Ecological Questions 32(2021)4 http://dx.doi.org/10.12775/EQ.2021.032

Prediction (on the content of radionuclides and heavy metals) of the *Solidago canadensis* L. use as a honey resource in Polesie

Oleksandr Lukash[1,*], Svitlana Strilets[1], Oleksandr Yakovenko[1], Iryna Miroshnyk[1], Nikolai Dayneko[2], Alina Sliuta[1] , Olena Kupchyk[1], Iryna Morozova[1], Olena Sazonova[1]

[1]T. Shevchenko National University "Chernihiv Collegium",
53, Hetman Polubotko Str., Chernihiv, 14013, Ukraine,
[2]F. Scoryna Gomel State University,
104, Sovetskaya Str., Gomel, 246003, Belarus
* corresponding author e-mail: lukash2011@ukr.net

Received: 29 July 2021 / Accepted: 8 September 2021

Abstract. In the context of the problem of the rational use of the meadow ecosystems of Polesie, which have been exposed to radioactive effect and have not been used economically for a long time, the indicators of radionuclides and heavy metals in soil and plants predict the possibility of using *Solidago canadensis* L. as a honey resource in summer and autumn periods. The article presents new research results in the direction of studying the species specificity of plants for the accumulation of radionuclides and heavy metals, which are aimed at solving the problem of obtaining the environmentally friendly bee-keeping products from non-traditional honey resources. The habitats of *Solidago canadensis* were studied in the floodplain of the Dnieper river, its tributaries of various orders and loess "islands" in Polesie – the transformed meadow ecosystems, phytocenoses of which belong to the *Molinio-Arrhenatheretea* R.Tx. 1937 class, and the ruderal *Artemisietea* vulgaris Lohmeyer et al. in Tx. ex von Rochow 1951 communities. The content of the radionuclides (^{137}Cs та ^{90}Sr) and heavy metals (Zn, Cd, Pb, Cu) in the soil and inflorescences of *Solidago canadensis* of 18 sites were analyzed. 11 sites of them, that were not contaminated by the Chernobyl disaster, were analyzed for honey samples. The linear regression equations for honey-plant and honey-soil systems, Pearson's correlation coefficient (r), significance level (p) and the determination coefficient (r^2) for predicting (by indicators of radionuclides and heavy metals in soil and plant) the possibility of honey gathering have been determined. According to the predicted indicators of the heavy metal content and specific activity of radionuclides, it was found that only the meadow ecosystems in the floodplain of the Iput river (the Zalissia village, Dobruskyi district, Gomel region, Belarus) out of 7 studied sites, which were exposed to radioactive contamination in 1986, are suitable for gathering goldenrod honey. In the case of honey gathering on the infested with the Canadian goldenrod meadows in the floodplains of the Dnieper, Sozh and Pakulka rivers, the maximum permissible concentration of cadmium or radionuclides in the products may exceed. It is emphasized that to assess the possibility of obtaining the environmentally friendly goldenrod honey, it is advisable to predict the content of radionuclides and heavy metals in both plants and soil. To do this, it is also necessary to take into account the calculated values of the highest content of heavy metals and the specific activity of radionuclides in soil and plants, at which the metal content in honey will be at the level of the maximum permissible concentration (MPC).

Keywords: heavy metals, honey, meadow ecosystems, Polesie, prediction, radionuclides, soil.

1. Introduction

Despite the significant amount of the researches conducted in the post-Chornobyl period on the ecological state of the natural and man-made ecosystems that were exposed to radioactive contamination, a number of problems related not only to obtaining normatively clean products

(Melnychuk, 2015), but also the rational use of the resources of these ecosystems needs to be solved.

One such problem is the use of melliferous recourses of the ecosystems that have been radioactively contaminated. With the general tendency of decreasing the content of some harmful substances in the environment, the ecological situation in certain regions has recently remained unfavorable for producing safe bee-keeping products (Razanov, 2009): there is a real threat of obtaining honey and pollen unfit for consumption.

According to the research conducted in the Belarusian Polesie, it is established that the levels of the radioactive contamination of the aboveground parts of the plants depend not only on the density of radioactive contamination of the soil, but also on the type of soil, its agrochemical and granulometric compositions, as well as vegetation and species and biomorphological composition (Dayneko & Timofeev, 2015).

For radioecological substantiation of the permissible levels of soil contamination of the Ukrainian Polesie meadow lands in the remote period after the Chornobyl disaster, it is proposed to use the ^{137}Cs absorption coefficients obtained during this period (Kymakovska, 2015). Belarusian scientists proved the species specificity of plants for the accumulation of radionuclides and heavy metals at different densities of soil contamination of meadow ecosystems (Dayneko & Timofeev, 2018, 2020).

