:

$$C_v \cdot (h_v, l)\big|_{v=water} = \bar{I}(h_v, l, \tau) \cdot \left[h_{water} \cdot (\lambda_{water} + \lambda_{rad}) \right]^{-1} \text{ ,} \tag{2.12}$$

where λ_{water} is a parameter that characterizes the reservoir water cleaning rate, day^{-1};

h_{water} is the reservoir depth at the cattle drinking place, m;

$\bar{I}(h_v, l, \tau)$ is the ^{131}I fallout density formed over a long time period τ (25-30 days by default) preceding point of time h_v at location l, Ci/(m^2·day).

The effective depth of a non-circulating stock tank at the cattle drinking place is recommended to be h_{water} = 0.5 m.

The parameter λ_{water} that characterizes the water purification rate in the stock tank takes into account ^{131}I sorption processes in bottom sediments as well as other losses (e.g., consumptive loss via cattle drinking). Because radioiodine has an extremely low sorptive capacity (distribution factor of $K_d \cong 0.2$ m^3/kg), for tanks and small ponds the value of λ_{water} is usually significantly lower than the decay constant ($\lambda_{water} << \lambda_{rad}$) and can be neglected.

^{131}I concentration in foodstuff ap of animal origin, $C_{ap}(t,l)$, is calculated as:

$$C_{ap}(t,l) = TF_{ap}\left[A_{cons}(t,l) + FS_a\left(\frac{f_{usl}Q_{usl}(t,l)}{\rho_{usl}} + \frac{f_{rz}Q_{rz}(t,l)}{\rho_{rz}}\right)\right] + TF_{ap}\cdot I(l,t)\cdot(M + 0.001\cdot R_w \cdot S)$$

(Ci/kg (wet weight)) (2.13)

where $A_{cons}(t,l)$ is the ^{131}I intake rate by the animal with food on day t at location l, Ci/day;

f_{usl} is the fraction of soil eaten by an animal from the surface ground layer of the total soil intake, dimensionless;

f_{rz} is the fraction of soil eaten by an animal from the root zone, dimensionless ($f_{usl} + f_{rz} = 1$);

M is the surface area of fodder in a manger for the grazing of cattle, m^2;

S is the inverse of the depth of the stock tank or pond (m^{-1}); and

R_w is the water consumption rate of the animal

For the conditions in the region of the Mayak PA, the second term of equation (2.13) is insignificant and can be neglected.

The ^{131}I concentration in milk $C_{cream,x}(t)$ delivered from the creamery x on day t is calculated as:

$$C_{cream,x}(t) = \sum_{l=1}^{L(x)} f_{cream,x}(t,l)\cdot\sum_{r=1} f_r(t,l)\cdot C_r(t,l), \quad \text{(Ci/l)}, \qquad (2.14)$$

where $C_r(t,l)$ is the ^{131}I concentration in milk of the herd of cows with eating pattern r at location l at time t, Ci/l;

$f_r(t,l)$ is the fraction of milk obtained from the herd of cows with eating pattern r and located at location l at time point t, dimensionless; and

$f_{cream,x}(t,l)$ is the fraction of milk at creamery x delivered from the dairy farm located at location l on day t, dimensionless.

The cows' milk specific activity (without correction for radioactive decay) in all grocery stores is calculated as:

$$C_{groc}(t,l) = \left\{\sum_{x=l}^{X(l)} f_{groc,x}(t,l)\cdot C_{cream,x}(t)\right\} + f_u(t,l)\cdot C_u(t,l) + f_{other}(t,l)\cdot C_{other}(t,l), \quad (2.15)$$

where $f_{groc,x}(t,l)$ is the fraction of milk in grocery stores delivered from creamery *X* and available at location *l* on day *t*, dimensionless;

$f_{other}(t,l)$ is the fraction of milk in grocery stores at location *l* and on day *t* delivered from known sources located outside the boundaries of the area under study, dimensionless;

$C_{other}(t,l)$ is the ^{131}I specific activity in milk from the known source located outside the area under study (usually taken as zero), Ci/l;

$f_u(t,l)$ is the fraction of milk in a grocery store delivered from unknown sources, dimensionless; and

$C_u(t,l)$ is the specific activity of milk of unknown origin, calculated in the same way as for milk from a herd of cows grazed at location *l* and fed on the basis of feeding regime1 (fresh pasture), Ci/l.

The specific activity of ^{131}I in leafy vegetables (without correction for radioactive decay during the vegetable storage period) available for sale in grocery stores, is calculated as:

$$C_{comlv,iv}(t,l) = \sum_{m=1}^{M(l)} f_{lv}(l,m) \cdot C_{lv,iv}(t,m), \tag{2.16}$$

$$C_{comlv,ov}(t,l) = \sum_{m=1}^{M(l)} f_{lv}(l,m) \cdot C_{lv,ov}(t,m), \tag{2.17}$$

where $C_{comlv,iv}(t,l)$ and $C_{comlv,ov}(t,l)$ are the specific activity of ^{131}I contained in the internal and external parts of leafy vegetables sold in grocery stores on day *t* and at location *l*, Ci/kg (wet weight);

$f_{lv}(l,m)$ – fraction of leafy vegetables purchased through retail and wholesale trading network at location *l* and grown at location *m*, dimensionless; and

$C_{lv,iv}(t,m)$ and $C_{lv,ov}(t,m)$ – specific activity of ^{131}I contained in internal and external parts of leafy vegetables on day *t* that were grown at location *m*, Ci/kg (wet weight).

3 Calculation of doses to individuals

Absorbed external radiation dose due to submersion in the cloud from ^{131}I, D_{imm}, is calculated as:

$$D_{imm}(V)=\frac{DF_{imm}(V)\cdot\chi(t,l)\cdot\left[f_{time}(V)+\left(1-f_{time}(V)\right)\cdot Sh1(V)\right]}{86400},\quad\left[\frac{rad}{day}\right]\qquad(3.1)$$

where V is an age and gender factor; and

86,400 is a conversion factor, s/day.

