DNIPRO STATE AGRARIAN AND ECONOMIC UNIVERSITY

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RADIOECOLOGY
OF AGRICULTURAL SOILS

MONOGRAPH

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The monograph considers topical questions on radiation pollution and restoration of agricultural lands, in particular the peculiarities of migration of radionuclides in soils of different types, the trophic chain: soil – plants – productive animals – humans; measures to minimize the accumulation of radionuclides in crop and livestock products; recommendations for agricultural production in contaminated areas. The material of modern scientific literature and results of own researches are used and systematized, the analysis of radionuclide pollution of agricultural lands in Dnipropetrovsk region is carried out.

The monograph is of interest to scientists, specialists in the field of agricultural radioecology, lectors of agricultural universities, higher education students of all levels who study disciplines of radioecological and radiobiological areas.

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CONTENT

INTRODUCTION

The study of the radioactive substances concentration and migration in agricultural production facilities and the effect of ionizing radiation on agricultural plants, animals and agrocenoses is the subject of agricultural radioecology.

Agricultural radioecology urgent tasks include:

1. Extensive systematic radiation monitoring of various spheres of management, including the assessment of the content of the main dose-forming natural and artificial radionuclides in the main objects of the environment: atmosphere, soil, water bodies, agricultural and forest lands.
2. Study of the features of radionuclides migration in soils of various types and in the chain: soil – plants – food – producing animals – human; the following quantitative assessment of the accumulation of radionuclides in individual links of the trophic chains.
3. Research of the features of the formation of absorbed doses of ionizing radiation in plants, animals and human due to internal irradiation of incorporated radionuclides, as well as their biological effect on certain species and groups.
4. Development of measures to minimize the accumulation of radionuclides in crop and livestock products and recommendations for agricultural production in contaminated areas.
5. Creation of mathematical models and computer systems that integrate the accumulated experimental information and make it possible to carry out long-term prediction of the behavior of radionuclides in natural objects and to estimate dose loads on living organisms.
6. Assessment of the role of product consumption by residents of radionuclide-contaminated areas as a source of additional human exposure.

I. RADIONUCLIDES MIGRATION IN THE ENVIRONMENT

1.1. Features of the radionuclides intake and the radiocapacity of agricultural ecosystems

Several sources of ionizing radiation act on objects of the environment and agricultural production, among which the main ones are:

– natural energy emission – an environmental factor that creates a natural background radiation and consists of cosmic radiation, radiation from external terrestrial sources and radiation from internal sources;

– artificial radionuclides formed in the course of nuclear reactions. A large amount of radioactive substances is formed during the explosion of an atomic bomb, the basis of which is a self-developing chain reaction of ^{235}U or ^{239}Pu separation (Kashparov, 2005; Prister, 2005; Hudkov et al., 2010).

Nuclear energy enterprises, whose work is associated with the extraction of uranium ore, its processing into enriched nuclear fuel, the production of fuel elements, the processing of spent fuel for subsequent use, the processing and disposal of radioactive waste, contribute to the environmental pollution. The listed production operations constitute the nuclear fuel cycle (NFC). At all stages of the NFC, radioactive substances may enter the environment.

Radioecological problems are exacerbated in conditions of disruption of technological processes at NFC enterprises, which is accompanied by accidents with the release of radioactive substances to the environment. As a result, radioactive contamination can get into natural ecosystems, agricultural land and lead to severe radioecological and socio-economic shifts (Klymenko, 2006; Hudkov et al., 2013).

Radioactive substances that enter the atmosphere gradually fall to the Earth's surface and concentrate in the soil. The spread of radioactive substances is influenced by: the initial height of the rise of radioactive substances; emission characteristics of fission products; weather conditions of the admission period; soil cover; chemical and physical properties of a radioactive substance.

Precipitation and air movement play an important role in the spread of radioactive substances. In this regard, a distinction is made between "wet" (the influx of radioactive substances onto the Earth's surface with rain and snow) and "dry" (precipitation of particles under the influence of gravity) radioactive fallout.

Radioactive substances that have fallen on the surface of the globe become an integral part of the biological cycles of the natural cycle of substances. They concentrate on three main objects: soil, water bodies, plants and through the food chain they enter the human body (Hudkov & Vinichuk, 2003, 2006).

On dry land, radioactive substances are transported by food chains: soil–plant–human, soil–plant–animal–human, so quickly that even those of them, the half-life of which is several days (for example, ^{131}I – 8 days), can accumulate in the human body in significant quantities.

The ecosystem radiocapacity is the maximum amount of radionuclides that can be contained in a particular ecosystem without disturbing its main trophic properties, that is, productivity, conditioning and reliability. To compare the radiocapacity of various ecosystems, the concept of *specific radiocapacity* is introduced – the ratio of the radiocapacity of a certain ecosystem to the area it occupies. The information given in the previous chapters allows us to formulate an important postulate: any ecosystem, small or large, simple or complex, is capable of firmly and for a sufficiently long time retaining radionuclides entering it through active accumulation or passive sorption, or even fixing for a long time significant amounts of radionuclides in activity (Klymenko, 2006; Hudkov et al., 2017).

However, it should be borne in mind that high levels of activity of radionuclides (up to $3{,}7 \times 10^7$ Bq, or 10^{-3} Ci/l and more) can be caused by very low chemical concentrations, to which the law of mass action is inapplicable, and therefore, toxicological problems regarding ecosystems contaminated with radionuclides, as a rule, do not arise.

The lack of the ability to firmly retain the accumulated radionuclides in any natural situation means a violation of trophic links between ecosystem components, destruction of migration routes and absorption of nutrients or their sorption, and therefrom degradation of the ecosystem. The ability of ecosystems to accumulate and firmly retain radionuclides invading at them is their fundamental property. A measure of this property of ecosystems can be the radiocapacity factor – the ratio of the activity of radionuclides that are firmly sorbed by the components of the ecosystem to the total radioactivity of this ecosystem. The upper limit is such a degree of radionuclide activity that does not disrupt the functioning of the ecosystem, that is, does not reduce its productivity, air conditioning ability and reliability.

Ecosystem performance, conditioning and reliability categories relate to undefined quantitative concepts. This is a natural consequence of the ecosystems natural properties. Thus, the performance of any ecosystem can very significantly depending on the season, weather conditions and many other factors. Conditioning depends on productivity, various loads on the ecosystem and the specific conditions of its existence. The ecosystems reliability, or the ability to preserve their characteristics in external changing conditions depends not only on the mode of such changes (that is, these changes are slow or they occur quickly, like disasters), but also on what features of the ecosystem are spoken about. Thus, we can talk about a violation of reliability with changes in the species stability of the ecosystem. However, if we mean the function that a certain ecosystem performs in relation to the ecosystem of the highest rank in the hierarchy of the biosphere (for example, the supply of oxygen to the biosphere or the absorption of carbon dioxide), then species stability recedes into the background, since even in the case of its significant changes, the ecosystem can perform this function well. The same goes for restoring the structure of a destroyed ecosystem. Therefore, deforestation or plowing of a natural meadow is the destruction of the corresponding ecosystems. However, if the anthropogenic impact is stopped, then after a few years or decades, these disturbances gradually decrease and the destroyed ecosystems are restored. Long-term anthropogenic impacts can affect the original ecosystem in such a way that it will irreversibly be replaced by a new ecosystem that is more consistent with the changed conditions. This entire means that a quantitative assessment of performance, air conditioning and reliability must be given for each specific ecosystem, be sure to note the features of the accompanying conditions.

1.2. Radionuclides migration in the soil

Radioecology of agricultural soils is an organic section of soil ecology, which consists of three interconnected blocks (Fig. 1.1):

– factorial (factor ecology or soil ecology);

– soil ecofunctions concept;

– preservation of soils and soil cover as an irreplaceable component of the biosphere and planet.

In the field of agricultural radioecology, it is especially important to solve the following problems: migration of radionuclides in the food chains of organisms and, above all, in the chain: soil – agricultural plants – livestock animals – crop and livestock products – human; termination or

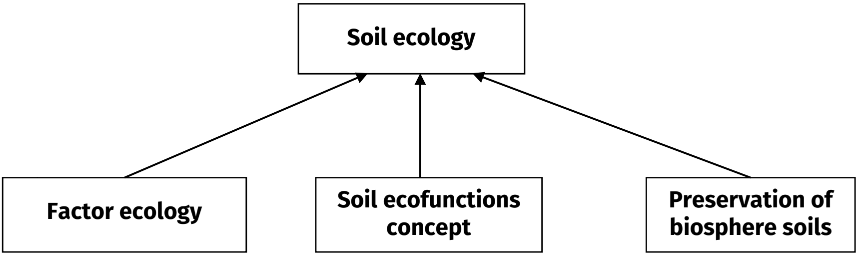

Figure 1.1. The main directions and tasks of the soil ecology development

weakening of ecological ties on any part of this route as a result of decontamination of agricultural land and water bodies contaminated with radionuclides, or the creation of special means to prevent and reduce their entry into animal and human organisms; identification of land and water areas contaminated with radioactive substances.

The soil is a kind of radioactive substances storage site and the first link in the chain of long-lived radioactive elements migration along trophic pathways to humans.

The following factors influence further behavior in the soil:

– radionuclides physical and chemical properties;

– soil granulometric and mineral composition;

– soil agrochemical characteristics (acidity, organic matter content, composition of exchangeable cations);

– soils physical and physicochemical properties;

– the composition of the vegetation cover in forest stands (especially the layer of tree species)

– climatic conditions in general, weather conditions of a specific year.

Technogenic substances enter the soil cover mainly from the atmosphere. Within a few years after the release of radioactive substances to the earth’s surface, most of them enter plant tissues, and from there into animal feed and human food. Intensive absorption of substances by soils prevents their vertical movement along the soil profile and penetration into groundwater and underlying mountain sediments.

The concentration of radioactive substances during migration, as a rule, decreases. For example, the concentration of most radioactive substances in plants is lower than in the soil on which these plants grow; the radioactivity of milk and animal meat is lower than that of plants that animals eat. But there are also opposite phenomena. In particular, the content of substances such as ^{90}Sr or ^{137}Cs, as a result of the transition from soil to plants, in many cases can increase. In this case, we can talk about the concentration (accumulation) of radioactive substances.

Agroecosystems play a leading role in the formation of the radiation dose for human due to the intake of radionuclides into the body along with agricultural products.

The most important element of the agroecosystem is undoubtedly the soil cover. Radionuclide contamination of the soil is determined by radionuclide fallout directly on the soil surface and by that part of the radionuclides that is washed off from plants by precipitation and blown away by the wind. Immediately after the fallout, almost all radionuclides are concentrated in the upper soil layer 1 cm thick. Then the mechanisms of filtration, washing out by rain, diffusion and mixing of the soil under the influence of wind, rain and burrowing representatives of the biota begin to operate. Biogenic factors play a significant role in the process of vertical migration of radionuclides in the soil: transportation through root systems, the presence of microorganisms and burrowing animals in the soil. As a result, radionuclides move in the soil at a speed of 1–3 cm per year. In this case, ^{137}Cs migrates more slowly, and ^{90}Sr migrates faster. In general, the soil is the most important storage site for the radionuclides accumulation. Its role is twofold: on the one hand, the soil strongly adsorbs the majority of radionuclides, reducing their availability to plants; on the other hand, the fixation of radionuclides by the solid phase of the soil leads to their long-term retention in the upper root layer of the soil and prevents the removal of radionuclides outside the root zone. The solid phase of the soil may contain radionuclides that enter it because of ion exchange, adsorption (capture by the colloidal fraction of the soil) and chemical precipitation (formation of independent compounds of radionuclides with soil colloids). It is known that according to the ability of radionuclides to sorption in soil, they can be placed in the following sequence:

$$\mathbf{^{106}Ru > {}^{90}Sr > {}^{144}Ce > {}^{90}Y > {}^{60}Co > {}^{137}Cs}$$

At the same time, for ^{90}Sr, the sorption capacity in soil is two orders of magnitude higher than for ^{137}Cs. Simultaneously with the sorption of radionuclides by soil particles, their desorption also occurs. According to their ability to desorb, radionuclides form the following series: ^{90}Sr > ^{106}Ru > ^{144}Ce > ^{60}Co > ^{137}Cs. Thus, according to this property, ^{90}Sr is much higher than another important radionuclide – ^{137}Cs.

To assess the migration and distribution of radionuclide activity after they enter the ecosystem, transfer and accumulation factors are usually used. Transfer factors (T_f) for different radionuclides and different representatives of biota can differ significantly. It is convenient to describe the migration of radionuclides in an ecosystem using stationary or dynamic compartment models that allow visualizing this process. T_f determination – is the most important radioecological procedure, which should precede the solution of problems not only regarding the dynamics of radionuclides in ecosystems, but also the influence of radionuclides on living representatives of any ecosystem.

Radionuclides absorbed by the soil are in it in various forms, differing in their mobility and, as a result, in their behavior in the soil and availability for biota.

The water-soluble form is that part of the radionuclides that freely enough passes from the soil into the water and is available for plants, fungi and microorganisms. The exchangeable form is a part of radionuclides that can be removed from the soil with 1H ammonium acetate solution (CH_3COONH_4).

A certain part of radionuclides of this form can also be available for living organisms. The non-exchangeable form is the amount of radionuclides that can be removed from the soil with 6 H hydrochloric acid (HCl) after the exchangeable form is washed out (pretreatment of the soil with ammonium acetate). A firmly fixed form is radionuclides that remain in the soil after it has been treated with hydrochloric acid.

Different types of soil absorb radioactive elements with different intensity (Table 1.1). The table shows that more radionuclides are sorbed in black soils than in loamy and sandy loam soils. This is explained by various factors, but mainly by the presence of a significant amount of finely dispersed particles in black soils.

The behavior of specific radioactive elements in the soil largely depends on the presence of their chemical analogs in macro quantities: elements that are chemically similar to radionuclides. For strontium, this is calcium, and for cesium, it is potassium. Strontium and calcium are sorbed by the soil from solution with almost the same intensity, therefore their ratio in solution and soil is quite close. For the cesium-potassium pair, these ratios differ, since cesium is sorbed from the solution by the solid phase of the soil much faster than its analog, potassium (Efremova & Izosimova, 2012).

Table 1.1

Radionuclides sorption in soils,%

Radionuclide	Sod-podzolic soil		Chernozem
	sandy loam	loamy soil	
^{90}Sr	66	92	96
^{137}Cs	98	99	99
^{106}Ru	49	65	61
^{144}Ce	98	99	100
^{147}Pm	96	98	99
^{60}Co	94	97	98

The application of chemical analogues of radionuclides into the soil (to reduce the intensity of their migration into cultivated plants) is quite often practiced in agricultural production. Such an increase in calcium in the soil leads to a decrease in the sorption of ^{90}Sr from solution. An increase in the latter in the soil solution increases the likelihood of this radionuclide entering plants. But after the application of significant doses of calcium, the ratio between ^{90}Sr and Ca in the soil solution changes in such a way that the intake of radionuclide into plants is significantly reduced (Hamidalddin, 2014).

The sorption of radionuclides by the solid phase largely depends on the presence of competing cations in the solution. For example, some researchers present a series of reducing the effect of competing ions on the sorption of radionuclides in the following form:

– for ^{90}Sr: $Al^{3+} > Fe^{3+} > Ba^{2+} > Ca^{+2}$,

– for ^{137}Cs: $Cs^{+} > Rb^{+} > NH_4^{+} > K^{+} > Na^{+}$.

By the ability to displace ^{60}Co; ^{91}Y and ^{144}Ce from the soil such series exist:

– for ^{60}Co: Na < K < Ca < Zn < Al < Fe < Cu,

– for ^{91}Y and ^{144}Ce in soil without humus Na < K < Ca < Zn < Cu < Al < Fe.

Depending on the concentration of stable isotopic carriers, acidity, the presence of other cations, etc. radionuclides were divided into 5 groups:

First group – Zn, Cd, Co. It is characterized by a non-exchange type of behavior. They are fixed in the soil by adsorption by minerals and the creation of complex compounds.

Second group – Na, Rb, Sr. It is characterized by an exchange type of behavior, therefore, the mechanism of fixation in the soil is ion exchange.

The migration of radionuclides of this group is largely influenced by the presence of other cations.

Third group – Cs. In microconcentrations it is characterized by non-exchange absorption, in macroconcentrations – by exchange one.

Fourth group – I, Ce, Pm, Zr, Nb, Fe, Ru. The type of behavior is polymorphic, and the mechanism of fixation in the soil is to create complexes and precipitate colloids.

Fifth group – Ag. Can behave in soil as radionuclides of the first, second and fourth groups.

Poorly soluble compounds can be formed by radionuclides when interacting with anions of the soil solution. For example, ^{90}Sr goes into a non-exchangeable state when it interacts with PO_4^{3-}, SO_4^{2-}, CO_3^{2-} anions, and if they and radiostrontium are present in the soil solution, then the sorption of the latter by the solid phase of the soil increases. According to the property of ^{90}Sr to bind into poorly soluble compounds in soils, various anions were put in such a row:

$$\mathbf{PO_4^{3-} > C_2O_4^{2-} > Cl^- = SO_4^{2-} > NO_3^-}$$

The mobility of radionuclides during sorption by soil is compared most often according to N. A. Tymofieieva and A. A. Tytlianova, who proposed such series of mobility:

– at sorption: ruthenium > strontium > cerium > yttrium > cobalt > cesium;

– at desorption: strontium >> ruthenium > cerium > cobalt >> cesium > yttrium.

Taking in consideration the above, it can be seen: a beta-emitter of strontium, which after the Chornobyl accident is one of the most common radionuclides, is also quite mobile. With that in mind, it is classified as a biologically hazardous radionuclide.

1.4. The role of radionuclides physico-chemical properties

Soil is the main source of natural radionuclides for the biosphere, and although not one, but the main link, which receives artificial radionuclides from the atmosphere.

The migration of radionuclides in the soil should be understood as the totality of processes leading to their movement in the soil and cause redistribution in depth and in the horizontal direction. In this regard, two types of migration are distinguished – vertical and horizontal, which pass simultaneously and therefore it makes no sense to consider them separately.

The migration abilities of radionuclides in soil and their inclusion in biological cycles are determined by a large number of properties of the radionuclides themselves, soil, and various environmental factors.

The role of the radionuclides' physico-chemical properties. Radionuclides that enter the environment can be in different physical and chemical forms – aerosols, hydrosols, particles sorbed on various materials and in other forms. Their mobility depends on the form of radionuclides in which they entered the environment (Ajaj & Moutaz, 2017).

Thus, radioactive contamination during the accident at the Chornobyl nuclear power plant was caused by three types of fallout: solid highly radioactive aerosols of various dispersion, the gas phase of individual radionuclides and radionuclides in a graphite matrix. The last specific type of radioactive particles was formed during the combustion of graphite blocks, which is used in nuclear reactors as a neutron moderator. There are two main groups of factors that lead to changes in the mobility and bioavailability of radionuclides over time. The first of them causes the so-called "ageing" of radionuclides. The essence of ageing is that over time, as a result of their diffusion into the crystal structure of certain minerals, the formation of various complex compounds, aggregation of particles into larger ones, their mobility in the soil decreases. The ageing of cesium radionuclides is well known, which results in a gradual decrease in their availability for root assimilation by plants.

Under the influence of the second group of factors, the mobility of radionuclides and their bioavailability, on the contrary, can increase. As can be seen from the above, coarse particles in the soil under the influence of water, oxygen, microflora and other factors can be destroyed over time, turning into fine particles. The radionuclides that make up their composition move from problematic forms to more accessible ones, which dissolve better in the soil solution and are quickly absorbed by plants.

Of great importance in the behavior of radionuclides in soil and their biological availability are chemical properties that determine their ability to adsorb and form complex compounds inaccessible to plants. In this way, the higher the ion charge, the stronger it is absorbed by the soil and forms more stable compounds with organic substances. The greater the mass and ionic radius, the less pronounced this ability is. In a free state, radionuclide ions are absorbed more intensively than in a hydrated or solvated state.

1.5. The role of mineralogical and granulometric composition of soils in the radionuclides absorption

Soil is a strong absorber of various elements, including radioactive substances. Its surface layer with the main part of the soil absorption complex has the highest absorption capacity. Therefore, natural lands retain the bulk of radioactive substances in the surface layer of the soil, and on arable land they are evenly distributed along the entire profile of the soil layer. Their retention into the circulation of substances is due, on the one hand, to the strength of the bond with parts of the soil, and on the other hand, to the ability of the plant roots to absorb. High strength of radioactive substances complexation is characteristic of heavy soils – black soils, chestnut, loams, which are rich in organic and mineral colloids, which form the basis of the absorption complex. It is minimal in light sandy soils.

The completeness of radionuclides sorption in soils largely depends on their mineralogical and granulometric composition. The absorptive capacity of the soil, among other factors, is based on the presence of a silt fraction and some clay minerals.

It has been established that the latter are an important weathering product and got their name from clays, of which they are an integral part. In terms of chemical composition, clay minerals are classified as secondary aluminosilicates and ferrosilicates and always contain some amount of associated water. Their crystal lattice has a layered structure, and the crystals themselves are quite small – they do not exceed 1–2 microns. Depending on the number of layers that are combined into elementary packages, two-, three- and four-layer minerals are distinguished. The intensity of sorption of radionuclides in the soil partially depends on their belonging to one group or another.

The sorption capacity of soils increases with the dispersion of its mechanical elements. Even within the same soil type, depending on the amount of clay particles with a diameter of less than 0.001 mm, the accumulation of radionuclides by plants can change by an order of magnitude. Most strongly radioactive fission products are retained by the silt fraction of the soil.

In addition, the finely dispersed clay and silt soil fractions contain a greater amount of minerals of the montmorillonite group, micas and hydromicas, which are three-layer minerals with high absorbency. The predominant minerals of sand fractions, even fine sand, are quartz and feldspars, the sorption properties of which are very low.

Fine silt and silty particles of highly dispersed soil fractions contain the largest amount of organic matter, which also significantly affects the migration of radionuclides. The transfer of radionuclides into plants decreases with an increase of the humus content in the soil. This is due to the fact that humic and fulvic acids of humus have a high ability to absorb and retain radionuclides, as well as form complex compounds with them, the entry of which into plants is difficult.

In larger silt fractions, the content of organic matter decreases sharply, and in fine sand they are almost absent.

Peat soils contain a very large amount of organic matter (up to 90 %). However, they are mainly represented by semi-decomposed plant residues and contain little humus. The mineral fraction, including the finely dispersed one, is negligible in peat soils. The amount of exchangeable cations is small. Therefore, the absorption capacity of peat soils is low and the ability to retain radionuclides is relatively low.

In general, the listed properties of soils form in them a certain nonspecific level of ability to sorption and retention of radionuclides. In ascending order of the ability of different types of soils to sorb radionuclides, they can be distributed in the following order: peat – podzolic – sod-podzolic – gray forest – meadow – gray soils – chestnut – black soils.

Minerals of the montmorillonite group have the highest absorbing capacity. These are three-layer minerals, the elementary package of which consists of two outer tetrahedral layers and an inner – octahedral layer. The vertices of the outer layers are directed towards the inner and are aligned with the vertices of the latter. The connection between neighboring elementary packages is rather weak, due to which water can enter this space, as well as exchangeable cations, including cations of some radioactive elements. Minerals of this group are characterized by isomorphic substitution of some ions by others. With such a substitution, radionuclides are included in the crystal lattice of montmorillonite. This type of absorption of cations of radioactive elements is called *intramicellar*. Argillaceous minerals of this group include ascanite, gumbrin, bentonite. All of them fix ^{137}Cs rather strongly and fix ^{90}Sr much weaker.

Near the montmorillonite group, another three-layer mineral, vermiculite, is quite close. It also has a crystal lattice that swells. The magnesium cations included in its composition can be replaced by radionuclide ions that enter the space between the packages. This mineral is characterized by some specificity of cesium ions sorption.

Simple two-layer minerals of the kaolinite group have the lowest ability to fix ^{137}Cs and ^{90}Sr. An elementary package of such minerals consists of one tetrahedral and one octahedral layers, the tops of which are directed inward and coincide. It seems as if the layers have grown together. But the connection between the packages is not very strong, which predetermines to a certain extent the non-exchange sorption of radionuclides.

We should also turn our attention to the absorption of cations of radionuclides by the surface of the crystal lattices of argillaceous minerals. This type of absorption, when radionuclides can enter the crystal lattice, but are quite easily replaced by cations of neutral salts, is called *extramicellar*.

In order of decreasing sorption capacity for radionuclides, argillaceous minerals can be placed in the following row: montmorillonite group > hydromica group > mica group > kaolinite group (Table 1.2)

Table 1.2

Sorption of radionuclides by minerals

Minerals group	Name	^{90}Sr		^{137}Cs	
		Deposited of absorbed one,%	Displaced by 0.1 N $CaCl_2$,% absorbed	Deposited of absorbed one,%	Displaced by 0.1 N $CaCl_2$,% absorbed
Montmorillonite	ascanite	99.1	13.9	99.9	3.3
	gumbrin	96.3	34.2	99.9	7.3
Kaolinite	kaolin	95.3	73.6	95.6	19.5
Hydromica	vermiculite	97.7	64.0	99.8	12.6
	hydroflogopite	95.4	52.9	99.6	7.0
Mica	bioptitis	94.0	70.6	97.3	46.6
	phlogopite	97.5	69.7	99.7	7.2

One of the main roles in the absorption of radioactive elements by the soil belongs to silt and sludge, which are highly dispersed particles. It is well known that the finer the soil fractions, the more fully they sorb radionuclides, the greater their moisture-retaining power, which also affects the migration and sorption of certain elements.