Currently, a lot of information has been accumulated about the state of radionuclide contamination of bee-keeping products in Polesie. The comparison of the level of contamination of honey samples in different periods after the Chornobyl disaster shows a significant decrease in the time of their specific activity by radiocaesium (Slavov & Furman, 1999). However, the level of the content not only of cesium-137 and strontium-90, but also of lead and cadmium in the bee-keeping products gathered in the contaminated areas of the northern Polesie of Ukraine exceeds (Razanov, 2009). For this area, there are high coefficients of the ^{137}Cs transition from soil to melliferous plants (Vasenkov et al., 2016).

D.V. Lisohurska (2017) proves that in order to predict the radioactive contamination of bee honey and pollen, it is advisable to use the coefficients of accumulation and transition of ^{137}Cs in flowers, because these indicators are characterized by the least variability. Note that the previous research was aimed at solving the problem of obtaining the environmentally friendly bee-keeping products in the areas exposed to radioactive contamination, from traditional melliferous resources.

The urgency of the problem of obtaining environmentally friendly honey is also evidenced by the recent years foreign publications on the analysis of heavy metals in honey samples in some regions, including Italy (Naccari et al., 2014), Iran (Mahmoudi et al., 2015) and improving the methods of analysis of heavy metals in bee-keeping products (Aghamirlou et al., 2015; Kupchyk, 2017).

The dependence of heavy metals in bee-keeping products on the level of the technological pollution of the agro-ecological environment was established for the Carpathian region (Kovalchuk & Fedoruk, 2013).

The use of the resources of some ecosystems that have been exposed to the technological (radioactive) effect and have not been used economically for a long time has been complicated by the fact that these ecosystems have become vulnerable to invasive species, including transformer species.

One of the most common transformer species in Polesie in general and technologically (radioactively) contaminated areas in particular is the Canadian goldenrod (*Solidago canadensis* L.) – a violent with the significant phenotypic and phenological variability that reproduces by seeds and restored by rhizomes. Due to this, it quickly colonizes disturbed areas and successfully inhabits various types of biotopes (Burda et al., 2015). In Polesie, the Canadian goldenrod is most rooted in the meadow ecosystems. It is worth noting that *Solidago canadensis* is an excellent autumn melliferous plant. Autumn honey gather from this plant is mostly supportive, and in favorable years it can give commercial honey. The entry of fresh honey and pollen into the hive stimulates the autumn growth of young bees for the winter and promotes the queen bees' autumn egg-laying.

The aim was to predict (according to the content of radionuclides and heavy metals in soil and plants) the possibility of using the *Solidago canadensis* transformer as a melliferous resource in summer and autumn periods on the meadow ecosystems of Polesie, which were contaminated during the Chernobyl disaster.

2. Study area

Poorly defined relief, considerable distribution of water-ice deposits of sand, and high marshiness are characteristic features of Polesie landscapes. The Dnieper is the main waterway of Polesie. The Dnieper divides Polesie into Right-bank and Left-bank Polesie. There are no significant differences between Right-bank Polesie and Left-Bank Polesie in the amount of weather elements (Lukash et al., 2020). Within Polesie on the territory of Left-Bank Polesie (Ukraine, the Chernihiv region) and Right-bank Polesie (Belarus, the Gomel region) the meadow ecosystems of the Dnieper floodplains and its tributaries of different order (the Desna, the Sozh, the Snov, the Oster, the Ubid, the Iput, the Smolianka, the Zamhlai, the Vzdvyzha, the Mylenka, the Pakulka) and loess "islands" (Mykhailo-Kotsiubynskyi, Sedniv and Tupychiv, Berezna and Mena and Sosnytsia) were studied. In the soil cover of the studied floodplain meadow ecosystems the meadow loam and sod clay soils predominate. The floodplain meadows are used as hayfields and pastures. The meadow carbonate saline soils are widespread in the studied areas of the loess "islands". The landscapes of the loess "islands" are characterized by much greater agricultural development: the ploughlands in some places reach more than 80%. Long-term use of the arable lands led not only to the stabilization of the composition of weed synusiae of agro-phytocoenoses, but also contributed to the increase of erosion and suffusion forms of the relief (Lukash et al., 2018).

3. Material and methods

Within the herbaceous-cereal moderately moist meadow ecosystems with the invasion of the Canadian goldenrod, the test plots were set where the geobotanical relevés were carried out, soil samples (from the depth of 0-10, 10-20 cm, 20-30 cm) and *Solidago canadensis* inflorescences were taken. In September 2018–2020, the samples of honey from *Solidago canadensis,* collected in the areas that were not exposed to radioactive contamination after the disaster at the Chernobyl atomic power station, were taken for analysis. 5 samples of soil, inflorescences and honey were taken from one site. Sampling was performed according to the current methods (Yakushev et al, 2004; GOST..., 1987; Handbook ..., 1997).