External absorbed dose to thyroid due to irradiation from contaminated soil surfaces is calculated as:

$$\begin{aligned}&D_{grd}(V)=A_{grd}\cdot\left[f_{time}(V)+\left(1-f_{time}(V)\right)\cdot Sh1(V)\right]\\&A_{grd}=Q_{usl}\cdot DF_{usl}+Q_{rz}\cdot DF_{rz}\end{aligned},\qquad(3.2)$$

The absorbed dose due to ^{131}I inhalation by an individual of age V is calculated as:

$$\begin{aligned}&D_{inh}(V)=BR(V)\cdot DF_{inh}(V)\cdot A_{inh}\cdot\left[f_{time}(V)+\left(1-f_{time}(V)\right)\cdot R_{io}\right]\\&A_{inh}=\frac{\chi(t,l)}{86400}+\Psi,\quad\Psi=\left[\begin{array}{l}Q_{usl}^{j}\cdot ML\cdot\left(\rho_{use}\right)^{-1}\\0\end{array}\right.\end{aligned},\qquad(3.3)$$

The parameter Ψ used in this equation is non-zero during the period when snow cover is absent (by default, from April 15 through November 15) and correspondingly is equal to zero during the period of continuous snow cover (November 16 through April 14).

Internal absorbed dose to the thyroid from consumption by an individual of foodstuffs of animal origin, $D_{ing,ap}(t,l)$, and plant origin, $D_{ing,veg1}(t,l)$, contaminated with ^{131}I is calculated as:

$$D_{ing,veg1}(t,l)=DF_{ing}(V)\cdot\sum_{p}C_{p}\left(t-th_{p},l\right)\cdot R_{p}\cdot f_{d}\cdot e^{-\lambda_{rad}\cdot th_{p}},\qquad(3.4)$$

$$D_{ing,ap}(t,l)=DF_{ing}(V)\cdot\sum_{ap}C_{ap}\left(t-th_{p},l\right)\cdot R_{p}\cdot e^{-\lambda_{rad}\cdot th_{p}},\qquad(3.5)$$

where $C_p(t\text{-}th_p,l)$ is the specific activity of ^{131}I in foodstuffs of plant origin at time t adjusted for holdup since harvest of length th_p at point l (p = leafy vegetables, grain crops, etc.), Ci/kg (dry weight);

$C_{ap}(t\text{-}th_p,l)$ is the specific activity of ^{131}I in human foodstuffs of animal origin at time t adjusted for holdup of length th_p at location l (ap = milk, chicken, eggs, etc.), Ci/l (milk) or Ci/kg (initial weight); and

R_p is the daily consumption of foodstuff p, kg/day (consumable weight) or l/day (milk).

The absorbed dose of internal radiation to the thyroid due to ingestion of ^{131}I contained in external and internal parts of leafy vegetables and fruit is calculated as:

$$D_{ing.veg2}\left(t,l\right)=DF_{ing}\cdot\sum_{p}\left[C_{p,iv}\left(t-th_p,l\right)+C_{p,ov}\left(t-th_p,l\right)\cdot L_{proc}\right]\cdot R_p\cdot f_d\cdot e^{-\lambda_{rad}\cdot th_p}, \quad (3.6)$$

where $C_{p,iv}\left(t-th_p,l\right)$ is the specific activity of ^{131}I in internal consumable parts of the foodstuffs at time t adjusted for holdup since harvest of length th_p at location l, Ci/kg (dry weight);

$C_{p,ov}\left(t-th_p,l\right)$ is the specific activity of ^{131}I in external consumable parts of the foodstuffs at time t adjusted for holdup of length th_p at location l, Ci/kg (dry weight);

The absorbed dose from external radiation to the thyroid of a mother, a fetus, and a newborn child due to submersion in the ^{131}I cloud and its accumulation in soil is calculated as:

$$D_{ext.bfeed}\left(l\right)=DF_{imm}\cdot A_{ext}+DF_{usl}\cdot B_{ext}+DF_{rz}\cdot C_{ext}, \quad (3.7)$$

$$A_{ext}=\sum_{t=\tau}^{T}\frac{\chi\left(t,l\right)\cdot\left[f_{time}+\left(1-f_{time}\right)\cdot Sh1\right]}{86400}, \quad (3.8)$$

$$B_{ext}=\sum_{t=\tau}^{T}Q_{usl}\left(t,l\right)\cdot\left[f_{time}+\left(1-f_{time}\right)\cdot Sh1\right], \quad (3.9)$$

$$C_{ext}=\sum_{t=\tau}^{T}Q_{rz}\left(t,l\right)\cdot\left[f_{time}+\left(1-f_{time}\right)\cdot Sh1\right], \quad (3.10)$$

where A_{ext} is the contribution to external exposure due to cloudshine from air concentration $\chi(t,l)$ accounting for the individual's fraction of time outdoors (unshielded), f_{time}, and shielding properties of buildings/constructions *Sh1*, Ci/(m^3·day);

B_{ext} is the contribution to external exposure from the soil surface layer for contamination density $Q_{usl}(t,l)$ taking into account such factors as f_{time} and *Sh1*, Ci/m^2;

C_{ext} is the contribution to external exposure from the soil root layer for contamination density $Q_{rz}(t,l)$ taking into account such factors as f_{time} and *Sh1*, Ci/m^2.