Fine sand fractions also fix radionuclides (Table 1.3).

Table 1.3

Sorption of radionuclides by fractions of sod-podzolic soil

Fraction	^{90}Sr		^{137}Cs	
	Absorbed, % of contributed	Driven out, % of absorbed	Absorbed, % of contributed	Driven out, % of absorbed
Fine sand	77.1	97.1	98.7	35.0
Silt:				
large	89.8	97.7	99.4	20.8
middle	95.2	91.8	99.4	21.0
small	97.1	78.9	99.7	6.7
sludge	97.5	63.9	99.7	2.8

At the same time, the percentage of ^{l37}Cs absorbed can reach 98.0 %, which is somewhat less than the silt fraction. But the difference also lies in the fact that a third of the absorbed radionuclide can be displaced from the grains of sand of the fraction. This, on the one hand, indicates that ^{l37}Cs is sorbed mainly by the mineral part of the soil, and on the other hand, that its mobility on sandy soils is much higher. Both fine fractions and fine sand ^{90}Sr are sorbed not as much as ^{137}Cs. In addition, it is fixed by them very weakly, therefore its mobility is almost always higher than that of ^{137}Cs.

Studies have established that the transfer factor of radionuclides into winter wheat depends on the content of physical clay fractions.

An increase in the content of physical clay fractions up to 30 % reduces the conversion coefficient in comparison with soil containing 5 % physical clay by almost 3 times.

It was noted that increasing concentration of ^{40}K, ^{238}U, ^{232}Th and ^{137}Cs in soil surface layer results to increase silt and clay contents in the soil. The soil profile with the highest average radionuclide activity concentration contained the highest amount of clay, and higher radionuclide activity was found in the soil had high clay content (Vukasinovic I. et al, 2010). The reason for high radionuclides activity in clays is due to the fact that clay minerals are mainly composed by aluminum silicates and they are characterized by small sized grain and negative charged surface (El-Arabi et al, 2006; Navas et al, 2002). In this way clay particles easily absorb cations on their surface. Also, a radionuclide is adsorbed onto clay surfaces which could be increased it with clay content.

In this connection, the Adaptive Neural-based Fuzzy Inference System (ANFIS) was used for prediction of sand, silt and clay content in a soil using natural radionuclides concentration (^{40}K, ^{238}U, ^{232}Th), and ^{137}Cs. The experimental results showed that constructed ANFIS was effectively able to predict sand, silt and clay contents (Al-Hamed et al., 2014). The prediction accuracy of the model was fairly good (predictive ability and for the coefficient of correlation) based on the results of the testing data performance, and the calculated coefficient of correlation of training and testing data.

II. FEATURES OF RADIATION POLLUTION OF AGRICULTURAL SOILS

2.1. Influence of agrochemical soil properties on the radionuclides mobility

The role of agrochemical soil properties. Radionuclides are usually found in soils in ultramicroamounts. So, with the ^{137}Cs content of $3.7×10^4$ Bq/m^2 (1 Ci/km^2) – the level above which the soil is now considered to be polluted, its mass concentration in the arable layer is $3.9×10^{-12}$ %, and ^{90}Sr – even less – $2.4×10^{-12}$ %. This corresponds to approximately 10^{-5} g/m^2, or 10 g/km^2. Such low concentrations of radionuclides in soils should cause a significant dependence of their behavior on the content of the corresponding stable isotopes, elements similar to them in the physicochemical properties of some chemical characteristics of soils (Akhtar et al., 2005).

The reaction of the soil solution affects the migration of radionuclides in different ways. For most of them, including ^{90}Sr and ^{137}Cs, with an increase in acidity, the strength of fixation in the soil decreases, mobility and entry into plants increase. Some radionuclides, in particular ^{59}Fe, ^{60}Co, ^{65}Zn, with an increase in pH, pass from the ionic form to various hydrolytic and complex compounds and become less accessible to plants.

The content of exchangeable calcium, which characterizes their so-called “carbonateness”, has a very great influence on the migration and availability of radionuclides in soils. In many soils, mainly in insufficiently moist areas, the content of carbonates is quite significant. With an increase in their content, the intake of ^{90}Sr from soil into plants decreases. The data presented in Table 2.1 show that with an increase in the carbonate content in black soils from 0 to 3.2 %, the accumulation of ^{90}Sr by plants decreases by 1.3–2.5 times, and the intake of ^{137}Cs increases.

The decrease in the ^{90}Sr input to plants on calcareous soils is usually explained by two reasons. First, at a high level of carbonates, non-exchangeable fixation of the radionuclide can occur. Secondly, strontium and calcium are chemical analogs. When entering plants, as well as in a living organism in general, certain competitive relationships can arise between them, and calcium, as an element, the content of which in the earth’s crust (2.96 %) is several orders of magnitude higher than the total strontium content ($3.4×10^{-2\%}$), can act as a kind of discriminator that limits the intake of strontium, including its radioactive isotopes.

Table 2.1

Accumulation factor (AF) of ^{90}Sr and ^{137}Cs by plants depending on the degree of carbonate content of black soils

Plants	Carbonate content,%			
	0	0.7	2.2	3.2
^{90}Sr				
Cabbage (cabbageheads)	0.19	0.16	0.17	0.08
Tomato (fruit)	0.36	0.22	0.16	0.25
Onion (bulb)	0.98	0.80	0.85	0.74
Corn (for silage)	0.88	0.58	0.59	0.74
^{137}Cs				
Cabbage (cabbageheads)	0.04	0.06	0.06	0.12
Tomato (fruit)	0.04	0.06	0.08	0.14
Onion (bulb)	0.05	0.05	0.06	0.07
Corn (for silage)	0.04	0.05	0.10	0.07

Not only with an increase in the carbonate content of the soil, that is, with an increase in the content of CO_3^{2-} anions, but also with an increase in the concentration of PO_4^{3-} i SO_4^{2-} anions, the sorption of ^{90}Sr increases due to the coexistence of strontium compounds that are hardly soluble and poorly absorbed by plants. Therefore, in soils with an increased content of exchangeable forms of phosphorus and sulfur, especially the former, there is a decrease in the transfer of ^{90}Sr into plants.

An increase in the content of exchangeable potassium in the soil reduces the migration and input of ^{137}Cs into plants. On the one hand, this is due to the fact that with a large amount of potassium in the soil, all exchangeable soil cations are replaced by it, which increases the sorption and fixation of cesium. On the other hand, this is due to the fact that between potassium and cesium, as between chemical analogs, there is a competitive relationship when entering plants, similar to those that occur between calcium and strontium.

The absorption and sorption of radionuclides by the soil strongly depends on the content of the corresponding stable nuclides in it – the higher the content of stable nuclides, the less radioactive is fixed in the soil and more enter the plants. This effect is explained by a simple dilution of radionuclides in the soil due to stable ones and a decrease in the proportion of radioactive ones in the total fixation of the element.

One of the main natural radioactive “pollutants” of soil and biosphere – ^{40}K deserves special attention. Its content in the arable layer is large enough – 2.7–21.6×10^4 Bq/m^2 (0.7–5.8 Ci/km^2). The maximum radioactivity due to ^{40}K is found in soils that developed on acidic igneous rocks and contain minerals with a high potassium content – biotite, muscovite, orthoclase. In the process of economic activity, the flows of potassium, and with it ^{40}K grow in the biosphere. At an average rate of potash fertilization of 60 kg/ha 1.35×10^6 Bq ^{40}K enters the soil. With a single application, this will not lead to a noticeable increase in the content of ^{40}K, but with many years of application of potash fertilizers, this can affect its balance.

Migration of ^{40}K in the soil, entry into plants and subsequent movement along the links of the biological chain is completely determined by the behavior of its stable carriers – ^{39}K and ^{41}K and depends on many of the already noted soil properties: carbonateness, the reaction of the environment, the content of various cations, and primarily sodium, the concentration of anions and other. But with any decrease in the intake of ^{40}K, there is also a decrease in the intake of potassium in general. It is one of the main nutrients.

It was already noted above that a significant amount of radionuclides is already quite firmly fixed in the first years after moving into the soil. At first sight, their migration should be determined by the ratio of water-soluble, exchangeable and other forms. It has been established that the more water-soluble and exchangeable forms of radionuclides in the soil, the faster they move. But after the radionuclides have entered the soil, various processes that change their mobility occur with them. Due to the formation of sparingly soluble and insoluble compounds, the chemical precipitation of radionuclides occurs, due to sorption by argillaceous minerals, the amount of a radioactive element in the crystal lattice increases over time. The course of all these processes is influenced by about 10 characteristics of soil conditions.

The agrochemical properties of soils have the most significant effect on the transition of radionuclides to agricultural crops (Table 2.2)

Soil acidity. In the forests of the territory of radioactive contamination of Ukraine, sod-podzolic, boggy and peat soils are most common. They are distinguished by significant acidity, so there is an increase in the proportion of water-soluble and exchangeable forms of ^{90}Sr and ^{137}Cs. In this regard, in soils of these types, the mobility of ^{90}Sr and ^{l37}Cs increases, the strength of their fixation in the soil decreases, and the intensity of their entry into plants increases.

Table 2.2

Dependence of the conversion coefficient of ^{137}Cs into winter wheat (y) on the properties of sod-podzolic soil (x)

Soil fertility indicator	Models obtained by O.M. Klymenko (2006)	Correlation ratio	Confidence interval	Models obtained by B.S. Prister, (1991)
Humus content H,% (X_1)	$y = 0.94 \times 0.48^{H}$	0.95	0; 1.26	$y = 1.02e-^{0,99H}$
Physical clay content PC,%, (X_2)	$y = 0.83 \times 0.95^{PC}$	0.97	0; 1.17	-
Exchangeable acidity, pH(KCL) (X_3)	$y = -1.46 + \frac{10.59}{pH}$	0.94	0; 0.94	$y = 142.6e^{-1,06pH}$
The sum of the absorbed bases of SPO, meq per 100 g of soil (X_4)	$y = -0.28 + \frac{6.39}{SPO}$	0.93	0; 1.22	$y = 71.5(SPO)^{-2,42}$
Calcium content Ca^{2+}, mg per 100 g of soil (X_5)	$y = -0.12 + \frac{3.72}{Ca}$	0.89	0; 1.01	$y = 14.6(Ca)^{-1,99}$
Mobile potassium content K, mg per 100 g of soil (X_6)	$y = -0.072 + \frac{0.099}{K}$	0.94	0; 1.06	$y = 0.025\ (K)^{-1,59}$

At the same time, ^{60}Co, ^{59}Fe, ^{65}Zn and some other radionuclides in acidic soils create various hydrolysis and complex compounds, which reduces their mobility. As for the radioactive elements, there may be several increases in their mobility when the acidity of the soil changes (Bundt, 2000).

These processes are based on: direct dissolution of chemical compounds; displacement of individual chemical elements into solution as a result of absorption of hydrogen ions in the soil; changes in the fixing strength of hydrolyzed forms, etc. The application of significant doses of Ca, K, Na carbonates into acidic sod-podzolic soils leads to a decrease in the intensity of ^{90}Sr and ^{137}Cs intake into plants.

An increase in carbonates in the soil leads to a decrease in the amount of fulvic acids, which, unlike humic ones, create more colloidal compounds. Therefore, on soils, the number of water-soluble forms of ^{90}Sr (carbonate chernozem) decreases threefold, and the amount of non-exchangeable radiostrontium increases by 4–6 %.

Soil texture. The soil texture affects its water, air, mechanical and chemical properties. Sands are mainly composed of primary minerals. As the size of sand particles decreases, their moisture content increases. The amount of argillaceous minerals in sandy soils is insignificant. In fractions of silt and sludge, the amount of secondary minerals increases. With an increase in the content of secondary minerals, the sorption capacity of soils increases. In addition, the degree of dispersion, the amount of humus and exchangeable cations in fine fractions affect the migration of radionuclides in soils (Mostafa et al., 2020).

Humus content. Humic and fulvic acids adsorb ions and create complex complexes with radioactive elements. Thus, they prevent the entry of radionuclides into plants. Some of the organic complexes with radionuclides are partially available for plants, while the availability of ^{90}Sr and ^{l37}Cs from fulvates is higher than from humates. The mobility of radionuclides changes depending on whether the newly formed organic complexes are in soluble or insoluble form. But most often, an increase in the humus content in the soil leads to a decrease in the intensity of the intake of radionuclides into plants. For example, in forest soils, the accumulation and content of radioactive elements is observed in the decomposed part of the forest litter and in the upper layer of the humus-eluvial horizon.

In sod-podzolic soils, an increase in the humus content from 1 to 3 % ensures a decrease in the transition of ^{137}Cs to winter wheat by almost 4.5 times.

What's interesting is that organic substances play a decisive role in the sorption of radioiodine. Thus, when ^{131}I is introduced into sod-podzolic soil, leached chernozem and lowland peat, a significant part of it (37–55 %) is associated with humic acids.

Content of chemical analogues of radionuclides. For the mobility of radionuclides in the "soil-plant" system, the content of their analogues – elements with similar chemical properties is important. For ^{l37}Cs and ^{90}Sr these are potassium and calcium. For cobalt, yttrium, cerium – iron and aluminum. A feature of these relationships is that radionuclides are contained in soils in trace amounts, and their chemical analogs – in macro amounts. Numerous experiments show that the presence of chemical analogs in the soil reduces the rate of sorption of radionuclides by the soil from solution. The basis of measures aimed at reducing the radioactive contamination of cultivated plants is the application of fertilizers containing stable isotopes of calcium and potassium into the soil.

Soil moisture. Soil moisture plays a very significant role in the migration of radionuclides in the soil. It was found that in sandy sod-podzolic soils, ^{90}Sr migrates in a vertical profile even with gravitational water. At the same time, ^{l37}Cs and ^{144}Ce do not have such a migration ability. The migration ability of ^{238}U increases with increasing soil moisture.

Animals affect the mobility of radionuclides in the soil. Worms, forest mice, moles make numerous passages along which the upper soil layers contaminated with radionuclides can crumble. In addition, animals participate in the mineralization of animal residues, forest litter and the movement of contaminated organic matter down the soil profile.

Plants are another factor that significantly affects the redistribution of radionuclides in the soil. Depending on the biological characteristics of plants, the accumulation factors of radionuclides can vary by 8–10 times. The absorption of radionuclides is affected by the penetration depth of the plant root system. Plants, the root system of which penetrates to great depths, accumulates less radionuclides than those plants in which the root system is formed in the upper layers contaminated with radionuclides.

2.2. Influence of weather and climatic conditions

Air movement, precipitation, ambient temperature and some other phenomena that characterize the features of weather and climatic conditions play an important role in the migration of radionuclides not only in the atmosphere, but also in the soil.

The movement of air, that is, the wind, is of great importance for their distribution. Due to the wind uplift from the soil surface and transfer, it becomes possible the secondary extremely fast movement of radioactive substances at a distance of tens of kilometers from the place of fallout, which can cause pollution or increase the level of pollution of cleaner soils.

There are three main types of wind soil uplift: real wind uplift – due to the movement of air above the soil surface; local wind uplift – due to the movement of air, which is created by the specifics of the terrain, the presence of forest plantations, buildings; mechanical wind uplift arising when agricultural machines perform field work, traffic.

The most important factor influencing the wind uplift of radioactive particles is the speed of air movement. The rise of soil particles occurs faster from dry surfaces, plowed fields, slopes that are blown by winds.

The season of the year when radionuclide contamination of the environment occurred largely determines the interaction of radionuclides with the soil. It will be minimal in winter with low temperatures and solid precipitation. Above-zero temperatures and high soil moisture in summer intensify it.

Radioactive particles, falling on the soil surface, are involved in the processes of vertical migration deep into the soil, which are very important. This leads to a decrease in the radiation dose rate of radionuclides above the soil surface, a decrease in their secondary transfer by wind and surface waters. At the same time, the amount of radionuclides that enter plants and pass into groundwater can vary significantly.

The rate of vertical transfer of radionuclides in the soil is largely determined by the above properties of radionuclides, the soil texture and mineralogical composition of the soil, and its agrochemical characteristics. But it mainly depends on the amount of precipitation.

Particles of various sizes with a stream of water can penetrate deeper through cracks that formed in dry weather, through the passages of worms and other organisms. This is the usual filtration – the movement of a liquid through a porous medium under the influence of gravitational forces. A certain role is played by diffusion movement – the movement of radionuclides in the direction of the concentration gradient – its leveling; convection transfer is the vertical movement of radionuclides with water, caused by a change in its density as a result of temperature or salinity differences.

In general, the process of vertical migration of radionuclides is rather slow. So, in the area of the accident at the Chernobyl nuclear power plant on unplowed sod-podzolic sandy soils of light texture 24 years after the fallout of radioactive products, about 90 % of radionuclides were contained in the upper 15–20-cm layer (Fig. 2.1). On soils with a heavier texture with a rich soil-absorbing complex, the vertical migration of radionuclides occurs even more slowly. In all types of soils, ^{90}Sr penetrates deeper than ^{137}Cs. This is certainly due to the greater solubility of strontium and the “ageing” of cesium.

Weather and climatic conditions have a significant impact on the horizontal migration of radionuclides – their transfer over the soil surface. With heavy rainfall in the summer-autumn period, significant washout of radionuclides from the catchment areas into the reservoir and their

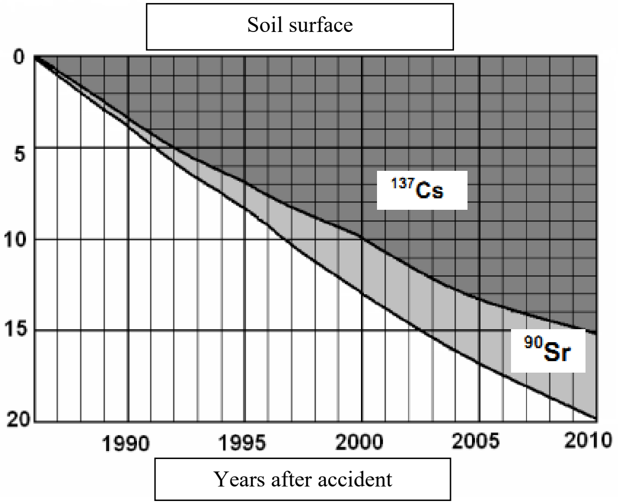

Figure 2.1. The rate of vertical migration of ^{137}Cs and ^{90}Sr radionuclides in sod-podzolic soil over the years after the accident at the Chornobyl nuclear power plant. Vertical axis – depth, cm

pollution of rivers, lakes, reservoirs – sources of drinking and irrigation water is possible. A similar situation can arise during the formation of a thick snow cover in winter and a sharp increase in temperature in spring, when, with rapid melting of snow and weak filtration of precipitation into frozen soil, the transfer of radionuclides over the surface increases.

In the processes of horizontal migration, an important role is played by the features of the terrain, the presence of vegetation on it. Specific surface irregularities, forest plantations and a lushness of herbaceous plants, in certain combinations, can almost completely delay the surface runoff of radionuclides. At the same time, steep slopes and lack of plants enhance it.

2.3. Soil decontamination

The most effective methods for reducing the collective equivalent doses of ionizing radiation for the regions of Ukraine turned out to be phyto-decontamination and mechanical decontamination of soils by removing a thin layer of soil (using turf-cutter). An optimal strategy for the rehabilitation of soils contaminated with radionuclides is proposed. The first version of the soil decontamination algorithm concerns areas that have not been plowed after the accident at the Chornobyl nuclear power plant. If these soils have a pronounced layer of sod, it is optimal to use a turf-cutter to remove it to a depth of 1–5 cm. At the same time C_D can reach 20–60.

If these soils are sandy and not covered with sod, then artificial turfing can be used. Artificial turf can then be decontaminated with a turf-cutter.

So, using this method, it is possible to achieve a high level of C_D (20–60) in almost all open areas that are contaminated with radionuclides and have not been plowed after the accident.

The second version of the decontamination algorithm was developed for soils that were plowed after the accident and whose radionuclide contamination covers a soil layer with a thickness of 0–20 cm. The most relevant for such soils is the use of the phyto decontamination method. The optimal system of crop rotation of plants with high accumulation factors (A_F = 2–10) and a significant yield (4–8 kg/m^2) allows to significantly reduce the level of radioactive contamination within 4–5 years (up to 5 times at ^{137}Cs).

To implement this universal soil decontamination algorithm, it is necessary to develop a special multi-module machine based on a turf-cutter, which will cut, pack the turf and load for removal.

To save the volume of soil removed, it is important to create a system of preliminary field monitoring. Such monitoring will allow scanning the area of radioactive contamination and determine in advance the location and depth of soil removal (Shevchenko et al., 2019).

Thus, based on two leading methods – the use of turf-cutter and phyto decontamination, it is possible in the near future to build an optimal strategy for the decontamination of the Ukrainian territories contaminated with radionuclides.

III. PRINCIPLES OF ORGANIZING AGRICULTURE IN TERRITORIES CONTAMINATED WITH RADIONUCLIDES

The radiation and ecological situation in the contaminated areas changes mainly as a result of natural radioactive decay, secondary wind transfer and vertical migration. At the same time, pollution of clean territories with agricultural products, machinery, animals, including birds, etc. occurs.

Radionuclides trapped in plants are distributed in them in different ways. Some are concentrated in the roots, others – in the aerial part of plants, mainly in the stems, leaves, seeds, etc. Moreover, in plants, radionuclides are in the form of a mobile fraction associated with structural and functional components. The more free fraction of radionuclides in plants, the more they are available for assimilation by the body of monogastric animals, and for polygastric animals, due to the peculiarities of their digestion, these processes are much more complicated.

The state and exchange of radionuclides in animals organs and tissues depend on many reasons, including their physicochemical properties, among which an important role belongs to their ability to form complexes and interact with tissue structures.

The vegetation phase is of great importance in the accumulation of radionuclides by plants.

The leaves of young plants absorb radionuclides in much larger quantities than the leaves of plants that complete growth and development.

The developmental phase of plants is important when retaining low-mobile radionuclides on their surface.

Radioactive substances that fell on the soil surface from the atmosphere and settled from the surface of plants can serve as a significant source of repeated mechanical pollution after the termination of the fallout. Contamination of plants with radioactive dust occurs when it is raised from the surface of the earth by the wind, grazing animals, when sprinkled with rain drops and processing or harvesting with agricultural machines. The additional contribution of ^{90}Sr, ^{106}Ru, and ^{144}Ce in the process of collecting natural herbs can reach 50 % of the ^{90}Sr input through the root systems.

In case of nonroot radionuclide contamination of vegetation, their transfer from feed to the body of animals and livestock products, as a rule, is higher than in case of root intake.

With continuous global fallout, the highest concentrations of radionuclides are found in crop products, less in livestock products. The concentration of ^{90}Sr and ^{137}Cs in feed exceeds the concentration in milk by 100 and 30 times, respectively, in meat – by 50 and 10 times. The ^{90}Sr, ^{131}I and ^{137}Cs have the highest mobility in the chain "air–plant–animal–livestock products", ^{106}Ru, ^{144}Ce and U isotopes are less mobile.

Consumption of agricultural products obtained in areas contaminated with radioactive substances is the main source of human exposure. Therefore, agricultural production in such territories should be aimed at solving the main problem – the production of crop and livestock products, the consumption of which without restrictions will not lead to an effective average annual equivalent human irradiation dose (Salih et al., 2019; Rilwan et al., 2022).

This is achieved by introducing the following measures into production:

1. Improving the general culture of agricultural production in compliance with the necessary radiation safety practices.
2. Carrying out special radioprotective measures, the main purpose of which is to minimize the transition of radionuclides to crop and livestock products.
3. Reorientation of agricultural production directions in contaminated territories, which will ensure the exclusion of obtaining certain types of products with an increased content of radionuclides.

If the introduction of these measures does not ensure the production of products that meet sanitary and hygienic standards, agricultural production in this territory is terminated.

Minimizing the spread of radioactive substances outside the contaminated areas is a very important principle of agricultural production in contaminated areas. It is achieved through afforestation, various types of reclamation work. These measures should not lead to significant changes in soil fertility, deterioration in product quality and cause other adverse consequences.

Export of agricultural products outside the contaminated area should be reduced to a rational minimum.

The latter, however, cannot be an obstacle for the use outside its borders of products in which the amount of radionuclides meets state sanitary and hygienic standards.