The syntaxa vegetation was identified on the ecological-floristic basis (Matuszkiewicz, 2019) using the deductive method proposed by K. Kopecký and S. Hejný (Kopecky & Hejny, 1974, 1978) to identify the derivative communities. Syntax names (classes, orders and alliances) are ordered according to Mucina et al. (2016).

The determination of ^{137}Cs in the soil, plant and honey samples was carried out on a Tennelec gamma spectrometric complex. The radiochemical determination of the specific activity of ^{90}Sr was carried out without separation in the system of strontium – calcium with the radiometric termination on the Canberra -2400 α-β-counter.

The content of heavy metals was determined on a voltamperometric TA-Lab analyzer ("Tomanalit", Russia) in the three-electrode electrochemical cell. An amalgam electrode was used as an indicator electrode. A silver chloride electrode filled with a solution of 1M potassium chloride was used as the reference electrode and the auxiliary electrode (Kupchyk, 2017).

The assessment of the content of radionuclides and heavy metals in the studied samples of soil, plants and honey was given by comparing the obtained results with the current normative indicators (Permissible..., 2006; Republican..., 2004; Natural..., 2007).

To process the results, the Statistica 10 software was used, using which the linear regression equations for the indicators of the specific activity of radionuclides and the content of heavy metals in honey – plant and honey – soil systems were obtained. The following abbreviations were used in the equations: y is the predicted value of the radionuclide / heavy metal content in honey, x is the actual value of the radionuclide / heavy metal content in inflorescences / soil. The coefficients were also calculated to assess the level of the statistical reliability of the obtained results, in particular: Pearson's correlation coefficient (r) – the statistical reliability coefficient, the correlation significance level (p), the determination coefficient (r^2) – the correspondence index, the reliability of the constructed regression model (Khalafyan, 2010). The closer the value of r to 1, the greater the degree of the linear connection; for $r > 0.75$ the correlation is strong. If p is less than 0.05, then the correlation is statistically reliable; under the condition of $p > 0.05$, the correlation is considered statistically unreliable; r^2 in the case of statistically reliable results should have a value in the range from 0 to 1 (Khalafyan, 2010). The cartographic material was made using QGIS 3.8.

4. Results and discussion

The studied phytocenoses of the meadow ecosystems of the floodplains of the Desna river, the Snov river, the Ubid river, the Zamhlai river, the Vzdvyzha river, the Mylenka river are the derivative *Solidago canadensis* communities of the *Arrhenatherion elatioris* Luquet 1926 alliance, the *Arrhenatheretalia elatioris* Tx. 1931 order, the *Molinio-Arrhenatheretea* R.Tx. 1937 class. The grass cover of these meadows is mostly sparse (the projective coverage is 60-70%), less often there are the areas with the projective coverage of 80-90%. The floristic composition of the phytocenoses, consisting of three sublayers, has 24-36 species: cereals – 4-8 species, sedge – 2-5 species, legumes – 7-10 species, grasses – 18-25 species. The main part of the grass cover are the species of mesophytic ecology, occasionally hydromesophytes and xeromesophytes. *Solidago canadensis* dominates in all meadow areas with the projective coverage of 25-50%. Co-dominants of the phytocenoses with the projective coverage of 15-20% are *Schedonorus pratensis* (Huds.) P.Beauv, *Festuca rubra* L. *Deschampsia caespitosa* (L.) P.Beauv., *Medicago lupulina* L., *Trifolium pratense* L. Among the asectators are *Trifolium repens* L., *Achillea submillefolium* Klokov et Krytzka, *Plantago lanceolata* L., *Potentilla anserina* L., *Prunella vulgaris* L., *Taraxacum officinale* Wigg. aggr., *Ranunculus acris* L.