The absorbed dose from internal radiation to the thyroid due to ^{131}I inhalation intake of a nursing mother, $D_{inh.mother}(l)$, a fetus, $D_{inh.fetus}(l)$, and a newborn child, $D_{inh.baby}(l)$, during a day is calculated on the basis of the following set of equations:

$$D_{inh.mother}(l) = DF_{inh} \cdot A_{inh.mother}(l); \tag{3.11}$$

$$D_{inh.fetus}(l) = DF_{pre} \cdot A_{inh.mother}(l); \tag{3.12}$$

$$D_{inh.baby}(l) = DF_{inh.baby} \cdot A_{inh.baby}(l) + DF_{nurs} \cdot A_{inh.mather}(l). \tag{3.13}$$

The intake of activity $A_{inh.x}(l)$ by a representative of a critical group (*x*) has contributions from the concentration of radionuclides in the air directly from the source $\chi(t,l)$ and by secondary wind resuspension of aerosols from the contaminated surface soil layer $Q_{usl}(t,l)$. The activity intake depends on age-related breathing rates *BR(V)* and individuals' fraction of time outdoors, f_{time}, as:

$$A_{inh.x}(l) = \begin{matrix} \sum_{t=\tau}^{T} BR(V) \cdot \frac{\chi(t,l)}{86400} \cdot \left[f_{time} + (1 - f_{time}) R_{io} \right] + \\ + \sum_{t=\tau}^{T} BR(V) \cdot Q_{usl}(t,l) \frac{ML}{\rho_{usl}} \left[f_{time} + (1 - f_{time}) \cdot R_{io} \right] \end{matrix}, \text{ (Ci/day).} \tag{3.14}$$

The absorbed dose from internal radiation to the thyroid due to ^{131}I ingestion for a nursing mother, $D_{ing.mother}(l)$, a fetus, $D_{ing.fetus}(l)$, and a new-born child, $D_{ing.baby}(l)$, is calculated on the basis of the following set of equations:

$$D_{ing.mother}\left(l\right)=DF_{ing.mother}\cdot A_{ing.mother}\left(l\right); \tag{3.15}$$

$$D_{ing.fetus}\left(l\right)=DF_{pre}\cdot A_{ing.mother}\left(l\right); \tag{3.16}$$

$$D_{ing.baby}\left(l\right)=DF_{ing.baby}\cdot A_{ing.baby}\left(l\right)+DF_{nurs}\cdot A_{ing.mather}\left(l\right). \tag{3.17}$$

and intake activity $A_{inh.x}\left(l\right)$ of a representative of the critical exposure group *x* has contributions from intakes of consumed foodstuffs of animal origin, $C_{ap}(t,l)$, and plant origin, $C_p(t,l)$

$$A_{ing.x}\left(l\right)=\sum_{t=\tau}^{T}\left[C_p\left(t,l\right)+C_{ap}\left(t,l\right)\right]\cdot f_d\cdot R_p\cdot e^{-\lambda_{rad}\cdot th_p}\text{, Ci/day.} \tag{3.18}$$

Conclusion

1. This report provides a description of the model of environmental radioiodine behavior based on Snyder et al. (1994).

2. This report describes the developed and proposed model of within-year variation of plant biomass density for the Mayak PA area (Appendix C).

3. Model parameters are provided that describe local conditions of the Mayak PA area. Some of these parameters will be superseded by those provided in Anspaugh and Napier (2009).

4. Supplementary numerical values of economic indices of animal husbandry and crop production for the compartment model of ^{131}I migration will be taken from Mokrov et al. (2007).

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Appendix A

Description and numerical values of the radioecological model parameters (Snyder et al. 1994)

Para-meter	Description of parameter	Units	Default value	Estimates: average	min	max	Type of* distribution
α	Empirical foliar interception constant	m^2/kg (dry weight)	–	–	1.0	4.0	U
λ_{leach}	Leaching rate of ^{131}I from root zone to deeper soil layers	day^{-1}	$3.2\cdot10^{-4}$	$3.2\cdot10^{-4}$	$4.0\cdot10^{-6}$	$5.0\cdot10^{-3}$	U
λ_{perc}	Percolation rate of ^{131}I from upper soil layer to root zone	day^{-1}	–	–	0.14	0.914	U
λ_{rad}	^{131}I radioactive decay constant	day^{-1}	$8.625\cdot10^{-2}$	–	–	–	–
λ_{weath}	rate of ^{131}I vegetation surface activity decrease due to weathering	day^{-1}	–	0.0495	0.0347	0.0866	T
ρ_{rz}	Average areal density of root soil layer with a depth of 0.1 to 15 cm	kg/m^2 (wet weight)	–	–	186	230	U
ρ_{usl}	Average areal density of upper soil layer with depth of 0.1 cm	kg/m^2 (wet weight)	–	–	1.10	1.45	U
BR	Daily age dependent breathing rates: (0-0.5) years	m^3/day	–	1.62	0.5	4.9	T
	(0.5-2.0) years		–	5.14	1.7	15.4	
	(2.0-7.0) years		–	8.71	2.9	26.1	
	(7.0-12.0) years		–	15.3	5.1	45.9	
	(12.0-17.0) years		–	17.7	5.9	53.9	
	17 years and over		–	22.0	7.3	66.0	
CR	^{131}I plant-to-soil concentration ratio	$\left(\frac{Ci/kg(dry)}{Ci/kg(dry)}\right)$	–	–	0.01	0.25	LU
DF_{imm}	Age-dependent immersion dose rate factor (relating to semi-infinite ^{131}I cloud)	–					U
	for absorbed dose to the thyroid	$\left(\frac{rad/day}{Ci/m^3}\right)$	–	$5.68\cdot10^3$	$2.8\cdot10^3$	$1.1\cdot10^4$	
	for effective equivalent dose to the thyroid	$\left(\frac{rem/day}{Ci/m^3}\right)$	–	$5.23\cdot10^3$	$2.6\cdot10^3$	$1.0\cdot10^4$	
DF_{ing}	Ingestion age- and gender dependent dose factor	–					LN
	for absorbed dose to the thyroid for:	rad/Ci	–				
	(0-0.5) years		–	$1.4\cdot10^7$	$2.2\cdot10^6$	$5.5\cdot10^7$	
	(0.5-2.0) years		–	$1.3\cdot10^7$	$2.0\cdot10^6$	$5.1\cdot10^7$	
	(2.0-7.0) years		–	$7.8\cdot10^6$	$1.2\cdot10^6$	$3.1\cdot10^7$	
	(7.0-12.0) years		–	$4.1\cdot10^6$	$6.4\cdot10^5$	$1.6\cdot10^7$	
	(12.0-17.0) years		–	$2.5\cdot10^6$	$3.9\cdot10^5$	$9.9\cdot10^6$	
	17 years and over (male)		–	$1.4\cdot10^6$	$2.2\cdot10^5$	$5.5\cdot10^6$	
	17 years and over (female)		–	$1.7\cdot10^6$	$2.7\cdot10^5$	$6.7\cdot10^6$	