3.1. Plant growing

Intakes of radionuclides into plants can be described using compartment models and transfer factors. Direct plant contamination covers the adsorption of radionuclides by the surface of leaves and stems, as well as uptake by the root system. Therefore, in radioecology, two types of radionuclide intake in a plant are distinguished: *root and nonroot.* Nonroot intake of radionuclides into plants is especially intense during precipitation or drip irrigation of plants with water containing radionuclides. The accumulation of radionuclides in plants due to the intake of air by nonroot and soil routes is described by the following formula:

$$C = a\,D_a + b\,D_{k}, \tag{3.1}$$

where C – radionuclides activity in plants, Bq/kg;

D_a – activity of radionuclides falling out of the air onto the vegetation cover during the growing season, Bq;
D_k – cumulative activity of radionuclides in soil;
a – air – plant transfer coefficient;
b – soil – plant transfer coefficient.

The intake of radionuclides from the air into plants is especially significant in the first period of fallout and during watering. In the first year after the Chernobyl NPP accident, almost 80–90 % of radionuclides entered plants by the nonroot route.

The main factors determining the root intake of radionuclides into plants are soil properties and the activity of radionuclides in them. The influence of other factors, namely the concentration of stable analogs of radionuclides in the soil, the content of humus, etc., are discussed above. The most important indicators are usually soil type and plant species. Therefore, the generalized tables of the accumulation (transfer) factors of radionuclides for various types of agricultural plants are divided by the main types of soils (Uchida et al., 2007; Gaffar et al., 2014).

The ingestion of radionuclides in polluted soil represents a major step in the introduction of radionuclides into the human food chain; this fact is portrayed as a soil-plant transfer factor, defined as the proportion between plant activity and soil-particular activity. Plants are the primary receptors of the radioactive tainting of the food chain following the arrival of radionuclides. The plant transfer factor soil is thought to be a standout amongst the most imperative parameters in the environmental safety assessment needed for a nuclear facility. This parameter is important for an environmental transfer model that can be utilized to anticipate radionuclide concentrations in crops used to appraise human dose consumption. Radionuclide transfer from soil to plant is communicated as transfer factor (TF), defined as the proportion of activity concentration (Bq/kg) of the plant's dry weight to the activity concentration of the soil dry weight (Bq/kg) (El-Gama et al., 2019).

The change in transfer factor might be because of the retention of radionuclides influenced by different parameters, for example, the soil and radionuclides physical and chemical characteristics, Plant species, development stages, rainfall, temperature, sunshine, and so forth.

Among the main natural radionuclides of ^{226}Ra, ^{232}Th and ^{40}K, the potassium content is most noteworthy in the TF. This is on the grounds that potassium is an imperative element that makes plants prolific. In spite of the fact that potassium is a radioactive element, it doesn't harm the water framework. Potassium is vital for plant development and adjusting to natural pressure. Subsequently, potassium has the most elevated number of transfer factor contrasted with radium and thorium (IAEA [International Atomic Energy Agency], 1994).

Accumulation (transfer) factors presented in Tables 3.1 and 3.2 are averaged over many parameters. The values of the accumulation factors of radionuclides given in the literature vary and, in comparison with the average values, can be 10 times higher. Therefore, it is advisable to use these tables to assess the reduction of radioactive contamination of agricultural vegetation only over large areas.

In respect to specific field or polygon, then it needs to use the real values of the accumulation factors of radionuclides for this field, which correspond to its characteristics, as well as the type and variety of plants grown on it.

The factor of ^{90}Sr accumulation in various agricultural plants varies, and for the studied varieties of cereals and legumes it can be 80 times more than the average, and for root crops and vegetables – 350 times. The ^{137}Cs accumulation is about 20 times less than ^{90}Sr accumulation. However, under some biogeochemical conditions (light peatlands of Polissia in Ukraine, for example, in the Rivne region), the ^{137}Cs input is higher than ^{90}Sr.

Table 3.1

Average factors of ^{137}Cs accumulation* in biomass of different types of agricultural plants

Soil type	Factor of ^{137}Cs accumulation in plants				
	Potatoes	Sugar beet	Vegetables	Cereal crops	Corn for grain
Sod-podzolic					
sandy	0.6	0.23	0.7	0.1	0.5
sandy loam	0.6	0.17	0.5	0.6	0.5
loamy	0.08	0.07	0.11	0.16	0.07
Gray forest					
sandy loam	0.2	0.03	0.03	0.04	0.02
medium loamy	0.02	0.03	0.03	0.04	0.02
Black soil					
light loamy	0.08	0.05	0.28	0.09	0.21
loamy	0.03	0.8	0.12	0.08	0.07
medium loamy	0.03	0.9	0.14	0.05	0.1
heavy loamy	0.01	0.02	0.14	0.05	0.08
sandy loam	0.5	0.15	0.2	0.2	0.2

Note: *Factor of ^{137}Cs accumulation – ratio of specific activity of the ^{137}Cs radionuclide (Bq/kg) to plant biomass.

Table 3.2

Average factors of ^{90}Sr accumulation* in biomass of different types of agricultural plants

Soil type	Factor of ^{90}Sr accumulation in plants							
	Wheat, grain	Potatoes, tubers	Red beet	Cabbage	Cucumbers	Tomatoes	Clover, hay	Herd grass, hay
Sod-podzolic								
sandy loam	0.7	0.35	1.2	0.9	0.35	0.14	20	7
light loamy	0.35	0.17	0.58	0.5	0.17	0.07	11	3,5
medium loamy	0.2	0.1	0.34	0.22	0.12	0.04	6	2
heavy loamy	0.12	0.06	0.2	0.16	0.08	0.02	4	-
Black soil	0.06	0.03	0.1	0.07	0.04	0.01	2	0,6

Note: *Factor of ^{90}Sr accumulation – ratio of specific activity of the ^{90}Sr radionuclide (Bq/kg) to plant biomass.

Consequently, the assimilation of radionuclides from the soil by plants in the process of their mineral nutrition depends primarily on the mobility (solubility) of radionuclides, which is determined by their physicochemical nature, agrochemical properties of soils, as well as the biological characteristics of plants and the conditions of their cultivation.

We examined the features of the accumulation of the most important radionuclides – ^{137}Cs and ^{90}Sr. Other radionuclides enter plants in small quantities due to significant sorption in soils. According to their ability to be absorbed by plants, radionuclides can be placed in the following sequence: ^{90}Sr > ^{131}I > ^{140}Ba > ^{137}Cs > ^{106}Ru > ^{144}Ce > ^{95}Zr > ^{95}Nb. Transuranic elements accumulate especially weakly in plants.

In the conditions of irrigated agriculture, water contaminated with radionuclides can be used for irrigation, and/or fields with radionuclide contamination of soil can be irrigated. These circumstances determine certain features of radioecological processes.

Two main methods of irrigation are used – sprinkling irrigation (drop method) and furrow irrigation. In the case of sprinkling irrigation, the doses of radionuclides are transferred into plants 10 times more than as a result of furrow irrigation. This is primarily due to the fact that in the first case, the nonroot intake of radionuclides into plants sharply increases (Table 3.3).

Table 3.3

Factor of radionuclides transfer* into grain and fodder crops with different methods of irrigation: sprinkling irrigation (1), furrow irrigation (2)

Crop	Factor of radionuclides transfer											
	^{60}Co		^{65}Zn		^{90}Sr		^{106}Ru		^{137}Cs		^{144}Ce	
	1	2	1	2	1	2	1	2	1	2	1	2
Corn vegetative mass	84	1.3	234	29	10	1,8	20	0,7	33	0,7	50	0.9
corn	5	0.03	81	14	0.2	0.3	0.07	0.004	1.3	0.2	0.05	0.04
Winter wheat												
straw	-	-	-	-	20	5.2	-	-	57	2.5	60	0.5
corn	-	-	-	-	1.2	1.8	-	-	7	0.2	5	0.03
alfalfa	17	10	374	61	33	15	52	7	79	12	254	12

Note: *Factor of radionuclides transfer – the ratio of the specific activity of radionuclides in biomass (Bq/kg) to their surface activity on the irrigated area (kBq/km^2).

With repeated irrigation, the significance of the soil and water routes for the intake of radionuclides levels off after 2–6 years of irrigation, depending on the type of soil, radionuclide and plant species. For ^{90}Sr this leveling occurs rather rapidly, and for ^{137}Cs the fraction of the soil input pathway remains for a long time less than from irrigation water.

Particularly significant is the effect of irrigation on soil contamination on which rice is grown. If for other plants the watering rate per season does not exceed 4000–6000 m^3/ha, then for rice it is 15000–20000 m^3/ha, which leads to a particularly high risk of radioactive contamination of paddy fields. However, there is no significant accumulation of radionuclides in the rice grain.

Table 3.4. shows the average radionuclide transfer factors for agricultural products in the area of sprinkling irrigation.

Table 3.4

Average factors of ^{137}Cs and ^{90}Sr accumulation in agricultural products in the area of irrigation by sprinkling

Product type	Radionuclides accumulation factor	
	^{90}Sr	^{137}Cs
Corn	0.12	0.9
Milk	0.43	10
Meat	0.026	18
Green vegetables	2.5	8
Cabbage	0.23	1.1
Tomato	8.5	18.5
Cucumbers	4.2	13
Potatoes	2	8
Root vegetables (beets, carrots)	6	17.7
Rice	0.11	2

Note: *Factor of accumulation – the ratio of the specific activity of radionuclides (Bq/kg) to their volumetric activity in irrigation water (Bq/l).

Prevention of radionuclides transfer from soil to plants, that is, inhibition of their movement in the initial and critical link of their short food chain, is one of the main modern tasks of not only agricultural radioecology, but also general radiobiology, since it is ultimately aimed at the human antiradiation protection (Yamada et al., 2012).

Depending on the properties of the soil, the degree of its contamination with radioactive substances, as well as the types of agricultural plants grown, the ways of using the crop and other conditions, various means are used that can greatly reduce the accumulation of radionuclides in crop and forage products. According to one of the classifications, they are divided into two groups:

1. Generally accepted measures, the application of which ensures the maintenance of the usual level of agriculture or even contributes to an increase in soil fertility, crop growth, crop quality and at the same time leads to a decrease in the transfer of radionuclides into plants.
2. Special measures, the main purpose of which is exclusively to reduce the intake of radionuclides into plants.

Such a distribution, of course, is conditional, since generally accepted means in certain situations can be interpreted as special and vice versa. Therefore, it is fair to define five main integrated systems for reducing the intake of radionuclides into plants, which take into account both generally accepted and special mechanical, agrotechnical, agrochemical, chemical and biological measures: soil cultivation, the use of chemical ameliorants and fertilizers, changes in the composition of plants in crop rotation, changes in the irrigation regime and the use of special substances and techniques.

3.2. Soil cultivation

After fallout, radioactive precipitation is concentrated mainly in the upper, rather thin layer of soil. At relatively low soil contamination levels, a sufficient measure can be processing with conventional milling machines or heavy disc harrows, as well as plowing with moldboard plows to the usual depth of 20–25 cm. Mixing the contaminated surface layer with a deeper one sharply reduces the spread of radioactive fallout with the wind and significantly reduces airborne contamination of plants, an order of magnitude reduces the radiation background of the area.

At high levels of contamination, an effective technique is to incorporate a contaminated soil layer with a subsoil plow to a depth of 50–75 cm with a soil overturning. This leads to a decrease in the accumulation of radioactive products by plants in the zone of the predominant location of root systems by 5–10 times.

Undoubtedly, as a result of such plowing of poor sod-podzolic soils, one can expect a significant deterioration in fertility almost to its complete loss. However, in some cases, it is necessary, since it reduces the possibility of surface wind uplift and transfer, washout of radioactive substances. In addition, with sufficient application of organic and mineral fertilizers, lime on acidic or gypsum on alkaline soils, the yield may not experience a significant decrease.

Deep plowing of radioactive substances is an energy-intensive activity that requires a lot of effort and money. Therefore, it can be recommended only in exceptional cases for certain crops and, as a rule, in small areas.

Removal of the topsoil is carried out at very high levels of contamination. Road sweeper, road-building or specially designed machinery that is unconventional for agronomic practice is used for this purpose.

However, the removal of the topsoil to a depth of only 5 cm gives a volume of up to 500 m^3 per 1 ha. Moreover, even with the help of special machines in the field, it is impossible to remove a layer of such a thickness, and therefore the volume of the soil mass can significantly increase. Such an amount of soil is difficult to remove, transport, and most importantly – to bury. Therefore, cleaning the soil surface using this technique can be recommended only in cases where the amount of radionuclides on them significantly exceeds the limits of permissible levels.

Sometimes at very high levels of contamination, it is recommended to deep fill the surface radioactive horizon with a thick (0.5–1 m) layer of clean soil taken from the depth. Unequivocally, such an event is difficult to hold in large areas. Like deep plowing, removal of the topsoil can only be applied locally.

Most of the considered methods, which are associated with soil cultivation, have the character of special measures and are effective only in the first year after the fallout of radioactive substances. If plowing was carried out and the surface contaminated layer was mixed to the depth of the arable layer, such measures do not make sense. It is needful, then, to use other means. One of the most effective for all subsequent years is the use of chemical ameliorants and fertilizers.

3.3. Application of chemical ameliorants and fertilizers

The role of chemical ameliorants as substances that improve the physical and chemical state of soils; mineral and organic fertilizers as suppliers of plant nutrients in conditions of land contamination with radionuclides does not change. However, they can acquire new functions related to their physicochemical and chemical properties. Under conditions of qualified use in certain forms, quantities and ratios, they can significantly reduce the intake of radionuclides into plants.

3.3.1. Lime application and the role of calcium

Radioactive substances often enter the environment in the form of insoluble and hardly soluble non-exchangeable forms. However, over time, upon contact with water, oxygen in the air, they can pass into a soluble exchangeable state. This is especially facilitated by the environment acidic reaction. And it was noticed that more radionuclides enter plants on acidic soils than on neutral or alkaline soils. In this regard, the method of acidic soils liming, which is widely used in agricultural practice, as it turns out, not only helps to improve the conditions for plant growth, but also to reduce the intake of radionuclides into them.

The main component of lime is calcium – a chemical analogue of strontium in the form of oxide, hydroxide and carbonic acid. Therefore, as a result of competition, antagonism between them, the supply of ^{90}Sr to plants decreases, as a rule, to a greater extent than the supply of ^{137}Cs.

Liming is usually used on podzolic, sod-podzolic, some bog and peat soils, less it is used on gray forest soils. On sod-podzolic and gray forest soils of Polissia, with a humus content of up to 3 %, the need for lime can be determined by the pH of the salt extract from the soil, taking into account its mechanical composition (Table 3.5).

Liming of acidic soils contaminated with radionuclides should be considered one of the main means that significantly inhibit the transition of radionuclides from soil to plants.

Table 3.5

Optimal doses of lime in terms of pure and dry calcium carbonate, t/ha

Mechanical soil composition	pH of the salt extract from the soil					
	4.5	4.6	4.8	5.0	5.2	5.4–6.0
Sandy loam and light loam soil	4.0	3.5	3.0	2.5	2.0	2.0
Medium loam soil	6.0	5.5	5.0	4.5	4.0	3.5

According to the data of various authors, obtained in 24 years after the accident at the Chornobyl nuclear power plant, it allows to reduce the ^{90}Sr content in potatoes up to 5–10 times, in the hay of legumes – 6–8 times, in vegetables – 4–6 times, in berries – 3–5 times. For ^{137}Cs, these multiplicities are, as a rule, somewhat lower. It is clear that the application of lime and other lime materials is possible only on acidic soils. As for alkaline soils, their enrichment with calcium can be carried out by plastering. Balanced amounts of limestone and gypsum can be applied on neutral soils. But it should be noted that the experience of soils plastering in order to reduce the intake of radionuclides into plants is much more modest than the experience of liming.

3.3.2. Potash fertilizers

The entry of ^{137}Cs into plants and its accumulation in the harvest is largely determined by the content in the soil and in the plants themselves of its chemical analogue – potassium. With an increase in the amount of potassium in the soil, the supply of ^{137}Cs to plants decreases. Therefore, the application of potash fertilizers in increased quantities, especially for potassium phyloplants, is one of the main ways to reduce the content of this radionuclide in crop production.

The experience of studying the effect of potash fertilizers on the supply of ^{137}Cs to agricultural plants is huge. It unambiguously testifies that their application on potassium-poor soils always leads to a significant decrease in the content of this radionuclide in the crop: in vegetables and potatoes – 4–8 times, in cereals and legumes – 3–6 times, in fodder grasses, cereal straw, flax – 3–7 times.

Foliar nutrition of plants with potassium significantly reduces the intake of ^{137}Cs both through the roots and through the leaves.

In general, the accumulation of ^{137}Cs by plants is inversely proportional to the content of exchangeable potassium in the soil. But the decrease in the levels of its content in plants depending on the dose of potassium is hyperbolic, that is, the effectiveness of potassium nutrition decreases with increasing doses.

However, an increase in the amount of potassium by two and three times in comparison with the generally accepted norms makes it possible to reduce the intake of the radionuclide by 3–6 times.

Strengthening the potassium nutrition of plants also reduces the intake of ^{90}Sr. This is especially pronounced also on podzolic and sod-podzolic soils. So, the addition of potash fertilizers on sod-podzolic soils of light texture reduces the accumulation of ^{90}Sr in the harvest of cereals, potatoes and vegetables by 2–3 times. The decrease in the intake of this radionuclide under the influence of potash fertilizers is usually explained by the well-known antagonism between potassium on the one hand, and calcium and ^{90}Sr on the other.

3.3.3. Phosphate fertilizers

Phosphate salts are able to form with strontium, as, incidentally, with other elements of the second group, poorly soluble or even practically insoluble compounds such as secondary and tertiary phosphates. Based on this, it was rightly assumed that the application of phosphorus fertilizers into the soil should reduce the transfer of ^{90}Sr to plants. Moreover, a large array of research and production data indicates that the application of phosphate fertilizers in any form at any difference reduces the accumulation of ^{90}Sr by almost all plant species in Fig. 3.1. Dependence of the levels of crop contamination with ^{137}Cs on the doses of potash fertilizers and the initial content of exchangeable potassium in the soil: (1–1, 2–2, 3–4, 4–10 and 5–20 mg/100 g) × 2–6 times. The most effective fertilizers are those containing calcium and potassium phosphates. Thus, the application of potassium phosphates into the soil several times reduces the content of both ^{90}Sr and ^{137}Cs in plants. Other phosphates – ammonium, sodium, magnesium affect mainly only the amount of ^{90}Sr.

If there are no contradictions regarding the effect of phosphate fertilizers on the intake of ^{90}Sr into plants, then they exist with respect to ^{137}Cs. On some soils, phosphate fertilizers in the form of superphosphates can enhance the accumulation of ^{137}Cs in plants. So, the application of superphosphate on leached black soils leads to an increase in the ^{137}Cs content in the productive organs of plants by 1.5–2 times. On poor sod-podzolic soils, this effect is practically not manifested. Nitrogen-phosphate fertilization without potassium often enhances the supply of ^{137}Cs to plants on all types of soils. In the black soils, an increase of almost 4 times was observed.

Moreover, fertilizer materials such as phosphates (which contain ^{238}U and ^{232}Th) and potassium, which are used in plant nitration processes, are considered to be important sources of soil contamination and become a source of radioactivity (Hussain & Hussain, 2011; Azeez et al, 2020). This phenomenon may result in potential radiological risks owing to external exposure during a resident time in the farms and internal exposure through ingestion of food grown on fertilizer soils. The compounds commercially of chemical fertilizers are named NPK (nitrogen (N), phosphorus (P) and potassium (K)). The ^{238}U and ^{232}Th enrichment in chemical fertilizers are linked to the high concentration in phosphate rock and the complicated chemical process in fertilizer production. The primary source of phosphate fertilizer is phosphate rocks of sedimentary origin, which contain relatively high concentrations of ^{238}U and ^{232}Th and its decay products. In NPK fertilizers, the potassium component increases the natural radioactivity, because of the presence of radioactive ^{40}K, whose natural abundance in potassium (K) is 0.0118 %. Using phosphate fertilizers over a period of many years could eventually increase the radium and uranium content of the soil and consequently increase radiation dose, which would result in the corresponding increase of the dose and cause diseases for the human body.

3.3.4. Nitrogen fertilizers

Care must be taken when using nitrogen fertilizers on soils contaminated with radionuclides. There is a lot of evidence that when they are introduced, the accumulation of both ^{137}Cs and ^{90}Sr in plants increases. The basis for this is the possible acidification of the soil solution and the growth under these conditions of the mobility of almost all nutrients, including radioactive ones, when using ammonium nitrate, a physiologically acidic form of nitrogen fertilizers, which is traditional for Ukraine and most European countries, as well as carbamide, which, decomposing into ammonia and carbon dioxide in the soil, can also contribute to a shift in the reaction of the medium towards acidification.

That is why it is not recommended to increase the doses of nitrogen fertilizers on soils contaminated with radionuclides, but to apply them in the amounts recommended for the usual growing conditions of the species on a given soil difference or even less. Nevertheless, the doses of phosphate and potash fertilizers should be increased by 1.5 and 2 times in order to minimize the presence of radionuclides, respectively.

The effect of the use of chemical fertilizers on natural radioactivity levels in agricultural soil was investigated. The obtained values of activity concentration show that the application of chemical fertilizers elevated the natural radioactivity level of the soil (Azeez et al, 2020). The radiological hazard parameters were also calculated in both the virgin and agricultural soil samples and compared with the international dose safety limit in the soil. The activity concentrations of naturally occurring radioactive nuclides in virgin and agricultural soil of the studied area were measured using gamma spectrometry. The obtained data revealed that the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in agricultural soil were higher than those in virgin by factors of (0.5–23.0)%, (0.2–16.9)%, and (0–13.4)%, resepectivily. The use of chemical fertilizers in the agricultural fields to enhance the crop yield causes an increase in the activity concentrations of natural radioactive nuclides, as well as the exposure of the farmers working in the agricultural fields, especially in those fields using potassium sulfate (K), urea ammonium super phosphate (NP), and nitro phosphate potash mixed (NPK) fertilizers with high concentrations of ^{226}Ra, ^{232}Th, and ^{40}K. The values of the activity concentrations of naturally occurring radionuclides in the virgin and the fertilized soil of the studied area were within the world average as proposed by UNSCEAR. The calculated values of the radiological hazard parameters (radium equivalent activity, the external hazard index, external absorbed gamma dose rates, outdoor annual effective dose, and excess lifetime cancer risk) for virgin and agricultural soil samples were in general also increased and modified by the effect of fertilizer use. However, in both virgin and fertilized soils, the level of these parameters was below the international dose limit in the soil as proposed by UNSCEAR and OECD. The conclusion of this work is that these farms and their soils and subsequently their products pose no health hazard for the population in terms of radiation impact.

3.3.5. Microfertilizers

A certain role in reducing the intake of radionuclides into plants belongs to microelements. The effect of microelements is especially significant on soils with their deficiency. These are the soils of Polissia and the north of the Forest-steppe, which are most susceptible to radionuclide contamination due to the accident at the Chernobyl nuclear power plant. Moreover, the multifaceted role that microelements play in the life of living organisms suggests various mechanisms of their influence on the behavior of radionuclides in the soil-plant system. Some of them, being chemical analogs of radionuclides, can enter into competition with them when they enter plants from the soil. They can affect the permeability of cell membranes for radionuclides with certain ionic radii, charge, geometry of coordination and electronic configurations; can activate or, conversely, slow down the transport systems of individual radionuclides; form complex compounds with various substances, including physiologically active ones, which affect the entry of radionuclides into plants and their movement into individual organs. In addition, all these effects can be especially acute in conditions of natural or artificial deficiency of microelements. It is then that their additional application will lead to the most pronounced positive results.

Thus, the introduction of lupine, peas, oats into the soil during sowing or foliar nutrition with solutions of zinc, manganese, copper, cobalt on sod-podzolic sandy soils reduces the accumulation of ^{90}Sr and ^{137}Cs in straw and grain by 1.5–2 times.

3.3.6. Organic fertilizers

The application of organic fertilizers into the soil increases the capacity of the soil absorption complex and can significantly reduce the intake of radionuclides into plants. In addition, organic fertilizers, the bulk of which are decomposed plant residues, containing in balanced amounts or close to such all macro- and microelements necessary for plants, many of which reduce the intake of radionuclides into plants. Poultry manure contains high amounts of calcium.

Especially effective is the application of manure, humus, low-lying peat, sapropel on soils of light texture. At the same time, organic fertilizers prevent the transition into plants not only of ^{90}Sr and ^{137}Cs, but also of many other radionuclides, such as ^{106}Ru, ^{144}Ce and even ^{239}Pu and ^{241}Am, which have no chemical analogs-antagonists among the nutrients.

When using organic and other local fertilizers, certain rules must be followed. Manure, compost, ash obtained in areas with high density of radioactive contamination can turn into a source of secondary soil contamination. Sapropels can also have a high level of pollution due to the concentration of radioactive particles from the catchment areas. Therefore, such fertilizers are not recommended for use in fields with low radionuclide content. It is also not recommended to apply them in vegetable and potato crop rotations, the products of which go directly to the human diet, often without any culinary treatment. It is most advisable to use such fertilizers for industrial crops, on seed-growing plots, in crop rotations of the fodder direction.