In the floodplains of the Sozh, the Iput, the Oster, the Smolianka, the Pakulka *Solidago canadensis*, which has the projective coverage of 60-90%, forms the the *Calamagrostio epigeiosi-Solidaginetum canadensis* ass. nov. hoc locco derivative community, belonging to the *Dauco-Melilotion* Göors ex Rostański et Gutte 1971 alliance, the *Onopordetalia acanthii* Br.-Bl. et Tx. ex Klika et Hadač 1944 order, the *Artemisietea vulgaris* Lohmeyer et al. in Tx. ex von Rochow 1951 class. The floristic saturation of the communities – 9-17 species. At various stages of succession in the composition of the grass cover *Artemisia vulgaris* L., *Convolvulus arvensis* L., *Elytrigia repens* (L.) Nevski co-dominate. Among other species mainly ruderal-weed species were found, in particular ruderal-weed (*Cichorium intybus* L., *Equisetum arvense* L., *Melandrium album* (Mill.) Garcke, *Artemisia absinthium* L., *Oenothera biennis* L., *Conyza canadensis* (L.) Cronq.) and meadow (*Tanacetum vulgare* L., *Vicia tetrasperma* (L.) Schreb., *Achillea submillefolium* Klokov et Krytzka, *Knautia arvensis* (L.) Coult.) species.

In the areas of the loess "islands" with compressed soil and the Dnieper floodplain *Solidago canadensis* is a part of the *Elytrigia repens* basal communities, the *Convolvulo arvensis-Agropyrion repentis* Görs 1967 alliance, the *Agropyretalia intermedio-repentis* T. Müller et Görs 1969 order, the *Artemisietea vulgaris* Lohmeyer et al. in Tx. ex von Rochow 1951 class, which are also confined to sandy sod-meadow soil differences with the level of subsoil waters up to 1.0-1.5 m. The participation of the dominants ranges from 20 to 50%. The phytocenoses are floristically poor and represent various succession stages and phases of substrate formation and consolidation. Co-dominants (*Calamagrostis epigeios* (L.) Roth, *Bromopsis inermis* (Leyss.) Holub, *Agrostis capillaris* L., *Koeleria delavignei*, and also *Poa angustifolia* L. in the Dnieper floodplain) have the projective coverage of 10-20%.

The results of the laboratory studies (Table 1) showed that in the soil samples, except for site 5, the content of heavy metals and the specific activity of radionuclides are within the acceptable limits. In the floodplain of the Desna river (the Kyselivka village, Chernihiv district), the maximum permissible concentration of zinc (47.53 mg / kg) exceeded.

Table 1. The content of heavy metals and radionuclides in the soil samples

Site		The content of heavy metal (mg / kg)				The specific activity of radionuclide (Bq / kg)	
#	Name	Zn	Cd	Pb	Cu	^{137}Cs	^{90}Sr
1	M.-Kotsiubynskyi loess "island", the Zhukotky village, Chernihiv district, Chernihiv region	34.362	0.010	0.533	2.121	24.8	31.6
2	The floodplain of the Oster river, the Kozelets urban village, Kozelets district, Chernihiv region	15.461	0.274	0.612	1.834	20.4	271
3	The floodplain of the Mylenka river, the Koriukivka urban village, Koriukivka district, Chernihiv region	18.532	0.361	0.673	0.915	42.5	52.0
4	Sedniv and Tupychiv loess "island", the Smychyn village, Horodnia district, Chernihiv region	9.748	0.082	0.109	0.675	25.7	29.5
5	The floodplain of the Desna river, the Kyselivka village, Chernihiv district, Chernihiv region	47.530	0.311	1.650	2.318	24.8	40.5

6	Zamhlai reclamation system, the Zamhlai urban village, Ripky district, Chernihiv region	11.575	0.125	0.134	0.520	19.9	45.7
7	Berezna and Mena and Sosnytsia loess "island", the Berezna urban village, Mena district, Chernihiv region	18.362	0.342	0.263	1.331	11.5	12.0
8	The floodplain of the Vzdvyzha river, the Drozdivka village, Kulykivka district, Chernihiv region	20.873	0.072	0.382	1.254	9.5	11.4
9	The floodplain of the Smolianka river, the Komarivka village, Borzna district, Chernihiv region	9.115	0.078	0.198	0.589	4.9	8.2
10	The floodplain of the Ubid river, the Kyriivka village, Sosnytsia district, Chernihiv region	0.053	0.097	0.116	0.673	4.4	2.3
11	The floodplain of the Snov river, the Zarichchia village, Snov district, Chernihiv region	0.105	0.054	0.131	0.195	1.8	2.2
12	The floodplain of the Pakulka river, the Pakul village, Chernihiv district, Chernihiv region	19.142	0.219	2.174	0.245	345.5	64.5
13	The floodplain of the Dnieper river, the Novoselky village, Ripky district, Chernihiv region	18.533	0.247	1.055	1.654	145.4	65.3
14	The floodplain of the Dnieper river, the Byvalki village, Loev district, Gomel region	9.530	0.35	10.6	1.832	128.3	158
15	The floodplain of the Iput river, the city of Dobrush, Gomel region	16.000	0.130	0.340	2.060	81	26.8
16	The floodplain of the Iput river, the Zalissia village, Dobrush district, Gomel region	4.220	0.07	0.15	2.555	176	11.6
17	The floodplain of the Sozh river, the Sherstyn village, Vetka district, Gomel region	3.710	0.14	0.330	2.430	39.5	5.8
18	The floodplain of the	2.800	0.07	0.70	0.870	396.0	23.5