Para-meter	Description of parameter	Units	Default value	Estimates average	min	max	Type of* distribution
DF_{ing}	for effective equivalent dose	rem/Ci	–	–	–	–	LN
	(0-0.5) years		–	$4.1\cdot10^5$	$6.4\cdot10^4$	$1.6\cdot10^6$	
	(0.5-2.0) years		–	$4.1\cdot10^5$	$6.4\cdot10^4$	$1.6\cdot10^6$	
	(2.0-7.0) years		–	$2.3\cdot10^5$	$3.6\cdot10^4$	$9.1\cdot10^5$	
	(7.0-12.0) years		–	$1.2\cdot10^5$	$1.9\cdot10^4$	$4.7\cdot10^5$	
	(12.0-17.0) years		–	$7.8\cdot10^4$	$1.2\cdot10^4$	$3.1\cdot10^5$	
	17 years and over (male)		–	$4.8\cdot10^4$	$7.5\cdot10^3$	$1.9\cdot10^5$	
	17 years and over (female)		–	$5.8\cdot10^4$	$9.1\cdot10^3$	$2.3\cdot10^5$	
DF_{inh}	Inhalation age- and gender dependent dose factor	–	–	–	–	–	LN
	for absorbed dose to the thyroid (0-0.5) years	rad/Ci	–	$8.5\cdot10^6$	$1.3\cdot10^6$	$3.3\cdot10^7$	
	(0.5-2.0) years		–	$8.1\cdot10^6$	$1.3\cdot10^6$	$3.2\cdot10^7$	
	(2.0-7.0) years		–	$4.8\cdot10^6$	$7.5\cdot10^5$	$1.9\cdot10^7$	
	(7.0-12.0) years		–	$2.4\cdot10^6$	$3.8\cdot10^5$	$9.5\cdot10^7$	
	(12.0-17.0) years		–	$1.5\cdot10^6$	$2.3\cdot10^5$	$5.9\cdot10^6$	
	17 years and over (male)		–	$1.0\cdot10^6$	$1.6\cdot10^5$	$3.9\cdot10^6$	
	17 years and over (female)		–	$1.2\cdot10^6$	$1.9\cdot10^5$	$4.7\cdot10^6$	
	for effective equivalent dose	rem/Ci	-	-	-	-	
	(0-0.5) years		–	$2.5\cdot10^5$	$3.9\cdot10^4$	$9.9\cdot10^5$	
	(0.5-2.0) years		–	$2.5\cdot10^5$	$3.9\cdot10^4$	$9.9\cdot10^5$	
	(2.0-7.0) years		–	$1.4\cdot10^5$	$2.2\cdot10^4$	$5.5\cdot10^5$	
	(7.0-12.0) years		–	$7.4\cdot10^4$	$1.2\cdot10^4$	$2.9\cdot10^5$	
	(12.0-17.0) years		–	$4.8\cdot10^4$	$7.5\cdot10^3$	$1.9\cdot10^5$	
	17 years and over (male)		–	$3.0\cdot10^4$	$4.7\cdot10^3$	$1.2\cdot10^5$	
	17 years and over (female)		–	$3.6\cdot10^4$	$5.6\cdot10^3$	$1.4\cdot10^5$	
DF_{nurs}	Dose factor relating the internal dose to the nursing baby resulting from intakes of the mother	–	–	–	–	–	LN
	– absorbed dose to the child's thyroid (rad) from the intake of ^{131}I by the mother (Ci)	rad/Ci	–	$2.4\cdot10^6$	$3.3\cdot10^5$	$1.0\cdot10^7$	
	– effective equivalent dose to the nursing baby (rem) from the intake of ^{131}I by the mother (Ci)	rem/Ci	–	$7.0\cdot10^4$	$9.4\cdot10^3$	$3.0\cdot10^5$	
DF_{pre}	Dose factor relating the dose to the fetus (i.e. prenatal) from intakes to the mother	rad/Ci	–	$2.3\cdot10^6$	$1.1\cdot10^6$	$4.6\cdot10^6$	T
DF_{rz}	Dose rate factor for ^{131}I in the soil root zone [2]	$\left(\frac{rem/day}{Ci/m^2}\right)$	–	–	49	88	U
DF_{usl}	Dose rate factor for upper soil layer or surface activity [2]	–	–	–	–	–	U
	– for absorbed dose to the thyroid	$\left(\frac{rad/day}{Ci/m^2}\right)$	–	–	84	120	
	– for effective equivalent dose	$\left(\frac{rem/day}{Ci/m^2}\right)$	–	–	77	110	