Thus, the use of chemical ameliorants and fertilizers on soils contaminated with radioactive substances, subject to certain rules and patterns, is one of the main ways to reduce their amount in plants. At the same time, it is necessary to take into account the fact that a decrease in the radioactivity of crop products is achieved not only by reducing their transfer from the soil, but also by diluting with an increase in yield.

3.4. Change of plant content in crop rotation

Different types of plants with different intensity absorb and accumulate individual radionuclides in their organs. Therefore, when planning measures to reduce their input into agricultural crops, special attention should be paid to the selection in crop rotation of both the species composition of plants and the varietal composition.

Calciphilous plants, primarily legumes, such as lupine, alfalfa, clover, vetch, peas, beans, forming their organs, together with calcium accumulate, so to speak, “wrongly” and its chemical analogue strontium, including ^{90}Sr. Cereals that absorb relatively small amounts of calcium accumulate much less ^{90}Sr. Therefore, the accumulation of this radionuclide by different plant species when grown under the same conditions can differ tens of times. The vegetative organs of grain and leguminous species accumulate ^{90}Sr in many times greater amounts than grain.

Of vegetable crops, which make up a significant share in the human diet, perhaps root crops and tubers accumulate ^{90}Sr most of all. In terms of their relative share in the diet, the first place is occupied by potatoes and beetroot. Cabbage also has a significant share. Similarly, calciphilous plants, such as the same lupine, corn, potatoes, beets, buckwheat and many others, together with potassium in large quantities accumulate its chemical analogs from the first group of the periodic table, including cesium with its ^{134}Cs and ^{137}Cs radioactive isotopes. In order of decreasing ^{137}Cs content in food products, individual plant species are placed in the following sequence: cereals and legumes – buckwheat–soybeans–beans–peas–oats–rye–wheat–barley–millet–triticale–corn; fodder (green mass) – yellow lupine–fodder cabbage–vetch–sunflower–clover–timothy grass–awnless fescue–corn; some technical – oilseed radish–rapeseed–sugar beet–sunflower flax; vegetable – cabbage–beetroot–salad–carrot–potato–cucumber–pumpkin–tomato.

Interspecific differences of agricultural plants in the accumulation of radionuclides reach many tens of times. Thus, the difference in the accumulation of ^{137}Cs in the grain of buckwheat and corn reaches 60 times, the productive organs of vegetable plants – 25 times. The amount of ^{90}Sr in the hay of leguminous grasses is 2–10 times higher than in cereals.

Varietal characteristics of plants can be of great importance in the formation of crop rotation in areas contaminated with radionuclides. Thus, individual pea varieties differ by 2.5 times in their ability to accumulate ^{90}Sr, and spring wheat varieties differ in their ability to accumulate ^{137}Cs – almost 2 times. As for winter wheat, the difference in the accumulation of this radionuclide by different varieties reaches 5 times. There is information about 3-fold fluctuations in the accumulation of ^{137}Cs in various varieties of corn and potatoes.

Data on the ability of certain plant species and their varieties to accumulate certain radionuclides should be used when organizing crop production in areas contaminated with radionuclides in order to obtain products with a minimum amount of radionuclides. For this, appropriate adjustments are made in crop rotations by replacing plant species with a high accumulation factor with those that have lower values. Sometimes, in order to reduce or avoid contamination of products, they even change the direction of crop production.

According to the recommendations of the Institute of Agriculture of the National Academy of Sciences of Ukraine, the following crop rotation should be used on sod-podzolic sandy soils contaminated with radionuclides:

1) winter crops with green fodder + post-harvest corn with green fodder,
2) winter rye,
3) potatoes,
4) oats;

on sod-podzolic sandy loam soils – the following:

1) corn with green fodder and silage,
2) winter rye,
3) potatoes,
4) barley with over-sowing of perennial grasses (cereal-legume mixtures),
5) perennial grasses,
6) winter wheat;

on gray forest loamy soils and black soils, there are no restrictions on the species set and crop rotation.

3.5. Irrigation regime change

With irrigation, the intensity of attraction of radionuclides into the biological cycle increases. There are three main ways of influence of irrigation on the accumulation of radionuclides in plants:

1. During irrigation, significant changes occur in the water regime of the soil, as a result of which the mobility of radionuclides and their availability for plant root systems can increase.
2. Due to changes in the nature of physiological processes, which are associated with changes in the intake and transportation of mineral nutrients in plants, changes occur both in the accumulation of individual elements and radionuclides.
3. During irrigation, the entry of radionuclides into plants can follow such migration chains that are not found in dry agriculture (for example, the transfer of radionuclides to plants directly from irrigation waters containing radioactive substances through aboveground organs).

Thus, favorable conditions for the entry of radionuclides into plants can be formed under irrigation. Their sources can be both polluted water and soil. The intake of radionuclides into plants depends on the method of irrigation. During sprinkling (and this method in Ukraine irrigates more than 95 % of irrigated lands) with contaminated water, radionuclides are absorbed mainly by the aboveground part of plants when irrigation water gets on leaves, flowers, fruits, stems. In this case, the intake of radionuclides into plants will be maximum.

With surface irrigation of the field along furrows, strip irrigation, flooding; with subsurface irrigating, when water flows through capillaries directly into the root layer from the system of subsoil moisturizers with drip irrigation, when water is supplied to the soil surface in the root collar zone, radionuclides are supplied through the roots. In this case, the accumulation of radionuclides will be much less, since some of them are absorbed by the soil. It should also be taken into account that some of the radionuclides are retained by the root system, absorbed by the walls of the leading vessels of the stem and other organs of the aerial part.

On the contrary, when irrigating with water not contaminated with radionuclides, preference should be given to sprinkling irrigation.

Watering with clean water contributes to deep soil leaching, the transfer of radionuclides from the surface horizons to deeper ones into the zone of root colonization, an increase in the mobility of radionuclides and their entry into plants.

The following general rules for changing the irrigation regime are distinguished.

They mainly relate to the most dangerous situation when irrigation is carried out with water containing radioactive substances. Such a situation has developed at the present time on the irrigated lands of the south of Ukraine, where irrigation is carried out with Dnipro water, which brings radionuclides from the northern part:

– if the choice of irrigation method is possible, give preference to surface irrigation;

– reduce the number of irrigations within the volume of the irrigation rate;

– give preference to watering in the first half of the growing season;

– avoid watering, especially sprinkling, during the formation and maturation of plant parts that make up the subject of the crop.

These restrictions on irrigation can certainly affect the productivity of agricultural plants, since any deviation from irrigation technology will lead to a violation of optimal growing conditions. But this is fully compensated for by the resulting crop production, which is cleaner in terms of radionuclide content.

3.6. Use of special substances and techniques

Quite a lot of various relatively simple and complex, natural and artificial substances are known, the placement of which into the soil reduces the transfer of radionuclides into plants. Among them, two main classes can be distinguished – adsorbents and complexonates. The one absorb radionuclides, making them inaccessible to plants, the other form complex compounds with radionuclides, converting them into difficultly soluble forms not assimilated by plants or, conversely, readily soluble, which are washed out from the root layer into the deep horizons of the soil.

As adsorbents, the most widespread are some natural minerals that have a high sorption capacity for radionuclides, in particular, zeolites, the deposits of which were found in the Carpathian mountains. Illites and vermiculites sorb ^{90}Sr and ^{137}Cs strongly and in large quantities, and montmorillonites and kaolinites, somewhat weaker. Minerals such as phlogopites, hydrophlogopites, glauconites, ascanites, gumbrins, biotites, bentonites are considered effective sorbents. Despite the relative cheapness, their use is associated with high costs, since it is advisable only at very high rates of their placement into the soil – up to 0.5–1 % to the volume of the arable layer. Therefore, this is 10–12 tons of finely ground mineral per hectare of field. With such a one-time application, it is possible to reduce the intake of radionuclides into plants by 1.5–3 times over the next several years. Sometimes these minerals are referred to as ameliorants, since their application significantly improves the mechanical properties of the soil.

The so-called “active coal”, a type of slag formed during the combustion of coal, has a pronounced sorption capacity. Its application on podzolic soils in amounts half as much as natural minerals allows achieving the same effect.

The application of aminopolycarboxylic acids and their derivatives into the soil greatly reduces the intake of many radionuclides into plants, including ^{239}Pu and ^{241}Am. These substances form complex water-soluble compounds with radionuclides, contributing to their rapid washout. However, this method is very expensive and has not yet become widespread in crop production.

A means of directly reducing the intake of radioactive substances into agricultural plants is the spraying of soil and vegetation with solutions of special chemical compounds, which form polymer films hardly soluble in water on them. Such a protective film suppresses the secondary dust transfer of radioactive particles, thereby reducing the degree of aerial contamination of plants and other organisms with radioactive substances.

Undoubtedly, all the methods considered are special, in most cases expensive and not very promising.

Generalized data on the action of some of the most effective methods for reducing the intake of radionuclides in agricultural plants are given in Table 3.6.

Table 3.6

The effectiveness of radioprotective measures in reducing the content of ^{137}Cs and ^{90}Sr in plants

Measures	Type of the soil	Reduction ratio relative to control	
		^{137}Cs	^{90}Sr
Liming	Sod-podzolic, light gray, forest, peat.	1.5–4.0 1.5–2.5	1.5–2.5 –
Application of increased (double) doses of phosphate and potassium fertilizers	Sod-podzolic, gray, forest, peat	1.5–2.0 1.8	1.2–1.5 –
Application of organic fertilizers, 40 t/ha and more	Sod-podzolic, gray, forest, peat	1.5–3.0	1.5–2.0
Joint application of lime, organic and mineral fertilizers	Sod-podzolic and sandy loam, gray, forest.	2.0–5.0	–
Application of adsorbent minerals (zeolite, kaolinite, vermiculite, bentonite)	Sod-podzolic, sandy and sandy loam	1.5–2.5	1.5–2.0

It should be noted that each of the considered complex systems of measures or individual techniques to prevent the transfer of radionuclides from the soil to agricultural plants in the conditions of the simultaneous use of several of them may not give an arithmetic increase in the degree of reduction in the deposition of radionuclides by plants. Moreover, against the background of several measures, their effect on the intake of fission products into plants can change significantly up to a decrease in the effectiveness of each of them when applied separately.

IV. RADIATION MONITORING IN THE FIELD OF AGROBUSINESS

4.1. Principles of organizing monitoring soil research in the field of agrobusiness

Work on soil protection requires the availability of information about the state of soils, about their changes under the influence of anthropogenic loads.

Unlike atmospheric air and natural waters, monitoring of the state and contamination of soils with mineral and organic toxicants is extremely limited and not properly organized. The ecological role of soil as a node of biosphere connections, where all metabolic processes between the earth's crust, hydrosphere, atmosphere and organisms inhabiting land take place most intensively, determines the need for a special organization of soil monitoring as an integral part of overall environmental monitoring. The need to organize a soil monitoring service is felt more and more acutely, since the magnitude of anthropogenic pressure on edaphotopes is constantly growing, and the rate of its growth is increasing. The total volume of global anthropogenic loads on the soil cover can be easily compared with the effect of natural factors (Bangotra et al., 2016; Angjeleska et al., 2020).

The general list of tasks and challenges facing soil monitoring is quite voluminous. In the future, new tasks are possible that arise with the advent of new technologies and the expansion of the range of organic and mineral substances synthesized by the chemical industry. Of course, some of today's tasks will be removed from the agenda in the near future; for example, with the transition of industrial enterprises to waste-free technology, there will be no need to control soil contamination with chemicals. But at present, such control is still needed.

Soil monitoring – it is diagnostics, prediction and management of the state of soils or control in the name of managing the expanded reproduction of their fertility.

The most important tasks of soil monitoring are:

– assessment of average annual soil losses as a result of water, irrigation and wind erosion;

– identification of regions with a deficit balance of the main elements of plant nutrition, identification and assessment of the rate of loss of humus, nitrogen and phosphorus; control over the content of plant nutrients;

– control over changes in soil acidity and alkalinity, especially in areas where high doses of mineral fertilizers are used, as well as during irrigation and the use of industrial waste;

– control over changes in the salt regime of irrigated edaphotopes and soils that are fertilized;

– control of soil contamination by heavy metals due to global subsidence;

– control over local contamination of soils with heavy metals in the zone of influence of industrial enterprises and transport highways, as well as contamination with pesticides in regions of their constant use, detergents and household waste in areas with a high contamination density;

– long-term and seasonal (according to the phases of plant development) control over moisture, temperature, structural state, water-physical properties of soils;

– assessment of the likely change in soil properties in the design of hydraulic construction, land reclamation, the introduction of new agricultural technologies and farming systems;

– inspection control over the size and correctness of the alienation of suitable for plowing soils for industrial and municipal purposes.

This is the most general and probably incomplete list of tasks that should be differentiated in accordance with the soil-geographical, climatic and economic zoning of the country.

The distribution of radionuclides in the biosphere, their ability to migrate along ecological chains and concentrate in individual links of food chains, have led to the problem of controlling radioactive contamination of agricultural land, soils, irrigation water, fodder, plant, livestock products, which makes it necessary to conduct targeted radiation monitoring of the agroindustrial complex (AIC) (Fig. 4.1)

Radiation monitoring of the AIC is a system of continuous observations (measurements), assessment and prediction of radioactive contamination of natural components and elements of biota, which are objects or products of human agricultural activities, and the reaction of the biotic component to the action of radiation.

Soil is the main source of radionuclide entry into terrestrial food chains.

As a result of fallout, radionuclides enter the earth’s surface, accumulate in the soil, are included in biogeochemical migration cycles and become new soil components. The soil is the most important and inertial link, and the rate of their distribution throughout the chain largely

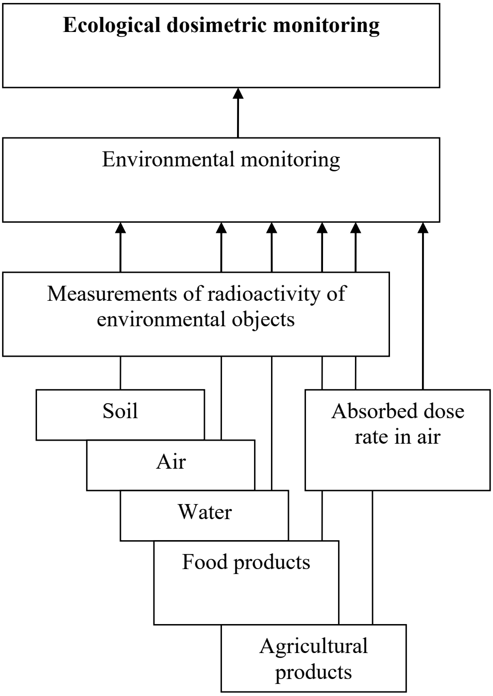

Figure 4.1. Ecological dosimetric monitoring structure

depends on the rate of migration of radionuclides in the soil (Ahmad et al., 2015; Osman et al., 2022).

As a result of movement in the soil and subsequent root uptake, radioactive substances enter parts of plants representing food and feed value. The accumulation of radionuclides in the plant mass can also occur due to the retention of a part of radioactive fallout from the atmosphere on the surface of plants – the aerial path of contamination. Such contamination plays an especially important role during the period of intense radioactive fallout from the atmosphere. Mechanical contamination of agricultural crops and natural grasses during the harvesting process or as a result of secondary wind uplift of radionuclides from the soil surface should also be taken into account.

The main source of intake of radionuclides in the body of animals is food, to a lesser extent it is water (about 2 % of the total content in the diet). However, it is impossible not to take into account such routes of entry as ingestion of soil particles by agricultural animals and inhalation of radioactive particles from the air or during secondary lifting from the grass stand.

Thus, the intake of radionuclides into the organism of agricultural animals and the products obtained from them should be considered in relation to their food sources – fodder plants, and the accumulation of radionuclides in plants – depending on the contamination of soil, atmosphere and water. Therefore, the objects of AIC radiation monitoring should be: the soil of arable and fodder lands; water used for irrigation and watering of agricultural land; food and forage plants, which play a major role in the diet of humans and animals; farm animals; livestock products (Elsaman et al., 2018; El-Gamal et al., 2019).

It is worth considering the differences between arable and permanent forage land (pastures, hayfields). Arable land, as a rule, is plowed annually to a depth of 25 cm, while the soils of permanent forage lands remain untouched for a long time. Soil cultivation leads to a change in the distribution of radionuclides in the soil, which should be taken into account when sampling for laboratory analysis. Among field crops, there are plants that are directly consumed by human or those that are processed for his needs, and fodder plants for animals. In the first group, the most important are: cereals, potatoes, leafy vegetables, root vegetables and tubers. Among fodder crops, plants on natural and artificial meadows and pastures, grain crops, potatoes, beets, corn should be considered. Of the livestock products, it is first of all necessary to control milk, meat of cattle, pork. Considering the possibility of contamination of plants and soil as a result of irrigation of agricultural land, it is necessary to monitor the content of radionuclides in the water of open water bodies.

The most objective source of information about the radiation situation in the agro-industrial sphere is direct measurements of the dose rate of γ- and β-radiation in the air at the surface of the earth and at a height of 1 m and the content of natural and artificial radionuclides in natural objects and agro-industrial products. The exposure dose rate is measured directly on the ground using field instruments (dosimeters or radiometers) and serves as an initial value for determining dose loads on biota.

To determine the level of radioactive contamination of soil, vegetation and livestock products, samples are taken and further analyzed in the laboratory. Sampling and initial processing of samples is an important step that has a decisive influence on ensuring the correctness of the final analysis results. The main requirements for samples are representativeness, adequacy, stability, the absence of any changes that change the conditioned components.

4.2. Radioecological monitoring of soils and agricultural products of the Dnipropetrovsk region

As a result of the disaster at the Chornobyl nuclear power plant, the environment is polluted by long-term radionuclides: ^{90}Sr, ^{137}Cs, ^{226}Ra, ^{239}Pu, etc. The ecological consequences of this accident in agricultural production are determined not only by the features of radioactive contamination, but also by genetic and evolutionary differences of individual soil varieties in natural agroecosystems.

The rate of self-cleaning of the environment depends on the rate of their radioactive decay, vertical and horizontal migration in soils. Often the determining factor in the level of plant pollution is not only the density of radioactive contamination of the soil, but also its physicochemical and agrochemical properties, mineralogical composition and water regime. Therefore, it is very important in the process of radioecological monitoring, modeling and forecasting of the situation to study and take into account all the features of the soil cover of contaminated areas.

Research into the migration of ^{137}Cs and ^{90}Sr in soils of agricultural ecosystems has not only theoretical, but also practical significance in connection with solving the problem of providing the population with ecologically clean products that are grown on agricultural land contaminated with radionuclides.

To substantiate and develop measures to improve the radiation situation of contaminated lands, data on the composition and density of contamination, their distribution and mobility in the soil profile, changes in these indicators over time are necessary. There are numerous results in the literature on the migration and mobility of radionuclides from global emissions in various soils. About 1.3 million hectares of agricultural land are contaminated. The density of radiocesium contamination for the bulk of these soils ranges from 1 to 15 Ci/km^2. Currently, these lands are the main sources of radiation load and a platform for the further spread of radionuclides in the environment.

In agricultural ecosystems, in contrast to natural ecosystems, additional factors act that modify the natural behavior of radioactive substances. Depending on the method of soil cultivation, there is a mechanical redistribution of radionuclides in the treated layer. Agro-reclamation measures and technologies change soil properties.

The processes of migration of radionuclides in soils, which cause specific distribution and accumulation in different conditions, and their quantitative assessment remain insufficiently studied. Determination of a quantitative assessment of the processes of mass transfer of ^{137}Cs and ^{90}Sr in soils of various agricultural ecosystems opens up new possible ways to increase the effectiveness of measures to prevent the fight against contamination of soil and agricultural products with radionuclides.

To substantiate and develop measures to improve the radiation situation of contaminated lands, data on the composition and density of contamination, their distribution and mobility in the soil profile, changes in these indicators over time are necessary.

The research objective was to analyze and generalize the current radioecological situation in agricultural production in the Dnipropetrovsk region.

Distribution of agricultural land contaminated with radionuclides by land type, soil type and coordinates of the sampling point of 29 certified monitoring experimental sites of the Dnipropetrovsk region is presented in Table 4.1.

Table 4.1

Characteristics of the monitoring sites of the Dnipropetrovsk region

Site No.	Location	Type agricultural lands	Type soil	Sampling point coordinates		
				longitude	latitude	altitude
1	Solone district	plowed field	Ordinary black soils	34,797239	48,007113	133
2	Nikopol district Dmytrivka settlement	plowed field	Ordinary black soils	34,522478	47,747856	90
3	Nikopol district Marhanets city	plowed field	Ordinary black soils	34,559064	47,663418	32
4	Nikopol district Chortomlyk settlement	plowed field	South black soils	34,124461	47,615781	33
5	Apostolove district	plowed field	South black soils	33,686529	47,634634	94
6	Shyroke district	plowed field	South black soils	33,299578	47,708511	75
7	Kryvyi Rih district	plowed field	Ordinary black soils	33,487803	47,931813	103
8	Sofiivka district	plowed field	Ordinary black soils	33,779533	48,001414	100

Continuation of Table 4.1

Site No.	Location	Type agricultural lands	Type soil	Sampling point coordinates		
				longitude	latitude	altitude
9	Krynychky district	plowed field	Ordinary black soils	34,322457	48,244855	130
10	Dnipropetrovsk district Mykolaivka settlement	plowed field	Ordinary black soils	34,678683	48,396041	124
11	Piatykhatky district Sukha Balka settlement	plowed field	Ordinary black soils	33,543085	48,36203	120
12	Piatykhatky district Saivka settlement	plowed field	Ordinary black soils	33,889257	48,345404	103
13	Petrykivka district	plowed field	Ordinary black soils	34,676016	48,646293	56
14	Syneknykove district Raivka settlement	plowed field	Ordinary black soils	35,422291	48,351812	144
15	Syneknykove district Rozdory settlement	plowed field	Ordinary black soils	35,7408	48,326458	100
16	Vasylkivka district	plowed field	Ordinary black soils	36,056365	48,168415	90
17	Pokrovsk district	plowed field	Ordinary black soils	36,277665	47,998414	110
18	Mezheva district	plowed field	Ordinary black soils	36,704787	48,245322	155
19	Petropavlivka district	plowed field	Ordinary black soils	36,25959	48,366967	90
20	Pavlohrad district	plowed field	Ordinary black soils	35,797965	48,538938	83
21	Verkhnodniprovsk district Vilnohirsk city	plowed field	Ordinary black soils	34,274505	48,651805	145

Continuation of Table 4.1

Site No.	Location	Type agricultural lands	Type soil	Sampling point coordinates		
				longitude	latitude	altitude
22	Verkhnodniprovsk district Mykolaivka settlement	plowed field	Ordinary black soils	34,430281	48,563991	150
23	Dnipropetrovsk district Doslidne village	plowed field	Ordinary black soils	34,804891	48,392018	
24	Novomoskovsk district	plowed field	Ordinary black soils	35,164473	48,81622	119
25	Dnipropetrovsk district Pidhorodnie settlement	plowed field	Ordinary black soils	35,095007	48,559173	56
26	Mahdalynivka district	plowed field	Ordinary black soils	34,923471	48,889297	106
27	Solone district	plowed field	Ordinary black soils	35,059067	48,186553	145
28	Dnipropetrovsk district Bratske settlement	plowed field	Ordinary black soils	35,030426	48,32715	58
29	Tomakivka district	plowed field	Ordinary black soils	34,651443	47,93767	133

Physico-chemical properties affect the nature of the soil formation process, soil fertility and plant development. A significant amount of radionuclides is already firmly fixed in the first years after moving into the soil. At first glance, their migration should be determined by the ratio of water-soluble, exchangeable, and other forms. It has been established that the more water-soluble and exchangeable forms of radionuclides in the soil, the faster they move. But after the radionuclides have entered the soil, various processes occur with them that change their mobility.

Soil density at almost all sites is within the permissible range – 1.15–1.30 g/cm^3, this is due to constant environmental conditions. The highest density is observed on the first experimental site both in 1986 and in 2010–1.43 and 1.44 g/cm^3, respectively.

For winter wheat, the optimal density range is 1.00–1.30 g/cm^3. The density of the soil is influenced by its mineralogical and granulometric composition, the content of humus in it, structure, etc. Agrophysical degradation, which manifests itself in soil compaction and deterioration of its structure, causes significant damage to soils. Its main reasons are: a high degree of open cultivation of soils; the use of intensive soil cultivation; non-compliance with crop sequence in crop rotation; insufficient amount of organic fertilizers that are applied to the soil.

The pH of the salt extract almost does not change, it fluctuates in the range of 6.6–7.85. On site No. 1, 9, soil acidification is observed (pH 6.6 and 6.46, respectively), on site No. 3 the soils are close to neutral (pH 7.3), on sites No. 17 and 29, the reaction of the soil solution is alkaline (pH 7, 8 and 7.85 respectively).

Soil acidity has an ambiguous effect on the biological mobility of radionuclides in them. For ^{90}Sr, ^{137}Cs, the intensity of the intake of radionuclides into plants increases with an increase in acidity.

Acidity also causes an indirect effect on the sorption of radionuclides by soils, changing the capacity of cation exchange.