	Dnieper river, the Komaryn village, Bragin district, Gomel region						
MPC (maximum permissible concentration – for heavy metals) MPSA (maximum permissible specific activity – for radionuclides)		37.000	0.400	25.000	3.000	775	465

In the samples of *Solidago canadensis* inflorescences the specific activity of radionuclides in most of the studied sites did not exceed (Table 2).

Table 2. The content of heavy metals and radionuclides in the *Solidago canadensis* inflorescences

Number of the site*	The content of heavy metal (mg / kg)				The specific activity of radionuclide (Bq / kg)	
	Zn	Cd	Pb	Cu	^{137}Cs	^{90}Sr
1	23.533	0.003	0.337	1.421	19.3	25.1
2	9.245	0.105	0.288	1.184	19.1	20.6
3	11.615	0.114	0.267	0.715	38.2	44.9
4	7.955	0.025	0.044	0.428	18.9	26.7
5	35.056	0.092	0.614	1.712	16.7	30.5
6	8.103	0.046	0.076	0.246	16.3	38.6
7	16.302	0.089	0.174	0.961	8.8	8.4
8	15.258	0.032	0.223	0.852	4.5	8.2
9	6.021	0.023	0.127	0.311	3.4	4.1
10	0.012	0.046	0.084	0.437	2.5	1.5
11	0.036	0.038	0.090	0.220	1.3	1.4
12	12.155	0.105	0.894	0.135	304.7	52.5
13	12.597	0.141	0.540	1.138	86.1	54.2
14	7.320	0.150	1.025	1.285	112.4	121.2
15	12.350	0.750	0.220	1.250	56.4	21.5
16	2.840	0.050	0.110	1.850	123.0	10.6
17	2.670	0.110	0.270	1.450	24.0	4.0
18	2.380	0.050	0.560	0.640	365.0	22.9
MPC (MPSA)**	23.000	0.100	10.000	3.000	500.0	200.0

* the name of the site as it is in Table 1.

However, the excess of the content of Zn was corded in the *Solidago canadensis* inflorescences from sites #1 (23.533 mg / kg at a maximum permissible Zn concentration of 23.000 mg / kg) and #5 (35.056 mg / kg, which is 1.5 times higher than the MPC). Exceeding the MPC of Cd, which is the indicator of its active absorption by plants, was established in 7 sites, in particular: #2 and #12 the content of Cd was 0.105 mg / kg, #3 – 0.114 mg / kg, #14 – 0.150 mg / kg, #13 –

0.141 mg / kg, #15 – 0.750 mg / kg, #17 – 0.110 mg / kg (MPC ≤ 0.100 mg / kg). Lead, which according to the degree of danger to living organisms is classified as the first (highest) class of danger, as well as cadmium, does not belong to the group of physiologically necessary microelements for plants. The excess of the content of Pb (MPC ≤ 10,000 mg / kg) was not established. The content of Cu in the studied plant samples does not exceed the MPC, which is 3 mg / kg, and ranges from 0.135 to 1.450 mg / kg. The content of the ^{137}Cs and ^{90}Sr radionuclides in the studied samples of the *Solidago canadensis* inflorescences was within the maximum permissible concentration.

The results of the analysis of the honey samples from sites 1–11, which are located within the territories that were not exposed to radioactive contamination after the Chernobyl disaster are presented in Table 3. Therefore, in these areas there were no restrictions on obtaining bee-keeping products.

Table 3. The content of heavy metals and radionuclides in the honey samples

Number of the site*	The content of heavy metal (mg / kg)				The specific activity of radionuclide (Bq / kg)	
	Zn	Cd	Pb	Cu	^{137}Cs	^{90}Sr
1	2.558	0/001	0.235	0.734	14.8	18.4
2	0.734	0.050	0.273	0.689	16.5	10.6
3	0.817	0.091	0.237	0.314	23.5	30.1
4	0.455	0.010	0.021	0.234	10.7	14.5
5	3.010	0.074	0.436	0.836	14.4	26.0
6	0.604	0.015	0.030	0.154	14.9	48.3
7	1.003	0.049	0.131	0.578	5.4	3.4
8	1.003	0.022	0.122	0.542	2.7	4.6
9	0.236	0.011	0.094	0.197	2.9	3.5
10	0.000	0.019	0.004	0.217	0.5	1.2
11	0.001	0.018	0.071	0.066	0.6	0.9
MPC (MPSA)	3.000	0.050	1.000	1.000	200	50

* the name of the site as it is in Table 1.