Parameter	Description of parameter	Units	Default value	Estimates			Type of* distribution
				average	min	max	
f_d	Dimensionless dry-weight to wet-weight conversion factor:	$\frac{kg\ (dry)}{kg\ (wet)}$	–	–	–	–	U
	leafy vegetables		–	–	0.05	0.09	
	other vegetables		–	–	0.04	0.26	
	fruit trees		–	–	0.13	0.35	
	grains		–	–	0.85	1.00	
FS_a	Daily soil ingestion rate for a chicken	kg/day (initial weight)	$3{\cdot}10^{-3}$	$3{\cdot}10^{-3}$	$6.0{\cdot}10^{-5}$	$1.2{\cdot}10^{-2}$	U
FS_a	Daily soil ingestion rate for cow (bull) at various durations of stay on pasture lands :	–	–	–	–	–	U
	24 h/d – all pasture	kg/day (initial weight)	–	0.5	0.25	1.0	
	12 h/d – half		–	1.0	0.50	1.5	
	0 h/d – no pasture		–	2.0	1.0	4.0	
f_{time}	Fraction of day spent outdoors:	–	–	–	–	–	T
	1. Children (male/female) from 0 to 2 years:		–	–	–	–	
	winter		–	0.0	0.0	0.13	
	spring		–	0.04	0.0	0.17	
	summer		–	0.13	0.0	0.29	
	autumn		–	0.04	0.0	0.17	
	2. Children (male/female) from 2 to 17 years (urban):	–	–	–	–	–	T
	winter		–	0.10 / 0.05	0.04 / 0.04	0.13 / 0.13	
	spring		–	0.13 / 0.08	0.04 / 0.04	0.17 / 0.17	
	summer		–	0.35 / 0.22	0.08 / 0.08	0.38 / 0.38	
	autumn		–	0.13 / 0.08	0.04 / 0.04	0.17 / 0.17	
	3. The same for rural population:	–	–	–	–	–	
	winter		–	0.13 / 0.08	0.04 / 0.04	0.17 / 0.17	
	spring		–	0.21 / 0.17	0.04 / 0.04	0.23 / 0.23	
	summer		–	0.34 / 0.32	0.13 / 0.13	0.50 / 0.50	
	autumn		–	0.21 / 0.08	0.04 / 0.04	0.23 / 0.23	
f_{time}	4. Adults in urban areas (17 years and over):	–	–	–	–	–	T
	winter		–	0.05 / 0.07	0.0 / 0.0	0.17 / 0.17	
	spring		–	0.18 / 0.29	0.0 / 0.0	0.31 / 0.31	
	summer		–	0.22 / 0.29	0.04 / 0.04	0.41 / 0.41	
	autumn		–	0.10 / 0.15	0.0 / 0.0	0.31 / 0.31	

Para-meter	Description of parameter	Units	Default value	Estimates			Type of* distribution
				average	min	max	
	5. Adults of rural areas (17 years and over):	–	–	–	–	–	
	winter		–	0.33 / 0.21	0.04 / 0.04	0.37 / 0.37	
	spring		–	0.44 / 0.36	0.04 / 0.04	0.50 / 0.50	
	summer		–	0.47 / 0.29	0.06 / 0.06	0.50 / 0.50	
	autumn		–	0.34 / 0.21	0.04 / 0.04	0.37 / 0.37	
f_{trans}	Fraction of outer vegetation deposition that translocates to the inner vegetation compartment	–	–	0.04	0.01	0.2	LN
k_s	Parameter taking into account inner and outer vegetation senescence processes	day^{-1}	–	–	–	–	–
	fresh grass		0.01	–	0.0001	0.01	
L_{proc}	Food processing retention fraction	–	–	–	0.15	0.75	U
ML	Mass loading factor for local soil in air	kg/m^3 (dry weight)	–	$7.0\cdot10^{-8}$	$1.4\cdot10^{-8}$	$3.5\cdot10^{-7}$	LN
R_{io}	Indoor to outdoor ^{131}I volumetric activities ratio	–	–	0.68	0.35	1.0	U
S	Stock tank dilution factor	m^{-1}	–	1.0	0.2	1.6	T
$Sh1$	Shielding factor for semi-infinite plumes (depending on wall properties)	–	–	0.50	0.05	0.93	U
TF_{ap}	Animal product transfer factor (specific activity of ^{131}I in beef (Ci/kg) per daily intake of ^{131}I to the cow's organism (Ci/day)	$\left(\frac{Ci/kg}{Ci/day}\right)$	–	–	0.004	0.054	U
TF_{ap}	The same for chicken eggs (wet weight)	$\left(\frac{Ci/kg}{Ci/day}\right)$	–	–	1.5	6.0	U
TF_{ap}	The same for goat's milk (Ci/l)	$\left(\frac{Ci/l}{Ci/day}\right)$	–	0.27 (0.205)	0.04	1.15	LN
TF_{ap}	The same for cow's milk (public herd cows)	$\left(\frac{Ci/l}{Ci/day}\right)$	–	0.012	0.0073	0.016	N
TF_{ap}	The same for cow's milk (private cows)	$\left(\frac{Ci/l}{Ci/day}\right)$	–	$9.2\cdot10^{-3}$ (0.012)	$1.6\cdot10^{-3}$	$5.2\cdot10^{-2}$	LN
TF_{ap}	The same for chicken meat	$\left(\frac{Ci/kg}{Ci/day}\right)$	–	–	$4.0\cdot10^{-3}$	$9.4\cdot10^{-2}$	U
th_p	Holdup time for stored feed crops:	–	–	–	–	–	U
	all kinds of vegetables, fruits, cereals	day	–	–	0.0	7.0	
	milk from private cows or goats		–	–	0.0	2.0	
	purchased (commercial) milk		–	–	1.0	4.0	

Para-meter	Description of parameter	Units	Default value	Estimates: average	min	max	Type of* distribution
	stored milk products (sour cream, butter, etc.)		–	–	14.0	60.0	
	meat (beef)		–	–	7.0	21.0	
	poultry		–	–	2.0	10.0	
	eggs		–	–	0	21	
V_d	Local deposition velocity of resuspended soil back to soil or vegetation $\frac{Ci/m^2}{Ci \cdot s/m^3} \cdot \frac{s}{day}$	m/day	–	–	86.4	$2.59 \cdot 10^3$	U

* *U – uniform; LU – lognormally uniform; N – normal; PU – piecewise-uniform; T – triangular; LN – lognormal.*