On the territory of radioactive contamination, soils are represented by ordinary black soils. They are characterized by moderate acidity, so there is a slight increase in the proportion of water-soluble and exchangeable forms of ^{90}Sr and ^{137}Cs.

In this regard, the mobility of ^{90}Sr and ^{137}Cs in soils of these types increases, the strength of their fixation in the soil decreases, and the intensity of their entry into plants increases. At the same time ^{60}Co, ^{59}Fe, ^{65}Zn and some other radionuclides in acidic soils create various hydrolysis and complex compounds, which reduces their mobility. However, the rate of movement of radioactive elements into the mineral part of the soil should be distinguished from their mobility in the soil and in the soil-plant system.

An increase in the rate of migration of radionuclides into the mineral part of the soil does not always coincide with an increase in the rate of entry into plants. In the mineral part of the soil, radioactive substances can be firmly fixed, which reduces the rate of their entry into plants.

The nitrogen content of nitrate, mobile phosphorus and exchangeable potassium in the soils of the studied monitoring sites and their influence on the distribution of radionuclides were determined.

The experimental data showed that, a decrease in the content of nitrate nitrogen occurred in almost all monitoring sites (No. 1, 3, 9, 17), except for site No. 29. The largest decrease in the content of nitrate nitrogen is observed at sites No. 1, 9 and 17–1.5 times, 1.6 and 1.5 times, respectively. On the contrary, at site No. 29, there was an increase in the content of nitrate nitrogen by 1.2 times.

It is a matter of common knowledge, that the lack of available nitrogen in the soil leads to a decrease in yield, and an increase in the dose of nitrogen fertilizers increases the accumulation of radionuclides in the plant.

A noticeable increase in the content of mobile phosphorus – 1.4 times is observed at sites No. 1, 3, 9 and 29. At site No. 17, the content increased by 1.1 times. The increase may indicate that the use of phosphate fertilizers in 2010 was used more intensively than in 1986.

Phosphate fertilizers help reduce the accumulation of ^{137}Cs in the crop yield, especially in soils with a low content of mobile phosphorus.

Observation of the behavior of ^{90}Sr in the soil–plant chain shows that the application of phosphorus fertilizers reduces the application of ^{90}Sr to the green mass of winter wheat. This can be explained by the fact that the saturation of the soil-absorbing complex with phosphorus promotes the formation of sparingly soluble strontium phosphates and reduces its availability for plants.

The application of phosphorus fertilizers at a dose of 50 kg/ha increases the yield by 7.9 c/ha of dry matter. Also, the ^{137}Cs level remains almost the same, while the ^{90}Sr level is reduced by 12 %.

The content of exchangeable potassium at sites No. 9, 17 and 29 increased markedly, by 1.2, 1.5 and 1.5 times, respectively. At site No. 3, the content decreased by 1.1 times, and at site No. 3, it decreased by 1.7 times.

Doses of potash fertilizers on agricultural lands contaminated with radionuclides are differentiated depending on the type of soil, the content of mobile potassium and the density of contamination with ^{137}Cs and ^{90}Sr.

An increase in the content of mobile potassium due to the chemical similarity of potassium and cesium leads to a decrease in the conversion of ^{137}Cs into plants. An increase in the dose of potash fertilizers on soils poorly supplied with mobile potassium reduces the intake of ^{137}Cs from 2 to 20 times, and ^{90}Sr – up to 1.5 times. Additional application of potassium fertilizer (K_2O) against the general background of $N_{60}K_{120}P_{60}$ reduces the accumulation of ^{137}Cs in perennial grasses by 5 times.

In the course of field experiments, it was found that the greatest decrease in ^{137}Cs from soil to agricultural plants was observed when potassium fertilizers were applied as part of a complete mineral fertilizer mixed with lime and manure. ($N_{60}K_{120}$ + manure, 50 t/ha, $N_{60}K_{120}$ + lime).

The content of exchangeable potassium also increased, but to a lesser extent than the content of phosphorus. The weighted average content of exchangeable potassium in agricultural soils of the Dnipropetrovsk region in 2010 increased compared to 1986 in 1.05 mg K_2O/100g of the soil with a maximum value of 25 mg K_2O/100g of the soil.

Under the influence of the intensification of agriculture, the content of exchangeable potassium increased on average in Ukraine by 1.5 mg K_2O/100 g of the soil. Residual phosphates and potassium are in the soil in a more mobile form than their natural counterparts, can be fully used by agricultural crops.

According to the Institute of Soil Science and Agrochemistry of the National Academy of Sciences of Ukraine, an increase in the content of residual phosphorus in the arable layer by 1 mg P_2O_5/100g of the soil provides an increase in the grain yield by 1.0–1.5 c/ha.

Organic matter has an important effect on the migration of radionuclides in the soil and their absorption by plants. For most radionuclides, an increase in the content of humus in the soil is a factor that reduces their input into plants. The humus content in dynamics from 1986 to 2010 did not change significantly. Basically, there was a slight decrease, most of all at the site No. 1 – by 0.9 times.

The behavior of radionuclides is associated with the organic matter of soils of a specific nature – humic and fulvic acids. The ability of humic acids to adsorb ions, as well as to form strong complex complexes with radionuclides affects their sorption in the soil and their entry into plants.

Radiological monitoring of radioactive contamination of soils of agricultural land in the Dnipropetrovsk region was carried out according to the "Methods of agrochemical certification of agricultural lands". Determination of the activity of ^{137}Cs and ^{90}Sr in soil and grain of wheat was carried out on the beta-spectrometer "SEB-01" and gamma-spectrometer "AMA-03F". According to the current legislation, territories contaminated with cesium-137 up to 1.0 Ci/km^2 are considered conditionally clean. Agricultural production in such areas is possible without restrictions. The concept of exchangeable potassium – photometric method with " indophenol green" according to CIANO.

The maximum permissible level of soil contamination density with radiocesium established in Ukraine should not exceed 1 Ci/km^2. When soils are contaminated with radiocesium more than 15 Ci/km^2, lands are removed from agricultural use. The maximum permissible density of radiostrontium contamination (compared to cesium) is much lower – 0,1 Ci/km^2.

Comparative analysis of the content of ^{137}Cs and ^{90}Sr radionuclides in the soils was done at the observation sites. The content of ^{137}Cs in soils has decreased markedly since 1986. The highest value is observed at site No. 1 – by 2.6 times. At sites No. 3 – by 1.3 times, No. 9 – by 1.4 times, No. 17 – by 1.5 times and at site No. 29 – by 1.3 times.

A decrease in the ^{90}Sr content was noticeable at site No. 17 – by 3.1 times. At site No. 1, the content decreased by 2.1 times, No. 3–1.7 times, No. 9–1.8 and No. 29–1.5 times.

The contents of ^{137}Cs and ^{90}Sr in 2010 were quite consistent with the predicted decrease in accordance with the half-life and migration processes.

Falling out to the surface of the Earth, radioactive strontium enters the soil. Radionuclides from the soil enter plants through the root system. Falling out on the soil surface, radionuclides can remain in its upper layers for many years. Favorable conditions for the migration of radionuclides in the soil and along the soil-plant chain are created only if the soil is poor in minerals such as calcium, potassium, sodium, phosphorus.

Comparing the data on the contents of ^{137}Cs and ^{90}Sr, it is clearly seen that the accumulation of ^{137}Cs in wheat straw is more intense than the accumulation in wheat grain: at site No. 1, the content of ^{137}Cs in winter wheat straw is 1.5 times higher than in wheat grain, at site No. 3.9.29–1.3 times, and at site No. 17, on the contrary, there is a decrease of ^{137}Cs content in winter wheat straw by 1.4 times than in the grain.

The content of ^{90}Sr at all sites decreased by 1.3 times. This is due to the fact that the distribution of radionuclides in the aerial parts of the plant also occurs in different ways. About half of their amount accumulates in the stem, much less in the leaf, even less in the head, and only a few percent in the grain. There is such a regular dependence: the further along the transport chain from the roots an organ is, the less radioactive substances it accumulates. For cereals, this relationship is positive. According to the current state hygienic standards, the activity of ^{137}Cs in food grains (wheat, rye, barley, corn, buckwheat) should not exceed 50 Bq/kg and ^{90}Sr – 20 Bq/kg.

The supply of ^{90}Sr to plants depends on the availability of exchangeable calcium in the soil. The accumulation of ^{90}Sr in plants also depends on their ability to store calcium. Calciophilic plants accumulate much more calcium than species indifferent to it, therefore they can accumulate much more ^{90}Sr.

Based on multi-year research, scientists have revealed a linear dependence of the concentrations of radionuclides in agricultural crops on the density of soil contamination (Chorna & Ananieva, 2021).

Table 4.2

Average values of the accumulation factors (AF) of radionuclides based on the results of studies in 2010

Crop	Main products (grain)		By-products (straw)	
	AF ^{137}Cs	AF ^{90}Sr	AF ^{137}Cs	AF ^{90}Sr
Winter wheat	0.29 ± 0.101	0.49 ± 0.114	0.72 ± 0.276	0.62 ± 0.211

Regardless of the crop type and the year after the accident, the coefficient of the transfer of radionuclides from soil to plant decreases depending on the type of soil: peat-boggy soil – sod-podzolic soil – gray forest soil – black soil, which indicates that the transfer of radionuclides depends on the soils agrochemical properties.

Features of mineral nutrition, different duration of the growing season, distribution of the root system in the soil and other biological characteristics of plants affect the accumulation of radionuclides by various plant species.

The interspecies difference in the accumulation of radionuclides during root intake can reach 10–30 times. ^{90}Sr is 2–6 times more intensively absorbed by legumes than by cereals. The ^{137}Cs content is generally higher in legumes than in cereals. The accumulation of radionuclides by different varieties of the same crop can vary by 1.1–1.3 times.

According to a macro-scale study of agricultural land in the region, 1306.6 hectares of arable soil contaminated with ^{137}Cs and ^{90}Sr were identified. The radiological monitoring grid is evenly distributed, which made it possible to obtain more detailed information on the radiation contamination of the territory.

The average density of radiocesium contamination of agricultural land is heterogeneous and ranges from 0.1 to 1 Ci/km^2 and radiostrontium up to 0.02 Ci/km^2.

It should be noted a slight decrease in the specific radioactivity of ^{137}Cs and ^{90}Sr in the soils of the observation sites. Calculations of the coefficients were carried out relative to the average values for four years, the content of radionuclides at the corresponding sites. The curves of approximation of the contents of ^{137}Cs and ^{90}Sr radionuclides in soils were very similar in the form of their content in grain. This indicates a direct dependence of the accumulation on the distribution of the radionuclide content in soils. The accumulation factors are approximated by an almost constant function and have average values for ^{137}Cs – 0.41, and ^{90}Sr – 0.56.

It is known that cesium radionuclides have the ability to bind to the soil over time, penetrating into the crystal lattice of minerals, as a result of which the process of "ageing" of this radionuclide occurs, which turns into a poorly soluble state and becomes inaccessible to plants. Unlike ^{137}Cs, ^{90}Sr retains its mobility and increases the accumulation rate in comparison with previous years. Countermeasures aimed at preventing the migration of strontium in crop production should be prioritized today.

Thus, during the post-accident period, the radiation situation on agricultural land of the Dnipropetrovsk region has improved.

The intensity of migration of radionuclides is largely determined by the acidity of the soil solution, as well as the content of potassium, phosphorus, and humus in the soil. These factors determine the increased mobility of radionuclides, their more intensive transition from soil to crop production. In our studies, we analyzed the factors that reflect the characteristics of 29 observation sites. The most influential were: humus, exchangeable potassium and phosphorus content. We discovered that the influence of these factors is a combination of direct additive factors. Humus is the basis for the fertility of any soil. Therefore, with agricultural use of soils, constant monitoring of the content and state of humus in soils is necessary. The balance of humus on arable land as a whole in Ukraine was in short supply and reached 0.1 t/ha. Moreover, in many regions this deficit exceeds 0.10 t/ha. We carried out a comparative analysis of the distribution of humus at 29 monitoring sites in 1986 and 2010.

During the period from 1986 to 2010, the agrochemical indicators of soil fertility in the studied sites improved. The weighted average content of mobile phosphorus during this time increased by 3.57 mg P_2O_5/100 g of the soil and reached its maximum value at 8, 16, 23 and 25 monitoring sites 20.0 mg P_2O_5/100 g of the soil.

The content of exchangeable potassium also increased, but to a lesser extent than phosphorus content. The weighted average content of exchangeable potassium in agricultural soils of the Dnipropetrovsk region increased in 2010 compared to 1986 by 1.05 mg K_2O/100g of the soil with a maximum value of 25 mg K_2O/100g of the soil. Under the influence of the intensification of agriculture, the content of exchangeable potassium increased on average in Ukraine by 1.5 mg K_2O/100 g of the soil. Residual phosphates and potassium are in the soil in a more mobile form than their natural counterparts, so they can be fully utilized by agricultural crops. According to the Institute of Soil Science and Agrochemistry of the National Academy of Sciences of Ukraine, an increase in the content of residual phosphorus in the arable layer by 1 mg P_2O_5/100g of the soil provides an increase in the grain yield by 1.0–1.5 t/ha.

The results obtained allow us to conclude that the distribution of ^{137}Cs and ^{90}Sr in the soils of monitoring sites and wheat grain is not the same.

The biological characteristics of plants, along with the agrochemical properties of soils (the content of humus, exchangeable potassium and phosphorus) can be attributed to the main factors that affect the transition of radiocesium and radiostrontium from soil to plants. Due to the correct selection of crops, the accumulation of radionuclides in agricultural products can be reduced. The intensity of migration of radionuclides is largely determined by the content of potassium, phosphorus and humus in the soil.

4.3. The role of artificial forest plantations in the formation of the radio-ecological status of agrocenoses

Forest improvement is one of the priority measures aimed at the protection and rational use of land and the reproduction of soil fertility. Forests are the most powerful factor in counteracting the arid climate of the southeastern regions of Ukraine, they protect the natural environment, are of significant importance for soil protection and water regulation, prevent the formation of hot dry winds and dust whirls, change the hydrological regime of the territory, etc. (Travleev et al., 2005; Rozum et al., 2017). The expansion of forest protective, recreational, decorative, reforestation plantations in the steppe Ukraine contributes to the improvement of soil fertility and an increase in the efficiency of using the natural resources of the territory. Resistant vegetation cover traps suspended sediment flow, shields part of the soil surface. The formation and development of the vegetation cover is accompanied by an increase in its buffer role in the migration of radionuclides (Gudkov & Vinichuk, 2006). In this regard, the role of artificial windbreakers in limiting the migration of radioactive isotopes of natural and artificial origin attracts considerable interest.

The concept of sustainable development of agroecosystems for the period up to 2025, approved by the Presidium of the National Academy of

Agrarian Sciences of Ukraine in 2003, provides for the intensification of work both to preserve forest gene pools and to purposefully increase the area of forest plantations (Furdychko, 2003). It has been established that a forest ecosystem is a type of ecosystem that firmly retains radionuclides. The forest can influence the migration of radionuclides on a global scale. Radionuclides deposited on tree crowns move to the forest litter under the influence of atmospheric precipitation and as a result of leaf fall and are involved in the main bioecological processes (Rudko & Bondar, 2020).

The accumulation of radionuclides in the constituent components of forest biocenoses is determined by the intake of radionuclides during root nutrition of plants (Gudkov & Vinichuk, 2006; Trokhymchuk, 2015). At the same time, the main place of concentration of radionuclides in the biogeocenosis is soil and organic litter fall. Moss carpet plays a significant role in the redistribution of radionuclides. Due to the decomposition of organic litter fall, there is a gradual deepening of radionuclides into the mineral part of the soil. The quantitative characteristics of this process differ from each other depending on the types of forest site (Krasnov & Landin, 2013; Melnyk, 2020).

The degree of soil moisture plays an important role for the rate of vertical migration. With an increase in humidity, the intensity of migration of radionuclides increases, and accordingly, their content in the forest litter increases. An important factor in the redistribution of radionuclides between the forest litter and the mineral part of the soil is the population composition of plantations. (Trokhymchuk, 2015; Markovic & Stevovic, 2019).

Extensive radioecological studies were carried out in the forest ecosystems of Ukraine after the accident at the Chornobyl nuclear power plant, but only a few of them were directly devoted to the study of the transition of radionuclides into plants, the characteristics of the accumulation and content of radionuclides in plant parts. The processes of migration of radioactive elements in artificial forest plantations have hardly been studied (Irklienko et al., 2001; Krasnov & Landin, 2013; Trokhymchuk, 2015; Melnyk, 2020; Chorna & Ananieva, 2020).

Samples of natural material were taken in 2020–2021 on the territory of agricultural land near the village of Maiorka of Dniprovskyi district. Sample plots were selected according to groupings of robinia with a predominance of 60-, 15-, and 5-year-old trees in the age structure. The thickness of the forest litter was 4.0, 2.5, and 1.0 cm, respectively. Soil samples were taken at a depth of 20–25 cm in accordance with standard GOST 4287:2004 (Tykhonenko et al., 2008).

The primary preparation of natural material consisted in grinding using a laboratory mill and drying in a dry heat oven to constant weight at a temperature of 105 °C. The specific activity of radionuclides was determined in samples weighing 10–20 g on a scintillation spectrometer of gamma radiation SEG-001 "AKP-C" and a spectrometer of beta radiation SEB-01–150 (Ukraine) in Bq/kg of dry weight.

To assess the overall level of radioactivity, which is created in the components of the ecosystem by the main dose-forming radionuclides, and the possible effect on the biota, the integral indicators of the effective specific radioactivity and the absorbed dose rate were calculated.

The integral indicator of the effective specific activity of natural radionuclides in soil and forest litter was calculated using the formula (Radiation Safety Standards of Ukraine-97, 1997):

$$\mathbf{A_{ef} = A_{Ra} + 1{,}31A_{Th} + 0{,}085A_{K}} \qquad \mathbf{(4.1)}$$

To assess the risk of radiation exposure to biota, the absorbed dose rate was calculated using the conversion factors recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation, 2000 (Abba et al., 2018; Abedin et al., 2019; Gad et al., 2019):

$$\mathbf{D = 0{,}462C_{Ra} + 0{,}604C_{Th} + 0{,}0417C_{K}} \qquad \mathbf{(4.2)}$$

The intensity of the background radiation was measured using a digital dosimeter-radiometer RKS-01 "STORA" (Ukraine). The power of the natural background radiation in the study area did not exceed the established sanitary and hygienic standards, the value ranged from 0.085 to 0.275 μSv/h.

The forests of the Dnipropetrovsk region have no industrial significance, they mainly perform ecological, protective and recreational functions and have an environmental, scientific, historical and cultural purpose. The beneficial properties of forests in the region are extraordinary, since they are able to reduce the negative effects of natural phenomena, protect the soil from erosion, prevent pollution and cleanse the natural environment, contribute to the regulation of water flow, improve the health of the population and its aesthetic education (Yakuba & Gorban, 2021). The forest belt significantly reduces the noise load, which is a problem in large industrial cities, which include the city of Dnipro and its satellites.

According to calculations, the optimal forest cover in the Dnipropetrovsk region should be 8–10 %, currently it is only 5.6 % (in Ukraine this indicator is 15.6 %) (Regional report, 2020).

In the Dnipropetrovsk region, a system of artificial forest plantations has been formed, it consists of large tracts, windbreakers, water protection plantations and areas of restoration plantations within natural forest ecosystems (ravine, floodplain and arena forests). They perform soil protection and water protection, phytomeliorative, recreational functions, increase landscape and species diversity, are reservations of valuable species of plants and animals that are part of ecological corridors and eco-nuclei in the system of the ecological network of Ukraine, have great ecological potential. However, in the modern period, a significant number of them are in an unsatisfactory destructive state, which is due to both natural reasons (age-related crisis state) and anthropogenic impact (deforestation, fire, etc.).

The object of our research was the processes of accumulation and migration of the main dose-forming radionuclides and the formation of effective specific radioactivity and absorbed dose rate in artificial forest plantations.

In order to study the features of the migration of ^{226}Ra, ^{232}Th, ^{40}K, ^{137}Cs and ^{90}Sr radioactive isotopes in the biogeocenosis of the sanitary-protective windbreaker, a radioecological analysis of three components of the ecosystem of artificial forest plantations of Robinia pseudoacacia L. was carried out – soil, forest litter, tree leaves.

The levels of natural and artificial radionuclides in the soil of artificial forest plantations of Robinia pseudoacacia. It was revealed that in the summer period ^{226}Ra concentrations in soil samples varied from 19.8 to 27.2 Bq/kg, and in locations where 60-year-old trunks prevailed, the level of ^{226}Ra in soil was lower by an average of 16.1 %. compared to arrays of younger trees (Fig. 4.2).

The content of ^{232}Th in the soil of the studied points was more uniform. The absolute values of the specific radioactivity of ^{232}Th were found in the range from 29.8 to 35.4 Bq/kg, the average statistical decrease in the places where older trees grew was 8.0 %. The level of ^{40}K in the soil ranged from 32.6 to 41.2 Bq/kg and decreased with an increase in the age of trees by an average of 17.1 %.

In the autumn and winter periods, insignificant increases in the ^{226}Ra content in the soil were found on average by 33 and 11 %, while the ^{232}Th content decreased by 45 %. The concentration of ^{40}K in the soil in the winter-autumn period almost doubled to 73.44 and 67.58 Bq/kg.

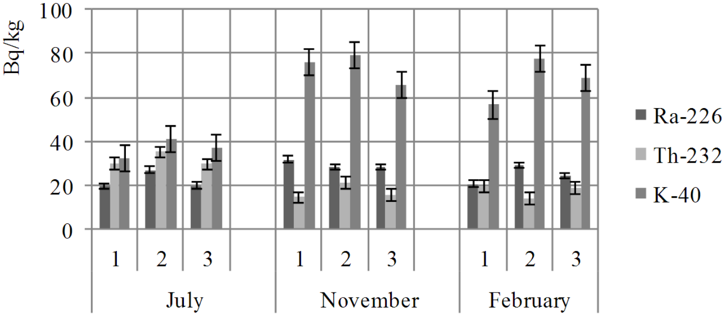

Figure 4.2. The levels of natural radionuclides (Bq/kg of dry weight) in the soil under artificial forest plantations of *Robinia pseudoacacia:* 1–60-year old trees, 2–15-year old trees, 3–5-year old trees

Obviously, a significant increase in the ^{40}K content is associated with its intense input from the above-soil layer. The results obtained are in good agreement with the data of other authors (Abba, 2018), who noted that the rate of migration of radionuclides depends on the granulometric composition of the soil in the following sequence: ^{40}K > ^{232}Th > ^{226}Ra.

The values of integral indicators of effective specific radioactivity in soil varied, respectively, from 59.04 to 77.07 Bq/kg in summer and from 51.30 to 54.43 Bq/kg in winter; absorbed dose rate – from 28.69 to 35.67 nGy/h in summer and from 23.81 to 25.67 nGy/h in winter (Table 4.3).

Table 4.3

Integral indicators of effective specific radioactivity (A) and absorbed dose rate (D) in the soil under artificial forest plantations of *Robinia pseudoacacia L*

Indicator	Sampling point	July	November	February
Effective specific radioactivity (A, Bq/kg)	1	62.0	57.63	51.30
	2	77.07	63.62	54.43
	3	59.04	54.68	55.26
Absorbed dose rate (D, nGy/h)	1	28.69	26.78	23.81
	2	35.67	29.42	25.29
	3	28.8	25.40	25.67

Note: 1–60-year old trees, 2–15-year old trees, 3–5-year old trees.

It should be noted that the values of the integral indicators did not change significantly during the studied seasons of the year, which indicated a redistribution of radioactive elements in the soil layers due to differences in their mobility and migration capacity. The data obtained indicated that the levels of radioactivity in the study area were within the permissible radiation background and did not pose a risk to biological objects.

The measured concentrations of ^{137}Cs and ^{90}Sr artificial radionuclides in the soil layer of the ecosystem of the Robinia pseudoacacia artificial forest belt were 20–40 times lower than in natural one (Fig. 4.3), which is consistent with their small proportion in the chemical composition of the soil. The levels of ^{137}Cs and ^{90}Sr in most cases did not depend in a regular way on the age structure of communities of tree plantations of Robinia pseudoacacia in the study area.

In the autumn-winter period, the concentrations of ^{137}Cs and ^{90}Sr radionuclides in the soil layer of the artificial forest belt ecosystem increased by 1.5–2 times, although they did not exceed the permissible norms. The ^{137}Cs content in the soil varied from 1.1 Bq/kg in summer to 2.33 Bq/kg in autumn and 2.97 Bq/kg in winter. Moreover, in the winter period, a uniform increase in the content of ^{137}Cs in the soil was noted in inverse relationship to the age of tree plantations of *Robinia pseudoacacia*.

Concentrations of ^{90}Sr varied from 0.57 Bq/kg in summer to 1.37 Bq/kg in autumn and 1.13 Bq/kg in winter, no dependence on the age structure of woody vegetation was observed.