The content of zinc in the honey samples varies within the norm of 0.001-2.558 mg / kg (MPC ≤ 3,000 mg / kg), except for the sample from site #5 (3.010 mg / kg), which is directly related to the excess Zn content in the soil samples (Table 1) and the *Solidago canadensis* inflorescences (Table 2) from this site.

It should be noted that the increased content of toxic Cd (MPC ≤ 0.050 mg / kg) in some samples of honey is due to the excessive content of heavy metals in the samples of plants and soil, in particular: in site #3 we observe the 1.82 times excess, in site #5 – 1.48 times.

Exceeding the MPC of Cu in any of the honey samples was not established. It should be noted that copper as a component of enzyme systems promotes metabolic processes and has a positive effect on the organism of honey bees in small and average concentrations. None of the honey samples contained Pb.

The specific activity of radionuclides in the honey samples does not exceed the maximum permissible concentration. It is worth noting that the content of radionuclides in the honey samples varies from site to site. Concerning ^{137}Cs, it is known that even between bee colonies in the same apiary, there can be a significant difference in the level of radionuclide contamination of honey. It depends not only on the content of cesium-137 in the soil, but also on the different ability of melliferous plants, that grow within the radius of the productive flight of bees, to absorb cesium-137 from the soil and secrete it with the nectar (Aleksenitser et al., 1996).

When predicting the possibility of gathering honey according to the specific activity of ^{137}Cs in plants, the following are established: the linear regression equation ($y = 0.5809 + 0.6746 \times x$), the value of Pearson's correlation coefficient ($r = 0.9577$), the correlation significance level ($p = 0, 00000$), the coefficient determination ($r^2 = 0.9172$). Graphically, it is shown in Figure 1.

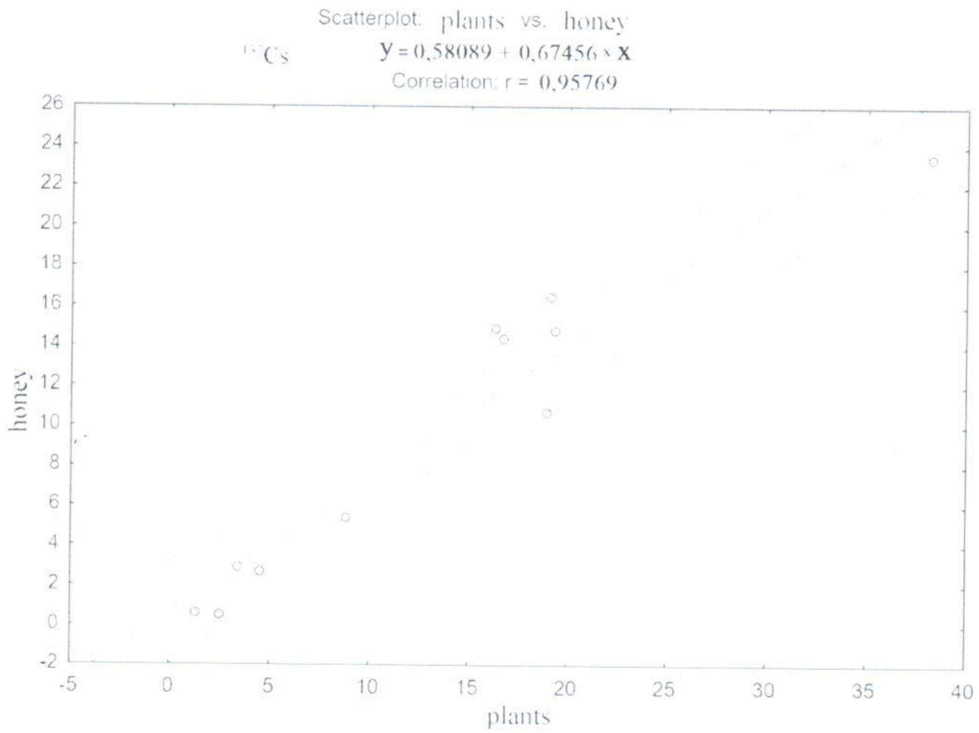

Figure 1. Dependence of the specific activity of ^{137}Cs in the honey on the specific activity of ^{137}Cs in the plants (the *Solidago canadensis* inflorescences)

Due to the linear regression equation, it was found that the specific activity of ^{137}Cs in the *Solidago canadensis* inflorescences, according to which the value of the specific activity of ^{137}Cs in the honey will be at the level of MPC (200 Bq / kg) and will be 295.6 Bq / kg. It is predicted that at the specific activity of ^{137}Cs within the norm, the value of the specific activity of the honey ^{137}Cs in sites 12 and 18 will exceed the MPSA and will be 203.1 Bq / kg and 246.8 Bq / kg, respectively (Table 4).