Appendix B

Refined data of the radioecological model

Table B.1. Consumption of fresh leafy vegetables by different age groups of Ozersk residents during the period of summer (vegetation)

kg/day

Consumption (fresh weight)	Age group (L)					
	3 month.	1 year	5 years	10 years	15 years	Adults
$M_{veget}(L)$	–	0.024	0.027	0.035	0.042	0.042

Table B.2. Recommended parameters of air and feed consumption for cows and goats (from 1949 to 1963)

Parameter	Designation, units	Cow	Goat
Daily consumption of herbage (fresh weight)	M_{grass}, kg/day	50 (45 – 60)	6.5 (5 – 8)
Daily consumption of pasture soil	M_{soil}, kg/day	1.2 (0.5 – 1.8)	0.06 (0.05 – 0.07)
Daily consumption of hay during stabling period (dry weight)	M_{hay}, kg/day	10 (8 – 12)	1,7 (1.3 – 2.0)
Daily consumption of water	M_{wates}, l/day	50	10
Average breathing rate	M_{air}, m^3/day	170	16.5
Fraction of time spent by an animal in open area during a grazing season:	$k_{outdoor}$, h/day		
– public herd;		24	–
– private herd.		16	16 – 18

Table B.3 – Recommended values of water, food and air consumption for chickens

Parameter	Designation, units	Mean consumption (range)
Average daily consumption of fresh plants during summer period	M_{food}, kg/day	0.130 (0.120 – 0.150)
Average daily consumption of soil with feed	M_{soil}, kg/day	0.003 (0.002 – 0.004)
Average daily consumption of water without regard for feed at keeping in a pen during summer period	M_{water}, l/day	0.65 (0.5 – 0.8)
Breathing rate	M_{air}, m^3/day	23

Appendix C

Methods for determining patterns of biomass changes for forage crops growing in the vicinity of the Mayak Production Association

This report discusses the main aspects of selection of the ^{131}I biological food chain model, adaptation of the model to Southern Urals conditions, and justification of numerical values of the control parameters. The ^{131}I food chain model builds upon the methods developed by the Hanford Environmental Dose Reconstruction (HEDR) Project [1]. The bulk of equations, numerical values, and statistical distributions of the parameters used correspond to the HEDR model [1].

The most significant differences concern the equations and parameters which describe the dynamics of changes in the biomass of above-ground plant biomass. The need to develop our unique approach is explained by meteorological and landscape peculiarities of the Southern Urals. Growth and senescence of the biomass of herbaceous crops growing within the enterprise impact area depends greatly on the variation of temperature and precipitation during the vegetation period. Changing these meteorological parameters results in variations in the forage crop yield by a factor of 5-10 in different years.

The main points of the empirical method proposed for Project 1.4 are described for calculating annual dynamics of the biomass of non-irrigated pasture vegetation (forage crops) as a function of long-term changes in meteorological conditions. The dependencies are based on extensive experimental material [2-7] obtained, primarily, by experts of the Mayak Experimental Scientific and Research Station (ONIS).

In the northern part of Chelyabinsk oblast, the grazing period lasts for 155 – 175 days. The period of vegetation growth is usually from April to July, senescence and complete withering is from August to October. The weight of completely withered grass (a layer formed over a year) varies from 10 to 100 metric centners per hectare (0.1 to 1 kg/m^2). Data on the average annual herbage yields in the Southern Urals and on the biomass dynamics during the vegetation period are given in Tables C.1 and C.2.

Table C.1 –Dynamics of vegetation growth by phases of development

Phases of vegetation cycle	Biocenosis: different grasses and grains of moderately wet uplands of forest zone			Weight of herbage eaten during the flowering period (metric centner/ha)	
	Month	Herbage state	% of weight during flowering	wet	air-dry
Tillering	May-June	Growth	25-30	38	12
Ear-formation	July	Growth	70-80		
Flowering	July-August	Maximum	100		
Bearing	August	Senescence	80-90		
Withering	September-October	Complete withering	70-80		

Table C.2 – Biomass of herbaceous vegetation, 1981-1984, based on ONIS data

Biocenosis	Biomass, metric centner /hectare	Biocenosis	Biomass, metric centner/hectare
Clover + timothy (1 year)	36 ± 2	Lands left after the 1957 accident	22 ± 2
Clover + timothy(2 year)	48 ± 3	Swamp	14 ± 1
Bluegrass-fescue meadow	33 ± 9	Birch forest grass	26 ± 6
Meadow with different grasses and grains	37 ± 9	Pine forest grass	7 ± 2
Barley meadow	28 ± 8	Aspen forest grass	7 ± 2
Wild growing herbaceous vegetation (average)	20 ± 9	-	-

Using experimental data on annual barley yields (fresh sprouts, straw) obtained from the ONIS experimental ground in 1959 – 1983, the dependence of average annual biomass of annual herbage on meteorological conditions was analyzed. The time period during which there was no ice cover on water reservoirs was hypothetically taken as the duration of the vegetation period. Total precipitation and a sum of positive temperatures above 10 ^{o}C during the vegetation period were considered as meteorological parameters.

The corresponding regression dependencies obtained for annual herbaceous vegetation are shown in Figures C.1 and C.2. Similar dependencies are typical for different plant associations located in the vicinity of the enterprise (Figure C. 3).