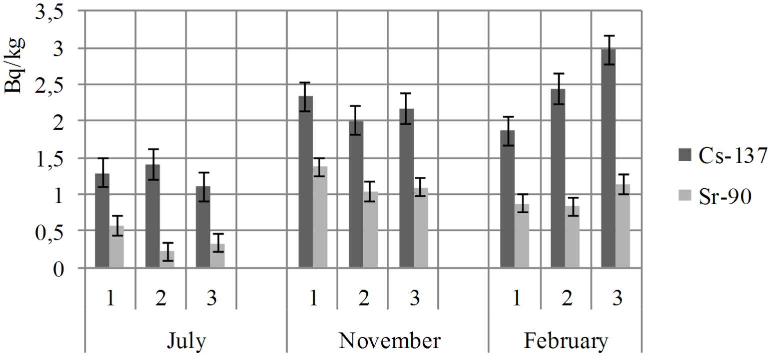

Figure 4.3. The levels of artificial radionuclides (Bq/kg of dry weight) in the soil under artificial forest plantations of *Robinia pseudoacacia:* 1–60-year old trees, 2–15-year old trees, 3–5-year old trees

The levels of natural and artificial radionuclides in the above-soil layer of artificial forest plantations of Robinia pseudoacacia. The above-soil layer of the windbreak consists of dead soil cover and forest litter, which are formed by fallen leaves, grass vegetation and other natural substrates. The processes of destruction and biochemical transformation of plant residues are intensively occurring in the forest litter, therefore it is one of the most important components of the forest group and a structural and functional component that unites the abiotic and biotic parts of the biogeocenosis into an integral system (Tsvetkova & Yakuba, 2011).

The study of the content of radionuclides in the samples of the above-soil layer of the windbreak showed that in the summer period ^{226}Ra concentrations varied from 24.0 to 25.7 Bq/kg, ^{232}Th concentration – from 32.1 to 40.2 Bq/kg, ^{40}K concentration – from 44.4 to 55.3 Bq/kg (Fig. 4.4).

In the autumn and winter periods, a uniform decrease in the content of natural radionuclides in the forest litter was observed, probably due to their vertical migration into deeper soil layers. The specific radioactivity absolute values of ^{226}Ra were found in the range from 14.03 to 26.43 Bq/kg in autumn and from 11.87 to 21.97 Bq/kg in winter, the seasonal decrease averaged 14.5 % and 30.2 %, respectively. The ^{232}Th content levels varied from 7.97 to 15.97 Bq/kg in autumn and from 12.80 to 16.97 Bq/kg in winter, the radioactivity of ^{232}Th decreased by an average of 63.5 % in the autumn–winter season.

For ^{226}Ra and ^{232}Th natural radionuclides, a regular decrease in the specific radioactivity in the above-soil layer was noted as the age of tree plantations decreased, the most pronounced was in winter.

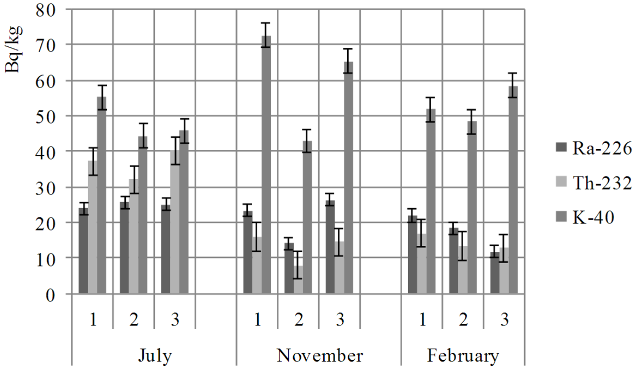

Figure 4.4. The levels of natural radionuclides (Bq/kg of dry weight) in the above-soil layer of artificial forest plantations of *Robinia pseudoacacia L.*: 1–60-year old trees, 2–15-year old trees, 3–5-year old trees

The levels of ^{40}K in forest litter ranged from 43.0 to 72.67 Bq/kg in autumn and from 48.43 to 58.57 Bq/kg in autumn. An increase in ^{40}K radioactivity by 24.4 % was noted in the autumn period, probably due to its intense influx into the above-soil layer with fallen leaves.

Integral indicators of effective specific radioactivity and absorbed dose rate in the above-soil layer varied depending on the season of the year (Table 4.4).

Table 4.4

Integral indicators of effective specific radioactivity (A) and absorbed dose rate (D) in the above-soil layer of artificial forest plantations of ***Robinia pseudoacacia***

Indicator	Sampling point	July	November	February
Effective specific radioactivity (A, Bq/kg)	1	77.43	50.56	48.60
	2	71.52	28.13	40.17
	3	81.66	50.95	33.62
Absorbed dose rate (D, nGy/h)	1	35.87	23.51	22.56
	2	33.11	13.08	18.67
	3	37.79	23.68	15.65

Note: 1–60-year old trees, 2–15-year old trees, 3–5-year old trees.

The values of the effective specific radioactivity indices varied, respectively, from 71.52 to 81.66 Bq/kg in summer and from 33.62 to 48.60 Bq/kg in winter; absorbed dose rate in forest litter – from 33.11 to 37.79 nGy/h in summer and from 15.65 to 22.56 nGy/h in winter, which also indicates a seasonal decrease in the background radiation due to the migration of dose-forming radionuclides into deeper soil layers.

Concentrations of ^{137}Cs artificial radioisotopes in forest litter varied from 1.2 to 1.32 Bq/kg in summer, from 0.96 to 2.07 Bq/kg in autumn, and from 0.90 to 1.70 Bq/kg in winter. The ^{90}Sr content levels were determined within the range of 0.6–0.12 Bq/kg in summer, 0.61–.27 Bq/kg in autumn, and 0.58–1.07 Bq/kg in winter (Fig. 4.5).

Thus, the radioactivity of ^{137}Cs and ^{90}Sr artificial isotopes increased in the autumn-winter period by 22.2 % and 76.7 %, respectively. For ^{90}Sr radionuclides, a regular decrease in the specific radioactivity in the forest litter was determined with a decrease in the age of tree plantations.

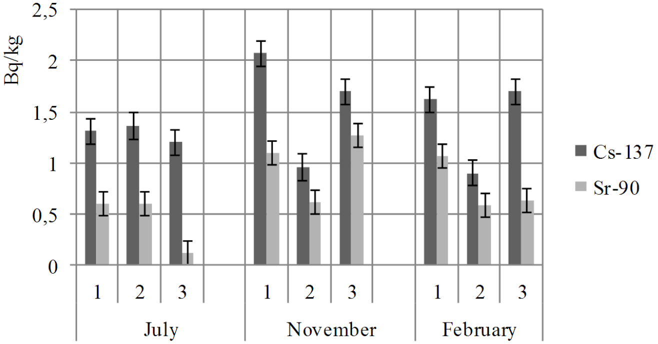

Figure 4.5. The levels of artificial radionuclides (Bq/kg of dry weight) in the above-soil layer of plantings of *Robinia pseudoacacia:* 1–60-year old trees, 2–15-year old trees, 3–5-year old trees

The levels of natural and artificial radionuclides in Robinia pseudoacacia L. leaves in artificial forest plantations. The levels of radioactive elements were determined in the leaf of *Robinia pseudoacacia*, one of the most widespread tree species in the steppe zone for the formation of protective, recreational, decorative, forest reclamation artificial plantations, which is also recommended as biological indicator (Aleekseeva, 2014). In summer, the concentration of radionuclides in the leaves of trees of different ages varied from 9.8 to 11.3 Bq/kg for ^{226}Ra, from 10.2 to 12.4 Bq/kg for ^{232}Th, and from 12.3 to 16.0 Bq/kg for ^{40}K (Fig. 4.6).

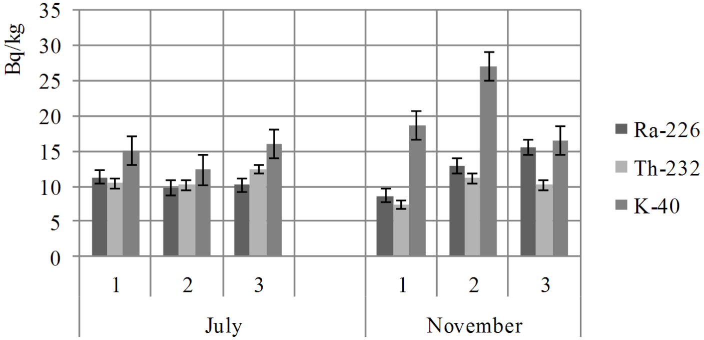

Figure 4.6. The levels of natural radionuclides (Bq/kg of dry weight) in the leaves of *Robinia pseudoacacia:* 1–60-year old trees, 2–15-year old trees, 3–5-year old trees

In autumn, the levels of ^{226}Ra in the Pseudoacacia robinia leaf were determined in the range from 8.67 to 15.5 Bq/kg, ^{232}Th – from 7.4 to 11.13 Bq/kg, ^{40}K – from 16.47 to 27.07 Bq/kg. In the autumn period, an increase in the content of natural radionuclides ^{226}Ra by 18.5 % and ^{40}K by 43.2 % was observed in the leaf mass. An inverse relationship was also found between the concentrations of ^{226}Ra and ^{232}Th radionuclides in the leaf and the age of *Robinia pseudoacacia* trees. Obviously, young trees accumulated radioactive elements at a higher rate due to more intensive processes of conducting solutions and synthesizing organic substances.

The highest concentrations of ^{226}Ra, ^{232}Th, ^{40}K natural terrigenous radionuclides and the value of integral indicators of effective radioactivity and absorbed dose rate were found in the composition of the forest litter, the lowest in the leaf. Perennial woody plants, in contrast to one-two-year-old herbaceous plants, accumulate radionuclides in wood, bark, shoots. And although the main mass of radionuclides is usually concentrated in the leaf, and the smallest in wood, the long-term closed cycle of substances: leaves – forest litter – soil – roots – trunk – leaves can lead to the fact that radionuclides involved in the biological cycle begin to be included in the tissues of plant components, intensively accumulate in their perennial organs, in particular in wood, roots, rhizomes and are excluded from the environment.

Concentrations of ^{137}Cs artificial radionuclides in the foliage of *Robinia pseudoacacia* trees were determined in the range from 0.16 to 0.39 Bq/kg in summer and from 0.49 to 0.80 Bq/kg in autumn. (Fig. 4.7).

The ^{90}Sr concentration in the leaf varied from 0.05 to 0.09 Bq/kg in the summer season and from 0.24 to 0.56 Bq/kg in the autumn sea-

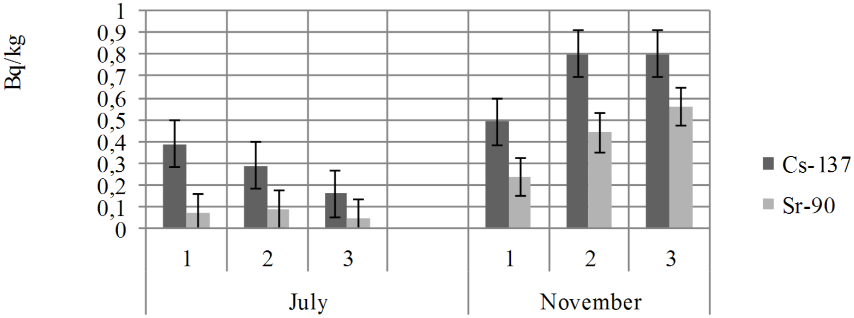

Figure 4.7. Levels of artificial radionuclides (Bq/kg of dry weight) in the leaves of *Robinia pseudoacacia:* 1–60-year old trees, 2–15-year old trees, 3–5-year old trees

son. Low concentrations of artificial radionuclides in biotic and abiotic components of the ecosystem are associated with their successive “aging” – a decrease in radioactivity because of the ascent of the half-life, removal outside the territory due to solid and liquid surface discharge.

Despite the low levels of the content of ^{137}Cs and ^{90}Sr artificial radionuclides, in autumn their accumulation in the foliage of trees was clearly traced, as a result of which the concentrations of ^{137}Cs and ^{90}Sr increased more than 2 times. In addition, in the autumn period, there was a pattern to an increase in the levels of ^{137}Cs and ^{90}Sr artificial radionuclides and the intensity of their accumulation in the leaf of young acacia trees.

Therefore, the highest concentrations of ^{226}Ra, ^{232}Th, ^{40}K natural radionuclides and the value of integral indicators of effective specific radioactivity and absorbed dose rate were found in forest litter, the lowest in foliage; the values of both integral indicators in the soil and forest litter were within the permissible radiation background and did not pose a risk to biological objects. As the age of the trees increased, the indices of the content of ^{226}Ra, ^{232}Th, ^{40}K natural radionuclides and specific radioactivity decreased in the surface layer of the soil. The values of the indicators of the effective specific radioactivity and the absorbed dose rate in the forest litter decreased during the autumn–winter period, which indicates a seasonal decrease in the radiation background due to the migration of dose-forming radionuclides into deeper soil layers. Changes in the concentrations of ^{137}Cs and ^{90}Sr artificial radioisotopes in the soil and forest litter did not show a regular relationship with the age structure of dendroflora groups, but were probably determined by other factors, such as the rate of their removal from the biological cycle, distance from the source of radioactivity, etc. In the autumn-winter period, the concentrations of ^{137}Cs and ^{90}Sr radionuclides in the soil layer of the artificial forest belt ecosystem increased by 1.5–2 times, although they did not exceed the permissible norms. There was a regularity in relation to the seasonal increase in the levels of ^{137}Cs and ^{90}Sr artificial radionuclides and the intensity of their accumulation in the leaf of predominantly young Robinia trees.

Thus, the data obtained confirm the significant role of artificial forest plantations in the migration of radioactive elements in the ecosystem.

CONCLUSION

All soil used anywhere in the world for agriculture contains radionuclides to a greater or lesser extent. Typical soils contain approximately 300 kBq/m^3 of ^{40}K to a depth of 20 cm. This radionuclide and others are then taken up by crops and transferred to food, leading to a concentration in food and feed of between 50 and 150 Bq/kg. The ingestion of radionuclides in food is one of the pathways leading to internal retention and contributes to human exposure from natural and man-made sources. Excessive contamination of agricultural land, such as may occur in a severe accident, can lead to unacceptable levels of radionuclides in food.

The radionuclide contaminants of most significance in agriculture are those which are relatively highly taken up by crops, have high rates of transfer to animal products such as milk and meat, and have relatively long radiological half-lives. However, the ecological pathways leading to crop contamination and the radioecological behaviour of the radionuclides are complex and are affected not only by the physical and chemical properties of the radionuclides but also by factors which include soil type, cropping system (including tillage), climate, season and, where relevant, biological half-life within animals. The major radionuclides of concern in agriculture following a large reactor accident are ^{131}I, ^{137}Cs, ^{134}Cs and ^{90}Sr. Direct deposition on plants is the major source of contamination of agricultural produce in temperate regions.

While the caesium isotopes and ^{90}Sr are relatively immobile in soil, uptake of roots is of less importance compared with plant deposition. However, soil type (particularly with regard to clay mineral composition and organic matter content), tillage practice and climate all affect propensity to move to groundwater. The same factors affect availability to plants insofar as they control concentrations in soil solution. In addition, because caesium and strontium are taken up by plants by the same mechanism as potassium and calcium respectively, the extent of their uptake depends on the availability of these elements. Thus, high levels of potassium fertilisation can reduce caesium uptake and liming can reduce strontium uptake.

The releases during the Chornobyl accident contaminated about 125000 km^2 of land in Belarus, Ukraine and Russia with radiocaesium levels greater than 37 kBq/m^2, and about 30000 km^2 with radiostrontium greater than 10 kBq/m^2. About 52000 km^2 of this total were in agricultural use; the remainder was forest, water bodies and urban centres. While the migration downwards of caesium in the soil is generally slow, especially in forests and peaty soil, it is extremely variable depending on many factors such as the soil type, pH, rainfall and agricultural tilling. The radionuclides are generally confined to particles with a matrix of uranium dioxide, graphite, iron-ceramic alloys, silicate-rare earth, and silicate combinations of these materials. The movement of these radionuclides in the soil not only depends on the soil characteristics but also on the chemical breakdown of these complexes by oxidation to release more mobile forms. The bulk of the fission products is distributed between organomineral and mineral parts of the soil largely in humic complexes. The 30-km exclusion zone has improved significantly partly due to natural processes and partly due to decontamination measures introduced.

There were also large variations in the deposition levels. During 1991 the ^{137}Cs activity concentrations in the 0–5 cm soil layer ranged from 25 to 1000 kBq/m^3 and were higher in natural than ploughed pastures. For all soils, between 60 and 95 % of all ^{137}Cs was found to be strongly bound to soil components. Ordinary ploughing disperses the radionuclides more evenly through the soil profile, reducing the activity concentration in the 0–5 cm layer and crop root uptake. However, it does spread the contamination throughout the soil, and the removal and disposal of the uppermost topsoil may well be a viable decontamination strategy.

The problem in the early phase of an accident is that the counter-measures designed to avoid human exposure are of a restrictive nature and often have to be imposed immediately, even before the levels of contamination are actually measured and known. These measures include the cessation of field work, of the consumption of fresh vegetables, of the pasturing of animals and poultry, and also the introduction of uncontaminated forage. Unfortunately, these measures were not introduced immediately and enhanced the doses to humans in Ukraine.

Furthermore, some initial extreme measures were introduced in the first few days of the accident when 15000 cows were slaughtered in Ukraine irrespective of their level of contamination, when the introduction of clean fodder could have minimised the incorporation of radiocaesium. Other counter-measures, such as the use of potassium fertilisers, decreased the uptake of radiocaesium by a factor of 2 to 14, as well as increased crop yield.

In some podzolic soils, lime in combination with manure and mineral fertilisers can reduce the accumulation of radiocaesium in some cereals and legumes by a factor of thirty. In peaty soils, sand and clay application can reduce the transfer of radiocaesium to plants by fixing it more firmly in the soil. The radiocaesium content of cattle for human consumption can be minimised by a staged introduction of clean feed during about ten weeks prior to slaughter. A policy of allocating critical food production to the least contaminated areas may be an effective common sense measure.

In 1993, the concentration of ^{137}Cs in the meat of cows from the Kolkhoz in the Sarny region, where countermeasures could be implemented effectively, tended to be much lower than that in the meat from private farms in the Dubritsva region. The meat of wild animals which could not be subjected to the same countermeasures had a generally high concentration of radio-caesium. Decontamination of animals by the use of Prussian Blue boli was found to be very effective where radiocaesium content of feed is high and where it may be difficult to introduce clean fodder. Depending on the local circumstances, many of the above mentioned agricultural countermeasures were introduced to reduce human exposure.

Since July 1986, the dose rate from external irradiation in some areas has decreased by a factor of forty, and in some places, it is less than 1% of its original value. Nevertheless, soil contamination with ^{137}Cs, ^{90}Sr and ^{239}Pu is still high and in Belarus, the most widely contaminated Republic, eight years after the accident 2640 km^2 of agricultural land had been excluded from use. Within a 40-km radius of the power plant, 2100 km^2 of land in the Poles'e state nature reserve have been excluded from use for an indefinite duration.

The uptake of plutonium from soil to plant parts lying above ground generally constitutes a small health hazard to the population from the ingestion of vegetables. It only becomes a problem in areas of high contamination where root vegetables are consumed, especially if they are not washed and peeled. The total content of the major radioactive contaminants in the 30-km zone has been estimated at 4.4 PBq for ^{137}Cs, 4 PBq for ^{90}Sr and 32 TBq for ^{239}Pu and ^{240}Pu.

However, it is not possible to predict the rate of reduction as this is dependent on so many variable factors, so that restrictions on the use of land are still necessary in the more contaminated regions in Belarus, Ukraine and Russia. In these areas, no lifting of restrictions is likely in the foreseeable future. It is not clear whether return to the 30 km exclusion zone will ever be possible, nor whether it would be feasible to utilise this land in other ways such as grazing for stud animals or hydroponic farming. It is however, to be recognised that a small number of generally elderly residents have returned to that area with the unofficial tolerance of the authorities.

In Europe, a similar variation in the downward migration of ^{137}Cs has been seen, from tightly bound for years in the near-surface layer in meadows, to a relatively rapid downward migration in sandy or marshy areas. For example, Caslano experienced the greatest deposition in Switzerland and the soil there has fallen to 42 % of the initial ^{137}Cs content in the six years after the accident, demonstrating the slow downward movement of caesium in soil. There, the ^{137}Cs from the accident has not penetrated to a depth of more than 10 cm, whereas the contribution from atmospheric nuclear weapon tests has reached 30 cm of depth.

In the United Kingdom, restrictions were placed on the movement and slaughter of 4.25 million sheep in areas in southwest Scotland, northeast England, north Wales and northern Ireland. This was due largely to root uptake of relatively mobile caesium from peaty soil, but the area affected and the number of sheep rejected are reducing, so that, by January 1994, some 438000 sheep were still restricted. In northeast Scotland, where lambs grazed on contaminated pasture, their activity decreased to about 13 % of the initial values after 115 days; where animals consumed uncontaminated feed, it fell to about 3.5 %. Restrictions on slaughter and distribution of sheep and reindeer, also, are still in force in some Nordic countries.

The regional average levels of ^{137}Cs in the diet of European Union citizens, which was the main source of exposure after the early phase of the accident, have been falling so that, by the end of 1990, they were approaching pre-accident levels. In Belgium, the average body burden of ^{137}Cs measured in adult males increased after May 1986 and reached a peak in late 1987, more than a year after the accident. This reflected the ingestion of contaminated food. The measured ecological half-life was about 13 months. A similar trend was reported in Austria.

In short, there is a continuous, if slow, reduction in the level of mainly ^{137}Cs activity in agricultural soil.

In the Ukraine, agriculture in most contaminated territories produces foodstuffs respecting the limits fixed the 25 June 1997: 100 Bq/l for milk products; 200 Bq/kg for meat; 20 Bq/kg for potatoes and bread. Currently, milk contamination levels are about 50 Bq/l.

However, there are large disparities in production in Ukraine, and some private farms continue to produce milk more contaminated than the level fixed by the new limits. This is due to animal grazing in contaminated meadows, and to the large differences of transfer coefficients for caesium (1 to 20) depending on the chemical composition of soils. Some experts predict that the fixation of caesium in soils will be enough in the next 4 to 8 years to prevent more contamination of foodstuffs, but some predictions seem more pessimistic.

In Ukraine, 8,4 million hectares of agricultural soil are contaminated with ^{137}Cs, and are subject to countermeasures, mostly the use of fertilisers:

- The 54900 hectares in the exclusion zone and the 35600 ha contaminated with more than 555 kBq/m^2 are exclude from agricultural farming.
- 130 800 ha are contaminated between 185 and 555 kBq/m^2, including 15 000 ha of peat bog where the transfer of caesium to plants is the highest.
- 1.1 million ha contaminated between 37 and 185 kBq/m^2, including 99500 ha of peat bog.
- 7238 millions ha contaminated between 3.7 and 37 kBq/m^2.

An exclusion zone of about 4000 km^2 has been defined, including a circular area with a radius of 30 km around the reactor. The areas affected are 2100 km^2 in Belarus, 2040 km^2 in Ukraine and 170 km^2 in the Russian Federation. All agricultural activities are forbidden, as is transfer of products. However, studies are underway as to how the less contaminated portions of this excluded land can be used.

Outside this area, 1.4 million of people are living on 30000 km^2 of land contaminated higher than 185 kBq/m^2, and 130000 people are living in areas where the contamination is higher than 555 kBq/m^2. For the territories where the annual dose is lower than 1mSv, life is considered as normal. When the annual dose is higher than 1 mSv per year, people receive social compensations.

The amount of agriculture products exceeding trade limits fixed by Ukraine, Russia and Bielorussia are now very low, in spite of new restrictive limits given by Ukraine in 1997 (100 Bq/kg for milk, 200 Bq/kg for meat, 20 Bq/kg for bread and potatoes). Today, the combination of soil transfers, physical half-life of ^{137}Cs and efficacy of the countermeasures could lead to an agricultural production that is lower than the fixed limits within the next 4 to 8 years. This means that, 20 to 25 years after the accident, food production could be operated without any restriction.

In early 2001, 2217 cities are still under radiological control in the Ukraine. In fact, only 1316 need permanent controls, but the population of the 901 remaining cities refuse the declassification of their areas because this could be associated with the end of financial and social compensation.

In the exclusion zone, the impact on fauna and flora is characterised by the extremely heterogenous deposition of radioactive particles, which produces a wide range of doses to which the biota were subjected. In some cases, even in very small geographic areas, the impacts differed by an order of magnitude.

Somes consequences of the accident for the natural plant and animal populations are determined by secondary ecological factors resulting from changes in human activities. For example, the forbidding of hunting alters the types and numbers of birds. In general, animal numbers have greatly increased compared to adjacent inhabited areas. These favourable conditions for large numbers of commercially hunted mammal species will be preserved.

The transfer of radionuclides by water and wind, and by extreme seasonal weather conditions has not led to long term contamination beyond the exclusion zone. In the exclusion zone, the future radioactive contamination will be reduced slowly through radioactive decay.