Table 4. The predicted specific activity of ^{137}Cs and ^{90}Sr (Bq / kg) in the *Solidago canadensis* honey

Number of the site*	On the content of the substratum in which the prediction is made	^{137}Cs		^{90}Sr	
		Absolute	Average	Absolute	Average
12	plant	203.1	204.25	31.7	31.55
	soil	205.4		31.4	
13	plant	58.6	72.35	32.7	32.25
	soil	86.1		31.8	
14	plant	76.4	76.15	72.6	74.90
	soil	75.9		77.2	
15	plant	38.6	43.15	13.2	20.00
	soil	47.7		26.8	
16	plant	83.5	93.90	6.7	9.15
	soil	104.3		11.6	
17	plant	16.8	19.85	2.8	4.30
	soil	22.9		5.8	
18	plant	246.8	241.15	14.1	18.80
	soil	235.5		23.5	
MPSA		200		50	

* the name of the site as it is in Table 1.

In Figure 2 the actual (sites 1-11) and predicted (sites 12-18) specific activity of radionuclides in the *Solidago canadensis* honey is compared.

The dependence of the specific activity of ^{137}Cs in the honey on the specific activity of ^{137}Cs in the soil is described by the equation: $y = -0.5894 + 0.5961 \times x$ (Fig. 3). The corresponding coefficients have the values: $r = 0.9439$; $p = 0.00001$; $r^2 = 0.8910$. The calculations allowed us to establish that the highest specific activity of ^{137}Cs in the soil, according to which the value of the specific activity of ^{137}Cs in the honey will be at the level of MPSA, is 336.5 Bq / kg. This index is also exceeded in sites 12 and 18 (Table 4, Fig. 2).

The dependence of the specific activity of ^{90}Sr in the plant-honey system is described by the equation $y = 0.4487 + 0.5953 \times x$; $r = 0.9710$; $p = 0.00000$; $r^2 = 0.9429$ (Fig. 4); the highest value of the specific activity of 90Sr of honey will be at the level of MPSA (50 Bq / kg) is 83.2 Bq / kg. The exceeding of these values was established in site 14: with the 121.2 Bq / kg specific activity of ^{90}Sr of soil, the predicted specific activity of honey is 72.6 Bq / kg (Table 4, Fig. 2).

For ^{90}Sr in the soil-honey system we have: $y = -0.1714 + 0.4899 \times x$ (Fig. 5); $r = 0.9681$; $p = 0.00000$; $r^2 = 0.9372$. With the 102.4 Bq / kg specific activity of ^{90}Sr in the soil, the predicted specific activity of ^{90}Sr in the honey will be at the maximum permissible level. According to the specific activity of ^{90}Sr of the *Solidago canadensis* inflorescences, the maximum permissible specific activity in site 14 was predicted to exceed 27.2 Bq / kg (Table 4, Fig. 2).

Figure 2. The actual (sites 1-11) and predicted (sites 12-18) specific activity of radionuclides in the *Solidago canadensis* honey

According to the predicted indices of the specific activity of ^{137}Cs and ^{90}Sr, the honey from sites 12, 14 and 18 will have the exceeding in the maximum permissible values. In this regard, in the floodplains of the Dnieper river (the Byvalki village, Loevskyi district and the Komaryn village, Bragin district, Gomel region) and the Pakulka river (the Pakul village, Chernihiv district, Chernihiv region) *Solidago canadensis* should be used for honey gather.