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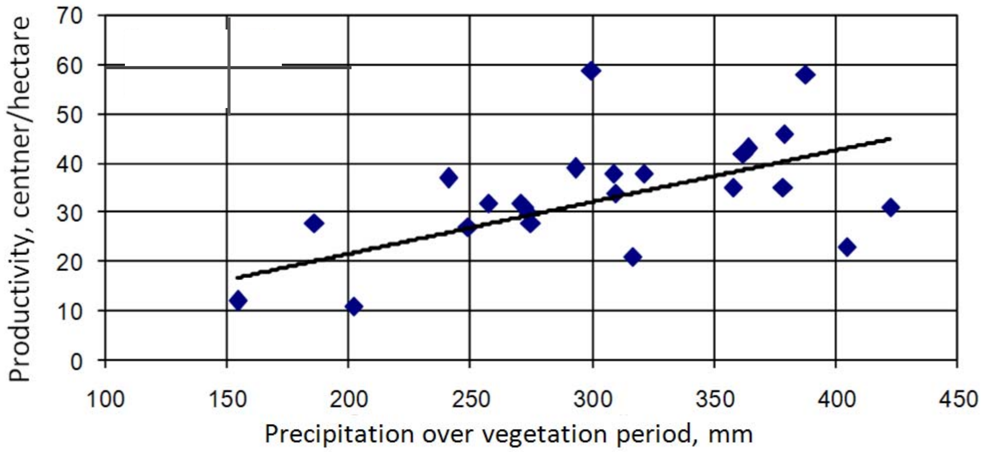

Figure C.1 – Dependence of the average annual biomass of annual herbage on precipitation during the vegetation period

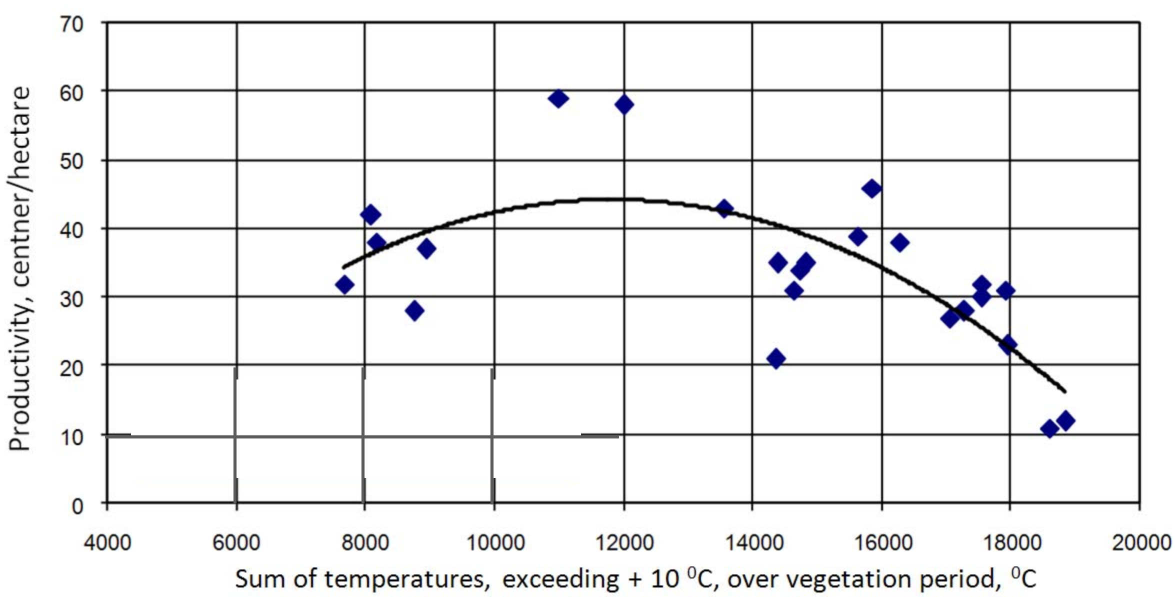

Figure C.2 – Dependence of the average annual biomass of annual herbage on air temperature during the vegetation period

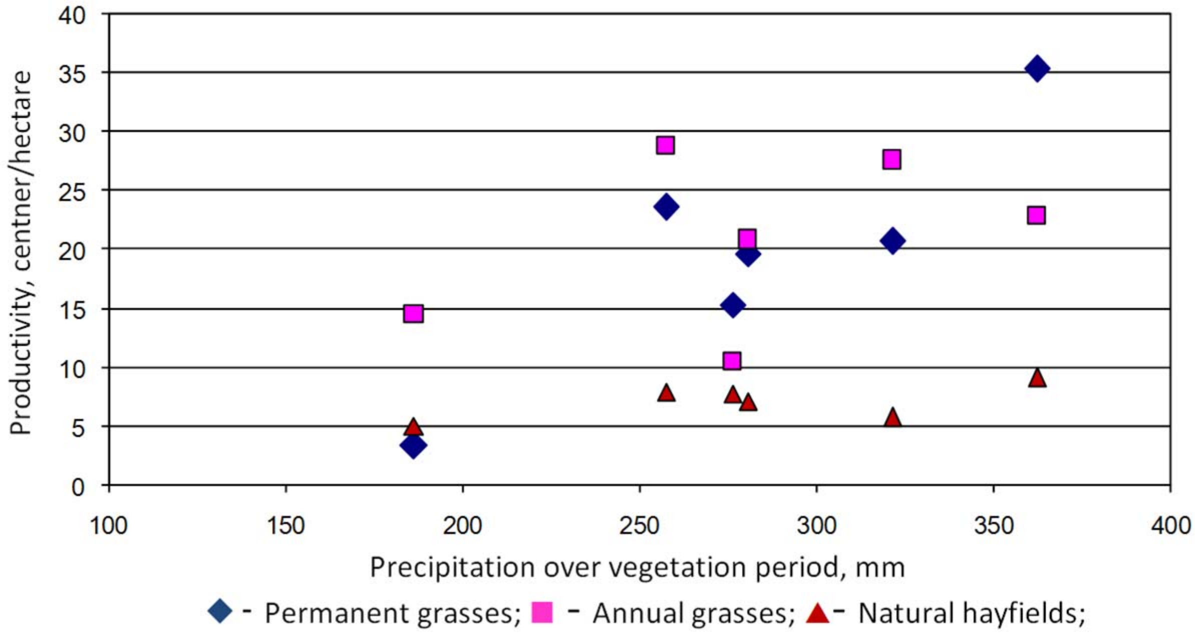

Figure C.3 – Dependence of the average annual biomass herbaceous vegetation on precipitation during the vegetation period (ONIS data, 1960)

While modeling the iodine migration in the chain from pasture grass to cows, the following assumptions were made:

1. Grazing and vegetation periods last from early May to late September (and the beginning of the grazing period is shifted 10-15 days in relation to the beginning of the vegetation period). The duration of vegetation and grazing periods for each year is calculated on the basis of specific climatic conditions.