The area in the exclusion zone covered by coniferous and deciduous forests will increase to 65–70 % of the whole zone. The areas of meadowland and swap land will be correspondingly significantly reduced and gradually replaced by forests. These changes create a stable and fire-resistant vegetation layer. Associated with destruction of drainage systems, the level of groundwater will rise.

Since the accident, trade of wood is regulated. Depending upon its use, commercialisation levels range from 740 to 11000 Bq of ^{137}Cs/kg. With this new regulation, 30 % of pines trees in the excluding zone are not usable.

In summary:

Many countermeasures to control the contamination of agricultural products were applied with varying levels of efficiency. Never-theless, within the former Soviet Union large areas of agricultural land are still excluded from use, and are expected to continue to be so for a long time. In a much larger area, although agricultural and farm animal activities are carried out, the food produced is subject to strict controls and restrictions on distribution and use.

Similar problems, although of a much lower severity, were experienced in some countries of Europe outside the former Soviet Union, where agricultural and farm animal production were subjected to controls and limitations for variable durations after the accident. Most of these restrictions were lifted several years ago. However, there are still some areas in Europe where restrictions on slaughter and distribution of animals are applied. This concerns, for example, several hundreds of thousands of sheep in the United Kingdom and large numbers of sheep and reindeer in some Nordic countries.

However, the rehabilitation programmes must create conditions attractive enough for a younger workforce, especially engineers and qualified workers, to return. It is necessary and quite possible to create conditions where the environmental contamination will not result in the exclusion of important dietary components from consumption.

REFERENCES

1. Abba H.T., Hassan W.M. S. W., & Saleh M.A. (2018). Evaluation of Environmental Natural Radioactivity Levels in Soil And Ground Water of Barkin Ladi, Plateau State, Nigeria. *Malaysian Journal of Fundamental and Applied Sciences*, 14 (3), 338–342.
2. Abedin J., Karim R., Hossain S., Deb N., Kamal M., Miah H.A., & Khandaker M.U. (2019). Spatial distribution of radionuclides in agricultural soil in the vicinity of a coal-fired brick kiln. *Arab J Geosci*, 12, 236 https://doi.org/10.1007/s12517–019–4355–7
3. Ahmad N., Jaafar M., & Alsaffar M. (2015). Natural Radioactivity in Virgin and Agricultural Soil and Its Environmental Implications in Sungai Petani, Kedah, Malaysia. *Pollution*, 1 (3), 305–313. doi: 10.7508/pj.2015.03.007.
4. Ajaj B., & Moutaz R. (2017). Determination of Primordial and Anthropogenic Radionuclide Concentrations in Agricultural Soil Of The United Arab Emirates Using Gamma-Ray Spectrometry. Theses. 735. https: //scholarworks.uaeu.ac.ae/all_theses/735.
5. Akhtar N., Tufail M., & Ashraf M. (2005). Natural Environmental Radioactivity and Estimation of Radiation Exposure from Saline Soils. *International Journal of Environmental Science & Technology*, 1 (4), 279–285.
6. Alekseeva T.M. (2014). Bioindication as a method of ecological assessment of the natural environment. *Bulletin of Mykhailo Ostrogradskyi Kremenchuh National Universitu*, 2/2014 (85), 166–171.
7. Al-Hamed S., Wahby M., Al-Sulaiman M., & Aboukarima A. (2014). Prediction of Soil Fractions (Sand, Silt and Clay) in Surface Layer Based on Natural Radionuclides Concentration in the Soil Using Adaptive Neuro Fuzzy Inference System. *Open Journal of Soil Science*, 4, 215–225. doi: 10.4236/ojss.2014.47024.
8. Angjeleska A., Dimitrieska-Stojković E., Hajrulai-Musliu1 Z., Črčeva-Nikolovska R., & Boškovska B. (2020). Natural Radioactivity Levels and Estimation of Radiation Exposure in Agricultural Soils from Skopje City Region. *Macedonian Journal of Chemistry and Chemical Engineering*, 39 (1), 77–87. doi: 10.20450/mjcce.2020.1904.
9. Azeez H.H., Mansour H.H., & Ahmad S.T. (2020). Effect of Using Chemical Fertilizers on Natural Radioactivity Levels in Agricultural Soil in

the Iraqi Kurdistan Region. *Polish Journal of Environmental Studies*, 29 (2), 1059–1068. https://doi.org/10.15244/pjoes/106032

10. Bangotra P., Mehra R., Kaur K., & Jakhu R. (2016). Study of Natural Radioactivity (^{226}Ra, ^{232}Th and ^{40}K) in Soil Samples for the Assessment of Average Effective Dose and Radiation Hazards. *Radiat. Prot. Dosimetry*, 171 (2), 277–281. doi: 10.1093/rpd/ncw074.
11. Bundt M., Albrecht A., Froidevaux P., Blaser P., & Flühler H., (2000). Impact of Preferential Flow on Radionuclide Distribution in Soil. *Environ. Sci. Technol.*, 34 (18), 3895–3899.
12. Chorna V. I., & Ananieva T. V. (2020). Features of the Migration of Radionuclides in the Artificial Forest Biogeocenosis. *Tavriia scientific bulletin. Series: Agricultural sciences.* Kherson State Agrarian and Economic University, Kherson: Helvetyka Publishing House, 116 (2), 158–164.
13. Chorna V. I., & Ananieva T. V. (2021). The Current Radioecological State of Agricultural Soils and Grain Products in the Dnipropetrovsk Region of Ukraine. *Achievements of Ukraine and the EU in ecology, biology, chemistry, geography and agricultural sciences. Col. Monograph.* Lublin, Riga: "Baltija Publishing", 348–363,
14. Efremova M., & Izosimova A. (2012). Contamination of Agricultural Soils with Radionuclides. *In: Sustainable Agriculture* (1500th ed., pp. 253–255). Retrieved from http://urn.kb.se/resolve?urn=urn: nbn: se: uu: diva-175348
15. El-Arabi A. M., Abbady A. G. E., & Hussein A. S. (2006) Gamma-Ray Measurements of Natural Radioactivity in Sedimentary Rocks from Egypt. *Nuclear Science and Technique*, 17, 123–128. http://dx.doi.org/10.1016/S1001–8042(06)60024–9
16. El-Gamal H., Hussien M. T., & Saleh E. E. (2019). Evaluation of Natural Radioactivity Levels in Soil and Various Foodstuffs from Delta Abyan, Yemen. *Journal of Radiation Research and Applied Sciences*, 12 (1), 226–233. https://doi.org/10.1080/16878507.2019.1646523.
17. Elsaman R., Omer M. A. A., El-Montaser M. S., & El-Taher A. (2018). Natural Radioactivity Levels and Radiological Hazards in Soil Samples Around Abu Karqas Sugar Factory. *Journal of Environmental Science and Technology*, 11, 28–38. doi: 10.3923/jest.2018.28.38.
18. Furdychko O. I. (2003). Forestry of Ukraine: Development Prospects in the Formation of Sustainable Agroecosystems. *Agroecological journal*, 3, 3–10.

19. Gad A., Saleh A., & Khalifa M. (2019). Assessment of Natural Radionuclides and Related Occupational Risk in Agricultural Soil, Southeastern Nile Delta, Egypt. *Arabian Journal of Geosciences*, 12, 188. https://doi.org/10.1007/s12517–019–4356–6.
20. Gaffar S., Ferdous M. J., Begum A., & Ullah S. M. (2014). Transfer of Natural Radionuclides from Soil to Plants in North Western Parts of Dhaka. *J. Soil Sci.*, 18, 61–74.
21. Hamidalddin H. Q. (2014). Determination of agriculture soil primordial radionuclide concentrations in Um Hablayn, north Jeddah west of Saudi Arabia Safia. *Int. J. Curr. Microbiol. App. Sci.*, 3 (6), 623–633.
22. Hudkov I. M., Haichenko V. A., Kashparov V. O., Kutlahmedov Yu. O., Hudkov D. I., & Lazarev M. M. (2010). *Radioecology*. Kyiv, Ukraine.
23. Hudkov I. M., Haichenko V. A., Kashparov V. O. et al. (2013). *Radioecology*. Kherson: OLDI PLUS, Ukraine.
24. Hudkov I. M., Haychenko V. A., & Kashparov V. O. (2017). *Agricultural radioecology* / Ed. Acad. NAAS of Ukraine I. M. Hudkov. Kyiv: Lira-K Publishing House, Ukraine.
25. Hudkov I. M., & Vinnichuk M. M. (2003). *Agricultural radiobiology*. Zhytomyr, Ukraine.
26. Hudkov I. M., & Vinichuk V. V. (2006). *Radiobiology and Radioecology.* Kyiv: NAUU, Ukraine.
27. Hussain R. O., & Hussain H. H. (2011). Investigation the Natural Radioactivity in Local and Imported Chemical Fertilizers. *Braz. Arch. Biol. Technol*., 54 (4), 777–782.
28. IAEA (International Atomic Energy Agency). (1994). *Handbook of parameter values for the prediction of radionuclide transfer in temperate environments* (A Guide Book Technical Report Series No. 364). Vienna, Austria.
29. Irklienko S. P., Buzun V. O., Dmytrenko O. H., & Turchak F. M. (2001). Functioning of Forest Ecosystems and Forestry in Zones of Unconditional Resettlement. *Nuclear Physics and Energy,* 2 (02), 127–132.
30. Kashparov V. O., Lazarev N. M., & Polishchuk S. V. (2005). Problems of agricultural radiology in Ukraine at the present stage. *Agroecological journal*, 3, 31–41.
31. Klymenko O. M. (2006). *Radioecology*. Kherson: OLDI PLUS, Ukraine.
32. Krasnov V. P., Landin V. P. (2013). Methodological Bases of Rehabilitation of Forest Ecosystems Contaminated with Radionuclides. *Balanced nature management,* 2–3/2013, 33–39.

33. Markovic J., & Stevovic S. (2019). Radioactive Isotopes in Soils and Their Impact on Plant Growth. Chapter. *In Metals in Soil. Contamination and Remediation. London: Intech Open Limited.* 1–11. doi: http://dx.doi.org/10.5772/intechopen.81881.
34. Melnyk V. V. (2020). Peculiarities of ^{137}Cs Distribution in Components of Forest Biogeocenosis of Fresh Forests of Ukrainian Polissya. *Bulletin of the Poltava State Agrarian Academy,* 2, 88–98. doi: 10.31210/visnyk2020.02.11.
35. Mostafa A. M.A., Uosif M. A.M., Elsaman R. *et al.* (2020). The Dependence of Natural Radioactivity Levels and Its Radiological Hazards on the Texture of Agricultural Soil in Upper Egypt. *Environ. Earth Sci.,* 79, 228. https://doi.org/10.1007/s12665–020–08946-z.
36. Navas A., Soto, J. and Machin, J. (2002) Edaphic and Physiographic Factors Affecting the Distribution of Natural Gamma-Emitting Radionuclides in the Soils of the Arnas Catchment in the Central Spanish Pyrenees. European Journal of Soil Science, 53, 629–638. http://dx.doi.org/10.1046/j.1365–2389.2002.00488.x
37. Osman R., Dawood Y. H., Melegy A., El-Bady M. S., Saleh A., & Gad A. (2022). Distributions and Risk Assessment of the Natural Radionuclides in the Soil of Shoubra El Kheima, South Nile Delta, Egypt. *Atmosphere*, 13, 98. https:// doi.org/10.3390/atmos13010098.
38. Prister B. R. (2005) Radioecological regularities of the radiation situation dynamics in the Ukrainian agriculture after the Chernobyl accident. *Agroecological journal*, 3, 13–21.
39. *Radiation Safety Standards of Ukraine*. (1997). State Hygienic Standards. Kyiv: Printing Department of the Ukrainian Center for State Sanitary Supervision of the Ministry of Health of Ukraine.
40. *Regional Report on the State of the Environment in the Dnipropetrovsk Region* (2020). Dnipro, Ukraine.
41. Rilwan U., Jafar M., Musa M., Idris M. M., & Waida J. (2022). Transfer of Natural Radionuclides from Soil to Plants in Nasarawa, Nasarawa State, Nigeria. *J. Rad. Nucl. Appl.*, 7 (2), 81–86. http://dx.doi.org/10.18576/jrna/07020.
42. Rozum P. I., Liubezna I. V., & Kalchenko O. M. (2017). Improving Efficiency of Using Agricultural Land. *Polissia Scientific Bulletin,* 3 (11), 193–196.
43. Rudko H. I., & Bondar O. I. (2020). *Macroecology of Ukraine. Ed. by H. I. Rudko.* Kyiv, Chernivtsi: Bukrek, Ukraine.

44. Salih N. F., Hussein Z. A., & Sedeeq S. Z. (2019). Environmental Radioactivity Levels in Agricultural Soil and Wheat Grains Collected from Wheat-Farming Lands of Koya District, Kurdistan Region-Iraq. *Radiat. Prot. Environ.*, 42 (1), 28–37.
45. Shevchenko V. A., Gubin V. K., & Kudryavtseva L. V. (2019). Use of reclamation technologies to reduce the intake of radionuclides into plants on contaminated agricultural lands. *Agroingeneria*, 1 (89), 33–38.
46. Travleev A. P., Belova N. A., & Zverkovsky V. M. (2005). Theoretical Bases of Forest Reclamation of Disturbed Lands in the Western Donbass in Dnipropetrovsk Region. *Pedology,* 16 (1–2), 19–29.
47. Trokhymchuk I. M. (2015). Afforestation in the Radiation-Contaminated Area. *Bulletin of Cherkasy University. Biological Sciences,* 19, 121–126.
48. Tsvetkova N. M., & Yakuba M. S. (2011). The Role of Forest Litter in the Accumulation And Distribution Of Heavy Metals In Ecosystems Of The Middle Part of the Dnipro Samara River. *Biodiversity and the role of animals in ecosystems: Materials of the V International Scientific Conference.* Dnipropetrovsk: DNU Publishing House, Ukraine, 43–45.
49. Tykhonenko D. H., Dehtiarov V. V., & Krokhin S. V. (2008)*. Workshop on Pedology.* Vinnytsia: Nova Knyha, Ukraine.
50. Uchida S., Tagami K., & Hirai I. (2007). Soil-to-Plant Transfer Factors of Stable Elements and Naturally Occurring Radionuclides (1) Upland Field Crops Collected in Japan. *Journal of Nuclear Science and Technology*, 44 (4), 628–640. doi: 10.1080/18811248.2007.9711851.
51. Vukasinovic I., Dordevic A., Rajkovic M. B., Todorovic D., & Pavlovic V. B. (2010). Distribution of natural radionuclides in anthrosol-type soil. *Turk J Agric For*, 34, 539–546. doi:10.3906/tar-0911–59.
52. Yakuba M. S., & Gorban V. A. (2021). Historical creations aspects and functioning features of field protective forest plantationsin the Steppe Zone of Ukraine. *Issues of steppe forestry and forest reclamation of soils,* 50, 35–42. doi: 10.15421/442104.
53. Yamada S., Sakoda A., & Ishimori Y. (2012). Technical Development to Remove Radionuclides from Agricultural Soils by Plants (Joint Research). *JAEA-Research 2012–015*.

Appendix 1

Average long-term values of trancfer factor of ^{137}Cs for different crops depending on the content of labil potassium in the soil, (Bq/kg)/(Ci/km^2)

Cereals and legumes (grain)														
The content of labile K, mg/100g	Corn	Wheat winter	Barley	Triticale	Wheat spring	Millet	Rye	Oat	Beans	Buckwheat	Soy	Pea	Vetch	Lupine yellow
Sod-podzolic soil														
0.5	33	44	41	67	56	70	81	230	330	420	340	370	48	2400
1	17	22	20	34	28	35	40	110	160	210	180	190	24	1200
2	8.3	11	10	17	14	18	20	57	82	100	86	94	12	600
3	4.4	5.8	5.4	8.8	7.4	9.2	11	30	43	55	45	49	63	320
4	4.1	5.5	5.1	8.4	7.0	8.8	10	29	41	52	43	47	60	300
5	3.3	4.4	4.1	6.7	5.6	7.0	8.1	23	33	42	34	37	48	240
7	2.3	3.1	2.9	4.7	3.9	4.9	5.7	16	23	29	24	26	33	170
9	1.8	2.4	2.2	3.7	3.1	3.8	4.4	13	18	23	19	21	26	130
11	1.5	2	1.9	3.1	2.6	3.2	3.7	11	15	19	16	17	22	110
13	1.3	1.7	1.6	2.6	2.2	2.7	3.2	8.9	13	16	13	15	19	95
15	1.1	1.5	1.4	2.3	1.9	2.4	2.8	7.8	11	14	12	13	16	83
20	0.82	1,1	1.0	1.7	1.4	1.8	2.0	5.7	8.2	10	8.6	9.4	12	61

Continuation of appendix 1

Cereals and legumes (grain)														
The content of labile K, mg/100g	Corn	Wheat winter	Barley	Triticale	Wheat spring	Millet	Rye	Oat	Beans	Buckwheat	Soy	Pea	Vetch	Lupine yellow
Black soil														
15	0.46	0.62	0.57	0.94	0.78	0.98	1.1	3.3	4.6	5.9	4.8	5.2	6.7	34
20	0.33	0.44	0.41	0.67	0.56	0.70	0.81	8.8	2.3	3.3	4.2	3.4	4.8	24
25	0.26	0.35	0.33	0.54	0.45	0.56	0.65	1.8	2.7	3.3	2.8	3.0	3.8	19
30	0.23	0.31	0.29	0.40	0.39	0.49	0.57	1.6	2.3	2.9	2.4	2.6	3.3	17
25	0.10	0.13	0.12	0.20	0.17	0.21	0.24	0.69	0.98	1.3	1.0	1.1	1.4	7.3
40	0.10	0.13	0.12	0.20	0.17	0.21	0.24	0.69	0.98	1.3	1.0	1.1	1.4	7.3
45	0.07	0.09	0.08	0.13	0.11	0.14	0.16	0.46	0.65	0.84	0.69	0.75	0.95	4.8
50	0.07	0.09	0.08	0.13	0.11	0.14	0.16	0.46	0.65	0.84	0.69	0.75	0.95	4.8
60	0.07	0.075	0.07	0.11	0.10	0.12	0.14	0.31	0.55	0.10	0.58	0.64	0.81	4.1
70	0.05	0.06	0.06	0.09	0.08	0.10	0.11	0.32	0.46	0.59	0.48	0.52	0.67	3.4
80	0.04	0.06	0.05	0.09	0.07	0.09	0.11	0.30	0.42	0.54	0.44	0.49	0.62	3.2
90	0.04	0.05	0.05	0.07	0.06	0.08	0.09	0.25	0.36	0.46	0.38	0.41	0.52	2.7
100	0.03	0.04	0.04	0.07	0.06	0.07	0.08	0.23	0.33	0.42	0.34	0.37	0.48	2.4

Continuation of appendix 1

Vegetables												
The content of labile K, mg/100g	Eggplants	Onion green	Onion batun, shoot	Chop the onion, shoot	Onion bulbous	Sweet pepper Ratunda	Sweet pepper California	Zucchini	Zucchini Odessa 52	Кабачки Грибовські 37	Гарбуз Мускатний	Гарбуз Стофунтовий
Sod-podzolic soil												
0.5	4.8	12	15	11	15	19	26	22	19	22	22	33
1	2.4	6.1	7.4	5.6	7.4	9.3	13	11.1	9.25	11.1	11.1	16.7
2	1.20	3.1	3.7	2.8	3.7	4.6	6.5	5.6	4.6	5.6	5.6	8.3
3	0.63	1.6	2.0	1.5	2.0	2.4	3.4	2.9	2.4	2.9	2.9	4.4
4	0.60	1.5	1.9	1.4	1.9	2.3	3.2	2.8	2.3	2.8	2.8	4.2
5	0.48	1.2	1.5	1.1	1.5	1.9	2.6	2.2	1.9	2.2	2.2	3.3
7	0.34	0.85	1.0	0.78	1.0	1.3	4.8	1.6	1.3	1.6	1.6	2.3
9	0.26	0.67	0.81	0.61	0.81	1.0	1.4	1.2	1.0	1.2	1.2	1.8
11	0.23	0.56	0.69	0.52	0.69	0.85	1.2	1.8	0.85	1.8	1.8	1.5
13	0.19	0.48	0.58	0.43	0.58	0.72	1.0	0.87	0.72	0.87	0.87	1.3
15	0.16	0.41	0.50	0.38	0.50	0.63	0.89	0.75	0.63	0.75	0.75	1.1
20	0.12	0.39	0.37	0.28	0.37	0.46	0.65	0.56	0.46	0.56	0.56	0.83

Continuation of appendix 1

Vegetables												
The content of labile K, mg/100g	Eggplants	Onion green	Onion batun, shoot	Chop the onion, shoot	Onion bulbous	Sweet pepper Ratunda	Sweet pepper California	Zucchini	Zucchini Odessa 52	Кабачки Грибовські 37	Гарбуз Мускат-ний	Гарбуз Стофунто-вий
Black soil												
15	0.07	0.18	0.21	0.16	0.21	0.26	0.36	0.31	0.26	0.31	0.31	0.047
20	0.05	0.12	0.15	0.11	0.15	0.19	0.26	0.22	0.19	0.22	0.22	0.33
25	0.04	0.10	0.12	0.09	0.12	0.15	0.21	0.18	0.15	0.18	0.18	0.27
30	0.03	0.09	0.10	0.08	0.10	0.13	0.18	0.16	0.13	0.16	0.16	0.23
25	0.014	0.037	0.044	0.033	0.044	0.056	0.078	0.067	0.066	0.067	0.067	0.10
40	0.014	0.037	0.044	0.033	0.044	0.056	0.078	0.067	0.066	0.067	0.067	0.10
45	0.0096	0.024	0.03	0.022	0.03	0.037	0.052	0.044	0.037	0.044	0.044	0.067
50	0.0096	0.024	0.03	0.022	0.03	0.037	0.052	0.044	0.037	0.044	0.044	0.067
60	0.0082	0.021	0.025	0.019	0.025	0.031	0.045	0.038	0.031	0.038	0.038	0.057
70	0.067	0.017	0.21	0.016	0.021	0.026	0.036	0.031	0.026	0.031	0.031	0.047
80	0.062	0.016	0.019	0.014	0.019	0.025	0.034	0.029	0.025	0.029	0.029	0.043
90	0.053	0.013	0.016	0.012	0.016	0.020	0.028	0.024	0.020	0.024	0.024	0.037
100	0.0050	0.012	0.015	0.011	0.015	0.019	0.026	0.022	0.019	0.022	0.022	0.033

Continuation of appendix 1

	Vegetables										
The content of labile K, mg/100g	Squashes	Garlic	Tomatoes					Cucumbers Competitor	Cucumbers Far-Eastern	Physalis strawberry	Physalis Mexican
			Ukrainian greenhouse	Dawn	Sparkle	Ordered 280	Leader				
Sod-podzolic soil											
0.5	33	33	15	30	37	37	44	41	67	33	41
1	17	17	734	15	19	19	22	20	33	17	20
2	8.3	8.3	3.7	7.4	9.3	9.3	11	10	17	8.3	10
3	4.4	4.4	2.0	3.9	4.9	4.9	5.9	5.4	8.8	4.4	5.4
4	4.2	4.2	1.9	3.7	4.6	4.6	5.6	5.1	8.3	4.2	5.1
5	3.3	3.3	1.5	3.0	3.7	3.7	4.4	4.1	6.7	3.3	4.1
7	2.3	2.3	1.0	2.1	2.6	2.6	3.1	2.9	4.7	2.3	2.9
9	1.8	1.8	0.81	1.6	2.0	2.0	2.4	2.2	3.7	1.8	2.2
11	1.5	1.5	0.68	1.4	1.7	1.7	2.0	1.9	3.1	1.5	1.9
13	1.3	1.3	0.58	1.2	1.4	1.4	1.7	1.6	2.6	1.3	1.6
15	1.1	1.1	0.50	1.0	1.3	1.3	1.5	1.4	2.3	1.1	1.4
20	0.83	0.83	0.37	0.74	0.93	0.93	1.8	1.0	1.7	0.83	1.0

Continuation of appendix 1

Vegetables											
The content of labile K, mg/100g	Squashes	Garlic	Tomatoes					Cucumbers Competitor	Cucumbers Far-Eastern	Physalis strawberry	Physalis Mexican
			Ukrainian greenhouse	Dawn	Sparkle	Ordered 280	Leader				
Black soil											
15	0.47	0.47	0.21	0.41	0.52	0.52	0.62	0.57	0.93	0.47	0.57
20	0.33	0.33	0.15	0.30	0.37	0.37	0.44	0.41	0.67	0.33	0.41
25	0.27	0.27	0.12	0.24	0.30	0.30	0.36	0.33	0.53	0.27	0.33
30	0.23	0.23	0.10	0.21	0.26	0.26	0.31	0.28	0.47	0.23	0.28
25	0.10	0.10	0.04	0.09	0.11	0.11	0.13	0.12	0.20	0.10	0.12
40	0.10	0.10	0.04	0.09	0.11	0.11	0.13	0.12	0.20	0.10	0.12
45	0.07	0.07	0.03	0.06	0.07	0.07	0.09	0.08	0.13	0.07	0.08
50	0.07	0.07	0.03	0.06	0.07	0.07	0.09	0.08	0.13	0.07	0.08
60	0.057	0.057	0.025	0.05	0.063	0.063	0.075	0.069	0.11	0.057	0.069
70	0.047	0.047	0.021	0.041	0.052	0.052	0.062	0.057	0.093	0.047	0.057
80	0.043	0.043	0.019	0.038	0.048	0.048	0.058	0.053	0.087	0.043	0.053
90	0.037	0.037	0.016	0.033	0.041	0.041	0.049	0.045	0.073	0.037	0.045
100	0.033	0.033	0.015	0.030	0.037	0.037	0.044	0.041	0.067	0.033	0.041