2. The annual average biomass, $\overline{B}$, of fodder herbaceous vegetation is assumed to be 30 metric centners per hectare (0.3 kg/m^2).

3. Two independent correction factors[1)] are introduced to account for the variability of meteorological parameters, i.e. the temperature, (k_2), and the amount of precipitation, (k_1), during the vegetation period. In order to obtain the factors, the regression dependencies (Figs. C.1, C.2) are normalized ($k_1 = k_2 = 1$) to the average sum of temperatures (T_Σ) above 10 ^{0}C over the vegetation period ($T_\Sigma = 13200$ ^{0}C) and to the mean level of precipitation (Λ) over the vegetation period ($\Lambda = 280$ mm), respectively.

The correction factors are specified by the following equations

[1] Strictly speaking, the correction factors can not be regarded as independent. However, a period of maximum releases of ^{131}I (1950-1960s) was characterized by insufficient humidification, i.e. a low amount of precipitation was accompanied, as a rule, by high temperatures, and vice versa.

$$k_1 = 0,00423 \cdot \Lambda^{0,97}, \quad k_1 = 1\Big|_{\overline{\Lambda}=280} \tag{C.1}$$

$$k_2 = -1,56 \cdot 10^{-8} \cdot T_{\Sigma}^2 + 0,00035 \cdot T_{\Sigma} - 0,9018, \quad k_2 = 1\Big|_{\overline{T_{\Sigma}}=13200} \tag{C.2}$$

4. Yield values for each year are found as a product of the average annual biomass, $\overline{B}$, and the correction factors k_1 and k_2.

$$B_i = \overline{B} \cdot k_1 \cdot k_2 \tag{C.3}$$

5. Based on data from Table 1, an integrated (accounting for growth and senescence functions) value of the biomass on day *j* of the vegetation period of year *i* has a log-normal distribution (Figure C.4) [8], as:

$$B_{i,j} = \overline{B} \cdot k_1^i \cdot k_2^i \cdot f_{\log-norm} = \overline{B} \cdot k_1^i \cdot k_2^i \cdot \left(y_0 + a \cdot exp\left[-\frac{1}{2 \cdot b^2} \cdot \ln^2\left(\frac{day_j}{x_0} \right) \right] \right)$$
$$B_{\min} \equiv B_{i,1} = \overline{B} \cdot k_1^i \cdot k_2^i \cdot \left(y_0 + a \cdot exp\left[\frac{\ln^2 x_0}{2 \cdot b^2} \right] \right) \tag{C.4}$$

$$\frac{dB_{i,j}}{dt} = -\overline{B} \cdot k_1^i \cdot k_2^i \cdot \frac{a}{b^2} \cdot \frac{1}{day_j} \cdot \ln\left(\frac{day_j}{x_0} \right) \cdot exp\left[-\frac{1}{2 \cdot b^2} \cdot \ln^2\left(\frac{day_j}{x_0} \right) \right] \tag{C.5}$$

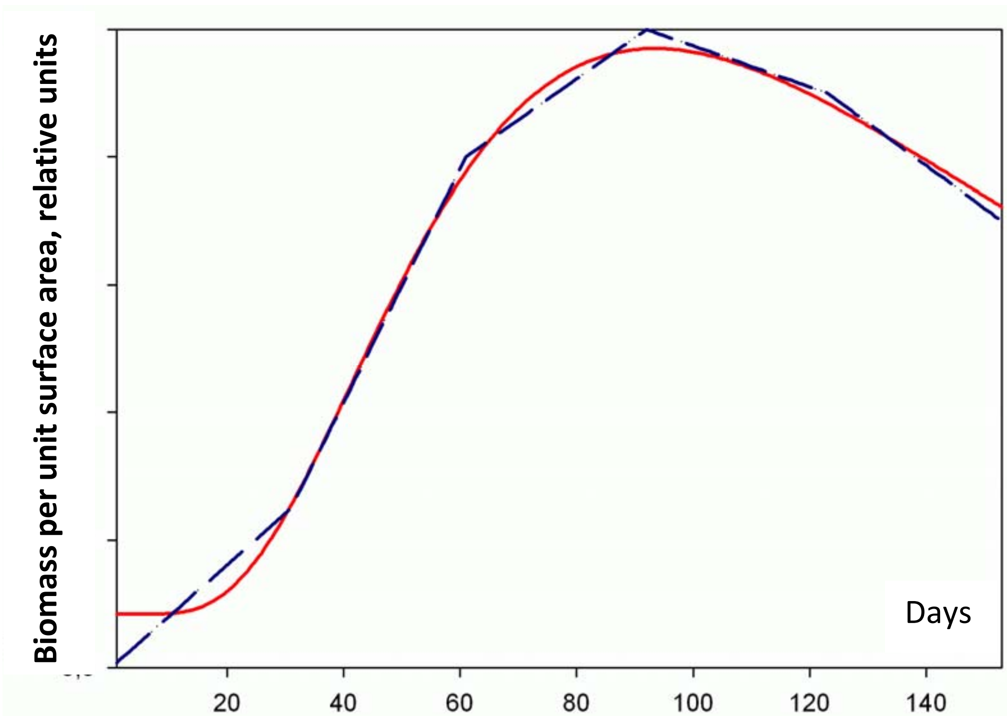

Figure C.4 – Distribution of the average annual biomass of herbaceous vegetation (in relative units) during the vegetation period (ONIS data, 1960s.)

References for Appendix C

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