Continuation of appendix 1

The content of labile K, mg/100g	Spinach	Carrots Nanska	Carrots Artek	Radish			Parsley	Coriander	Calendula	Cabbage		
				Zarya	The red giant	Red with a white tip				Amager 611	Braunschweig	Savoy
Sod-podzolic soil												
0.5	41	48	56	56	67	110	37	63	63	63	59	67
1	20	24	28	28	33	54	19	32	32	32	30	33
2	10	12	14	14	17	27	9	16	16	16	15	17
3	5.4	6.3	7.3	7.3	8.8	14	4.9	8.4	8.4	8.4	7.8	8.8
4	5.1	6.0	6.9	6.9	8.3	13	4.6	7.9	7.9	7.9	7.4	8.3
5	4.1	4.8	5.6	5.6	6.7	11	3.7	6.3	6.3	6.3	5.9	6.7
7	2.9	3.4	3.9	3.9	4.7	7.5	2.6	4.4	4.4	4.4	4.1	4.7
9	2.2	2.7	3.1	3.1	3.7	5.9	2.0	3.5	3.5	3.5	3.3	3.7
11	1.9	2.2	2.6	2.6	3.1	4.9	1.7	2.9	2.9	2.9	2.7	3.1
13	1.6	1.9	2.2	2.2	2.6	4.2	1.4	2.5	2.5	2.5	2.4	2.6
15	1.4	1.6	1.9	1.9	2.3	3.7	1.3	2.1	2.1	2.1	2.0	2.3
20	1.0	1.2	1.4	1.4	1.7	2.7	0.3	1.6	1.6	1.6	1.5	1.7

Continuation of appendix 1

The content of labile K, mg/100g	Spinach	Carrots Nanska	Carrots Artek	Radish			Parsley	Coriander	Calendula	Cabbage		
				Zarya	The red giant	Red with a white tip				Amager 611	Braunschweig	Savoy
Black soil												
15	0.57	0.67	0.78	0.78	0.93	1.5	0.52	0.88	0.88	0.88	0.83	0.93
20	0.41	0.48	0.56	0.56	0.67	1.07	0.37	0.63	0.63	0.63	0.59	0.67
25	0.33	0.38	0.44	0.44	0.53	0.86	0.30	0.50	0.50	0.50	0.47	0.53
30	0.28	0.34	0.39	0.39	0.47	0.75	0.26	0.44	0.44	0.44	0.41	0.47
25	0.12	0.14	0.17	0.17	0.20	0.32	0.11	0.19	0.19	0.19	0.18	0.20
40	0.12	0.14	0.17	0.17	0.20	0.32	0.11	0.19	0.19	0.19	0.18	0.20
45	0.08	0.10	0.11	0.11	0.13	0.21	0.07	0.13	0.13	0.13	0.12	0.13
50	0.08	0.10	0.11	0.11	0.13	0.21	0.07	0.13	0.13	0.13	0.12	0.13
60	0.069	0.082	0.094	0.094	0.11	0.18	0.063	0.11	0.11	0.11	0.10	0.13
70	0.057	0.067	0.078	0.078	0.093	0.15	0.052	0.088	0.088	0.088	0.083	0.093
80	0.053	0.063	0.072	0.072	0.087	0.14	0.048	0.082	0.082	0.082	0.077	0.087
90	0.045	0.053	0.061	0.061	0.073	0.12	0.041	0.070	0.070	0.070	0.065	0.073
100	0.041	0.048	0.056	0.056	0.067	0.11	0.037	0.063	0.063	0.063	0.059	0.067

Continuation of appendix 1

Vegetables (continuation)												
The content of labile K, mg/100g	Cabbage							Pepper bitter	Parsnip	Fennel	Hrybovsky dill	Dukhmyan Onion
	Red-cocky	Snow White	Brussels	Cauliflower	Early cabbage	Kohlrabi	Branchy					
Sod-podzolic soil												
0.5	70	81	130	63	110	120	120	74	78	89	89	100
1	35	41	65	32	54	59	59	37	39	44	44	50
2	18	20	32	16	27	30	30	19	19	22	22	25
3	9.3	11	17	8.3	14	16	16	9.8	10	12	12	13
4	8.8	10	16	7.9	13	15	15	9.3	9.7	11	11	13
5	7.0	8.1	13	6.3	11	12	12	7.4	7.8	8.9	8.9	10
7	4.9	5.7	9.1	4.4	7.5	8.3	8.3	5.2	5.4	6.2	6.2	7.0
9	3.9	4.5	7.1	3.5	5.9	6.5	6.5	4.1	4.3	4.9	4.9	5.5
11	3.2	3.7	6.0	2.9	4.9	5.5	5.5	3.5	3.6	4.1	4.1	4.6
13	2.7	3.2	5.1	2.5	4.2	4.6	4.6	2.9	3.0	3.5	3.5	3.9
15	2.4	2.8	4.4	2.1	3.7	4.0	4.0	2.5	2.6	3.0	3.0	3.4
20	1.8	2.0	3.2	1.6	2.7	3.0	3.0	1.9	1.9	2.2	2.2	2.5

Continuation of appendix 1

Black soil												
15	0.98	1.1	1.8	0.89	1.5	1.7	1.7	1.0	1.1	1.2	1.2	1.4
20	0.70	0.81	1.3	0.69	1.1	1.2	1.2	0.74	0.78	0.89	0.89	1.0
25	0.56	0.65	1.0	0.50	0.86	0.95	0.95	0.59	0.62	0.71	0.71	0.8
30	0.49	0.57	0.99	0.44	0.75	0.83	0.83	0.52	0.54	0.62	0.62	0.7
25	0.21	0.24	0.39	0.19	0.32	0.36	0.36	0.22	0.23	0.27	0.27	0.3
40	0.21	0.24	0.39	0.19	0.32	0.36	0.36	0.22	0.23	0.27	0.27	0.3
45	0.14	0.16	0.26	0.13	0.21	0.24	0.24	0.15	0.16	0.18	0.18	0.2
50	0.14	0.16	0.26	0.13	0.21	0.24	0.24	0.15	0.16	0.18	0.18	0.2
60	0.12	0.14	0.22	0.11	0.18	0.20	0.20	0.13	0.13	0.15	0.15	0.17
70	0.10	0.11	0.18	0.089	0.15	0.16	0.16	0.10	0.10	0.12	0.12	0.14
80	0.09	0.11	0.168	0.082	0.14	0.15	0.15	0.096	0.10	0.12	0.12	0..13
90	0.08	0.09	0.14	0.069	0.12	0.13	0.13	0.081	0.0850	0.098	0.098	0.11
100	0.07	0.081	0.13	0.063	0.11	0.12	0.12	0.074	0.078	0.089	0.089	0.10

Continuation of appendix 1

Vegetables (continuation)												
The content of labile K, mg/100g	Salad	Table beet				Black radish	Hysop	Sorrel	Savory	Snakehead vegetable	Watercress salad	Salad mustard
		Claret 237	Nosivsky	Red ball	Early miracle							
Sod-podzolic soil												
0.5	100	110	100	130	140	120	140	140	85	230	240	320
1	52	54	50	63	69	61	72	72	93	110	120	59
2	26	27	25	32	34	31	36	36	46	57	59	80
3	14	14	13	17	18	16	19	19	24	30	31	42
4	13	13	13	16	17	15	18	18	23	29	30	40
5	10	11	10	13	14	12	14	14	19	23	24	32
7	7.3	7.5	7.0	8.8	9.6	8.6	10	10	13	16	17	22
9	5.7	5.9	5.5	6.9	7.5	6.7	739	739	10	13	13	18
11	4.8	4.9	4.6	5.8	6.3	5.6	6.6	6.6	8.5	11	11	15
13	4.0	4.2	3.9	4.9	5.3	4.8	5.6	5.6	7.2	9.0	9.2	12
15	3.5	3.7	3.4	4.3	4.7	4.2	4.9	4.9	6.3	7.8	8.1	11
20	2.6	2.7	2.5	3.2	3.4	3.1	3.6	3.6	4.6	5.7	5.9	8
1	2	3	4	5	6	7	8	9	10	11	12	13

Vegetables (continuation)												
The content of labile K, mg/100g	Salad	Table beet				Black radish	Hysop	Sorrel	Savory	Snakehead vegetable	Watercress salad	Salad mustard
		Claret 237	Nosivsky	Red ball	Early miracle							
Black soil												
15	1.5	1.5	1.4	1.8	1.9	1.7	2.0	2.0	2.6	3.2	3.3	4.5
20	1.0	1.1	1.0	1.3	1.4	1.2	1.4	1.4	1.9	2.3	2.4	3.2
25	0.83	0.86	0.8	1.0	1.1	0.98	1.2	1.2	1.5	1.8	1.9	2.6
30	0.73	0.75	0.7	0.88	0.96	0.85	1.0	1.0	1.3	1.6	1.7	2.2
25	0.31	0.32	0.3	0.38	0.41	0.37	0.43	0.43	0.56	0.69	0.71	0.95
40	0.31	0.32	0.3	0.38	0.41	0.37	0.43	0.43	0.56	0.69	0.71	0.95
45	0.21	0.21	0.2	0.25	0.27	0.24	0.29	0.29	0.37	0.46	0.47	0.64
50	0.21	0.21	0.2	0.25	0.27	0.24	0.29	0.29	0.37	0.46	0.47	0.64
60	0.18	0.18	0.17	0.21	0.23	0.21	0.25	0.25	0.32	0.39	0.40	0.54
70	0.15	0.15	0.14	0.18	0.19	0.17	0.20	0.20	0.26	0.32	0.33	0.45
80	0.14	0.14	0.13	0.16	0.18	0.16	0.19	0.19	0.24	0.30	0.31	0.41
90	0.11	0.12	0.11	0.14	0.15	0.13	0.16	0.16	0.20	0.25	0.26	0.35
100	0.10	0.11	0.10	0.13	0.14	0.12	0.14	0.14	0.19	0.23	0.24	0.32

Continuation of appendix 1

Vegetables (continuation)						
The content of labile K, mg/100g	Potato					Artichoke
	Nevsky	“Nezabudka”	Lugovsky	Dawn	Cascade	
Sod-podzolic soil						
0.5	63	63	63	89	44	63
1	32	32	32	44	22	32
2	16	16	16	22	11	16
3	8.3	8.3	8.3	12	5.9	8.3
4	7.9	7.9	7.9	11	5.6	7.9
5	6.3	6.3	6.3	8.9	4.4	6.3
7	4.4	4.4	4.4	6.2	3.1	4.4
9	3.5	3.5	3.5	4.9	2.4	3.5
11	2.9	2.9	2.9	4.1	2.0	2.9
13	2.5	2.5	2.5	3.5	1.7	2.5
15	2.1	2.1	2.1	3.0	1.5	2.1
20	1.6	1.6	1.6	2.2	1.8	1.6

Continuation of appendix 1

Vegetables (continuation)						
The content of labile K, mg/100g	Potato					Artichoke
	Nevsky	“Nezabudka”	Lugovsky	Dawn	Cascade	
Black soil						
15	0.89	0.89	0.89	1.2	0.62	0.89
20	0.69	0.69	0.69	0.89	0.44	0.69
25	0.50	0.50	0.50	0.71	0.36	0.50
30	0.44	0.44	0.44	0.62	0.31	0.44
25	0.19	0.19	0.19	0.27	0.13	0.19
40	0.19	0.19	0.19	0.27	0.13	0.19
45	0.13	0.13	0.13	0.18	0.09	0.13
50	0.13	0.13	0.13	0.18	0.09	0.13
60	0.11	0.11	0.11	0.15	0.075	0.11
70	0.089	0.089	0.089	0.12	0.062	0.089
80	0.082	0.082	0.082	0.12	0.058	0.082
90	0.069	0.069	0.069	0.098	0.049	0.069
100	0.063	0.063	0.063	0.089	0.044	0.063

Appendix 2

Values of permissible levels of specific activities of radionuclides ^{137}Cs and ^{90}Sr in food and drinking water

№	Name	Acceptable level, Bq/kg	
		^{137}Cs	^{90}Sr
1	***Grain, flour, cereals, and bakery products***		
	1.1. Food grains, including wheat, rye, oat, barley, millet, buckwheat, rice, corn, sorghum, and other grain crops.	50	20
	1.2. Flour, flour baking mixes, groats, starch; pasta, cereal products; semi-finished grain products, finished products, including fast breakfast, cereals muesli, etc.	30	10
	1.3. Bread and bakery products, including ones with additives; flour products, confectionery, semi-finished dough products.	20	5
2	***Milk and dairy products***		
	2.1. Raw commercial milk for industrial processing (except baby food products), liquid milk and cream, whey; fermented milk products, fermented milk desserts, etc.; products made on the basis of milk and cream (ice cream, cakes, drinks, desserts, etc.).	100	20
	2.2. Butter (including cow butter, spreads, milk fat, etc.).	200	40
	2.3. Rennet hard cheeses, processed cheeses.	200	100
	2.4. Concentrated or condensed milk and cream.	300	60
	2.5. Dry dairy products, including milk, cream, etc.; food concentrates based on milk.	500	100
3	***Meat and meat products***		
	3.1. Meat of slaughtered animals, poultry (fresh, chilled, frozen) without bones for industrial processing, meat, food offal (including raw intestines, food blood) of slaughtered animals and poultry fresh, frozen, processed with various methods; products of their processing, including semi-finished products, sausages, canned meat and meat and vegetables.	200	20
	3.2. Meat of wild animals and poultry.	400	40
4	***Fish, non-fish fishery objects and their processing products***		
	4.1. Fresh and frozen fish, processed with various methods; fish oil, caviar (including artificial), fish semi-finished products, ready-made fish products (butter, pastes, etc.), fish preserves.	150	35

Continuation of appendix 2

№	Name	Acceptable level, Bq/kg	
		^{137}Cs	^{90}Sr
	4.2. Non-fish fishery objects (crustaceans, molluscs, etc.), fresh and frozen, processed with various methods; products of their processing, including semi-finished products, canned goods.	150	35
	4.3. Dried fish and non-fish fishing objects (crustaceans, mollusks, etc.).	300	70
	4.4. Sea grasses and their processing products.	200	70
	4.5. Algae and sea grass dried.	600	200
5	***Poultry eggs and their processing products***		
	5.1. Poultry eggs and liquid egg products; semi-finished products and finished products from poultry eggs.	100	30
	5.2. Dried products of poultry egg processing (egg powder, dry mixtures).	400	100
6	Vegetables and their processing products		
	6.1. Fresh potatoes and processed products, including culinary products, semi-finished products.	60	20
	6.2. Fresh vegetables (leafy, melon, root crops), legumes, sweet corn; processed products, juices, canned goods, etc.	40	20
	6.3. Vegetable concentrates (including tomato paste, tomato sauces, ketchups, etc.).	120	50
	6.4. Dried vegetables, their processing products.	240	80
7	***Fruits and berries***		
	7.1. Fresh, frozen, canned fruits and berries; fruit and berry juices.	70	10
	7.2. Fruit and berry processing products (jams, pastes, jams, marmalades, jellies, etc.).	140	20
	7.3. Dry fruits and berries.	280	40
	7.4. Nuts and their processing products.	70	10
8	Sugar, confectionery, chocolate and products thereof; chewing gum.	50	30
9	Wild mushrooms and berries fresh, frozen, canned.	500	50
10	Dried wild mushrooms and berries.	2500	250
11	Seeds of oil crops (sunflower, sesame, poppy, etc.); products of their processing, with the exception of vegetable fats and oils.	70	10

Continuation of appendix 2

№	Name	Acceptable level, Bq/kg	
		^{137}Cs	^{90}Sr
12	Vegetable fats and oils, products made on their basis (margarines, creams, etc.).	100	30
13	Baich tea, flavored, with herbal additives, green coffee, roasted; cocoa beans, cocoa powder; dry soluble drinks based on tea, cocoa, coffee and substitutes.	200	50
	Drinks		
14	The water drinkable.	2	2
15	15.1. Mineral Water.	10	5
	15.2. Non-alcoholic and low-alcohol drinks, including based on vegetable raw materials; beer, kvass.	20	20
	15.3. Alcoholic beverages (except beer).	50	30
16	Dried medicinal plants; phyto teas, mate (Paraguayan tea), karkade, etc.	200	100
17	Tobacco and tobacco products.	120	50
18	Spices and their mixtures; seasonings, including sauces, salad dressings, mayonnaise.	120	50
19	Food additives (dyes, stabilizers, flavorings, fillers, etc.); vinegar, baking soda; yeast; food concentrates; instant soups.	150	50
20	Food salt and salt mixtures.	120	30
21	Honey and beekeeping products.	200	50

Appendix 3

Table 1

Average values of transfer coefficients (Kt) of radionuclides from the daily ration to livestock products (% of the content in the ration per 1 kg of product)

Product type	Radionuclides	
	^{137}Cs	^{90}Sr
Milk of cows	1.0	0.13
Goat's milk	6.0	0.6
Beef*	4.0	0.04
Horsemeat	8.0	0.08
Pork	15	0.10
Mutton	15	0.10
Chicken meat	45	0.20
Eggs	3.5	3.2

Note: *The transfer coefficient to meat of calves under 6 months of age is equal of 17%

Continuation of appendix 3

Table 2

Coefficients of the transition of ^{137}Cs to fodder crops (Bq/kg) at a density of the territory contamination of 1 kBq/m^2

Agricultural crops	Soil type, pH of salt extract			
	Peat bogs soil PH=4.0–5.0	Sod-podzolic soil PH=4.5–5.5	Gray forest soil PH=5.6–6.5	Black soil PH=6.6–7.5
Hay of natural herbs	15.0	4.1	1.8	0.15
Hay of sown herbs	4.5	2.9	1.4	0.10
Herbs from natural pastures	4.9	1.0	1.5	0.05
Herbs from cultivated pastures	1.6	0.7	0.4	0.03
Alfalfa	–	0.8	0.2	0.06
Clover	1.9	1.6	0.3	0.1
Vico-oat mixture	–	0.7	0.3	0.11
Lupine	–	12.9	6.4	1.1
Winter rapeseed	–	0.46	0.08	0.01
Winter barley	0.28	0.12	0.04	0.01
Fodder beetroot	0.90	0.40	0.18	0.07
Corn for silage	0.35	0.15	0.09	0.01
Potato	0.35	0.14	0.08	0.02

Continuation of appendix 3

Table 3

Coefficients of the transition of ^{137}Cs into grain and straw (Bq/kg) at a density of the territory contamination of 1 Ci/km^2

Agricultural crops	Soil type					
	Sod-podzolic soil		Gray forest soil		Black soil	
	grain	straw	grain	straw	grain	straw
Corn	3.3	2.0	0.56	3.4	0.1	0.6
Winter wheat	4.4	14.4	0.75	2.3	0.13	1.4
Barley	4.1	9.0	0.7	1.5	0.12	0.3
Spring wheat	5.6	11.0	0.9	2.0	0.2	0.75
Oat	23.0	36.0	3.9	7.1	0.69	1.1
Soy	34.0	34.0	5.8	5.7	1.0	1.0
Pea	37.0	51.0	6.4	8.7	1.1	1.5
Lupine	240.0	129.0	41.0	22.0	7.3	3.9

Continuation of appendix 3

Table 4

Coefficients of the transition of ^{90}Sr to fodder crops (Bq/kg) at a density of the territory contamination of 1 Ci/km^2

Agricultural crops	Soil type, pH of salt extract			
	Peat bogs soil PH=4.0–5.0	Sod-podzolic soil PH=4.5–5.5	Gray forest soil PH=5.6–6.5	Black soil PH=6.6–7.5
Hay of natural herbs	28.0	30.0	7.0	3.8
Hay of sown herbs	15.0	14.0	4.0	2.0
Herbs from natural pastures	7.2	7.5	1.8	0.9
Herbs from cultivated pastures	4.2	3.8	1.0	0.5
Alfalfa	–	24.0	12.0	4.5
Clover	32.0	38.0	7.0	2.7
Lupine	–	124.0	55.0	24.0
Fodder beetroot	0.78	0.32	0.12	0.05
Potato	0.60	0.5	0.35	0.07
Corn for silage	4.4	6.2	0.90	0.60

Continuation of appendix 3

Table 5

Coefficients of the transition of ^{90}Sr into grain and straw (Bq/kg) at a density of the territory contamination of 1Ci/km^2

Agricultural crops	Soil type					
	Sod-podzolic soil		Gray forest soil		Black soil	
	grain	straw	grain	straw	grain	straw
Corn	0.2	3.0	0.05	0.75	0.1	1.5
Winter wheat	2.4	50.4	0.3	0.96	0.15	2.9
Barley	3.8	36.0	0.5	11.0	0.2	4.0
Spring wheat	4.0	84.0	0.5	10.0	0.3	6.0
Oat	3.8	76.0	0.5	11.0	0.2	4.0
Pea	7.2	281.0	0.9	32.4	0.4	14.5

Continuation of appendix 3

Table 6

Daily consumption of dry fodder and water by farm animals

Type of animal	Dry feed consumption (kg/day)		Water consumption (l/day)
	average	range	
Dairy cows	16.1	10–25	50–100
Beef cattle (500 kg)	7.2	5–10	20–60
Calves (160 kg)	1.9	1.5–3.5	5–15
Dairy goats	1.3	1.0–3.5	5–10
Dairy sheep	1.3	1.0–2.5	5–8
Meat sheep (50 kg)	1.1	0.5–3.0	6–10
Pigs (110 kg)	2.4	2.0–3.0	6–10
Laying hens	0.1	0.07–0.15	0.1–0.3
Broilers	0.07	0.05–0.15	0.1–0.3

Continuation of appendix 3

Table 7

Forecast of the ^{137}Cs content in diets, milk and meat of cattle (public sector, grazing) with a soil pollution density of 162 kBq/m^2

Feed	Weight, kg	Concentration of ^{137}Cs in 1 kg of feed, Bq/kg	Content of ^{137}Cs in the diet, Bq/ration	Expected concentrations of ^{137}Cs	
Herbs from domesticated pasture	50	0.7 × 162 = 113	113 ×50 = 5650	56.5	226
Concentrates (barley groats)	5	4.1 ×4.4 = 18	18 × 5 = 90	0.9	3.6
Total:			5740	57.4	229.6

Appendix 4

Statistical error (correction) coefficients (K) for describing the radioactive decay of elements

t/T	K	$e^{-\lambda t}$	t/T	K	$e^{-\lambda t}$	t/T	K	$e^{-\lambda t}$
0.02	1.01	0.985	0.48	1.39	0.717	1.70	3.25	0.308
0.04	1.03	0.972	0.50	1.41	0.707	1.80	3.47	0.288
0.06	1.05	0.959	0.55	1.46	0.683	1.90	3.72	0.268
0.08	1.06	0.946	0.60	1.52	0.659	2.00	4.00	0.250
0.10	1.07	0.933	0.65	1.57	0.637	2.10	4.31	0.233
0.12	1.09	0.920	0.70	1.62	0.615	2.20	4.57	0.218
0.14	1.11	0.907	0.75	1.68	0.594	2.30	4.90	0.203
0.16	1.12	0.894	0.80	1.73	0.574	2.40	5.26	0.190
0.18	1.14	0.882	0.85	1.80	0.555	2.50	5.64	0.177
0.20	1.15	0.870	0.90	1.86	0.536	2.60	6.05	0.165
0.22	1.16	0.858	0.95	1.93	0.518	2.70	6.49	0.154
0.24	1.18	0.846	1.00	2.00	0.500	2.80	6.96	0.144
0.26	1.19	0.835	1.05	1.05	0.483	2.90	7.46	0.134
0.28	1.21	0.823	1.10	1.13	0.467	3.00	8.00	0.125
0.30	1.23	0.712	1.15	2.20	0.451	3.20	9.12	0.109
0.32	1.25	0.801	1.20	2.29	0.435	3.40	10.54	0.095
0.34	1.26	0.790	1.25	2.36	0.420	3.60	12.01	0.083
0.36	1.28	0.779	1.30	2.46	0.406	3.80	13.87	0.072
0.38	1.30	0.769	1.35	2.54	0.392	4.00	16.00	0.062
0.40	1.32	0.758	1.40	2.63	0.379	4.20	18.17	0.054
0.42	1.34	0.748	1.45	2.72	0.366	4.40	21.12	0.047
0.44	1.35	0.737	1.50	2.82	0.354	4.60	24.29	0.041
0.46	1.37	0.727	1.55	3.02	0.330	5.00	32.00	0.031

Наукове видання

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