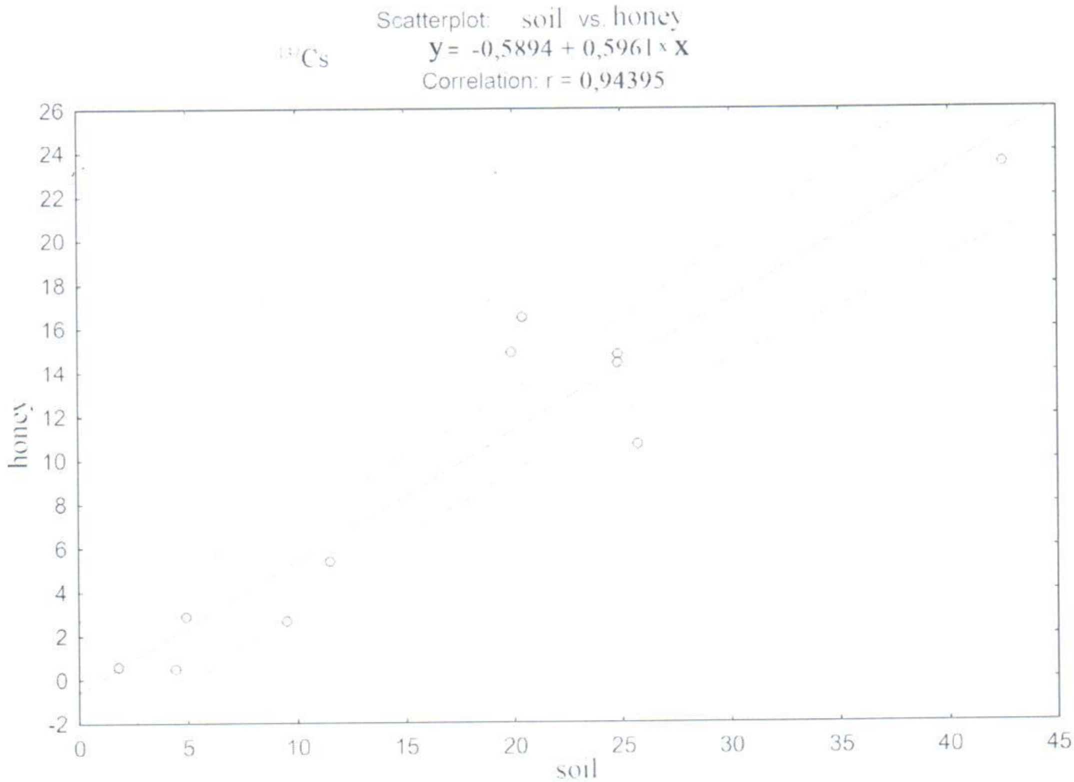

Figure 3. Dependence of the specific activity of ^{137}Cs in the honey on the specific activity of ^{137}Cs in the soil

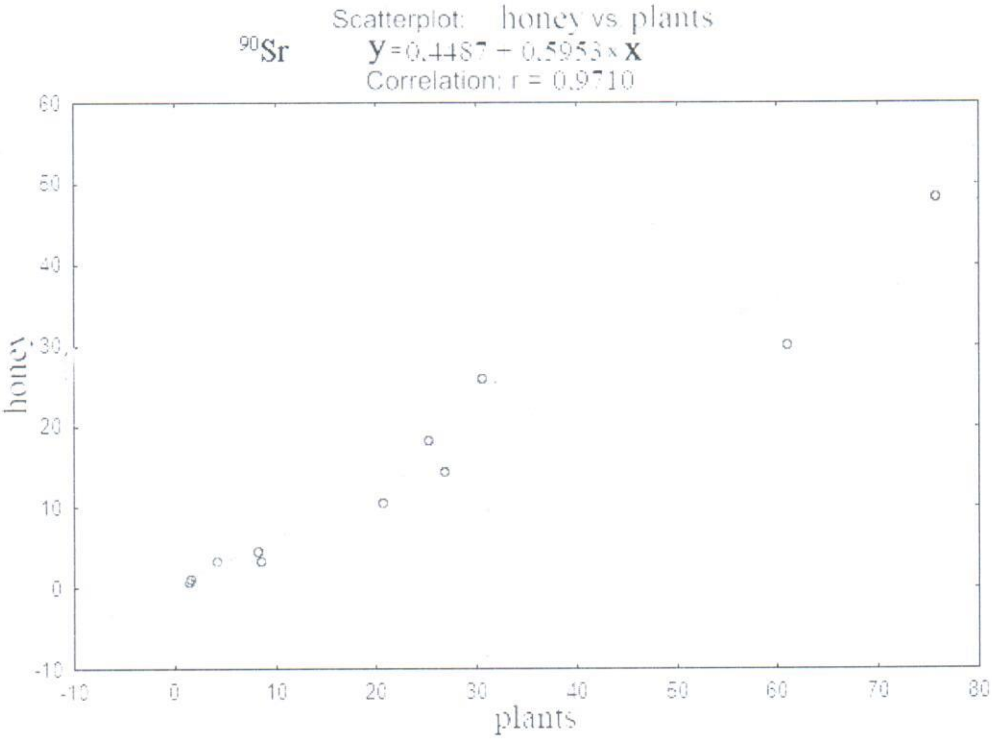

Figure 4. Dependence of the specific activity of ^{90}Sr in the honey on the specific activity of ^{90}Sr in the plants (the *Solidago canadensis* inflorescences)

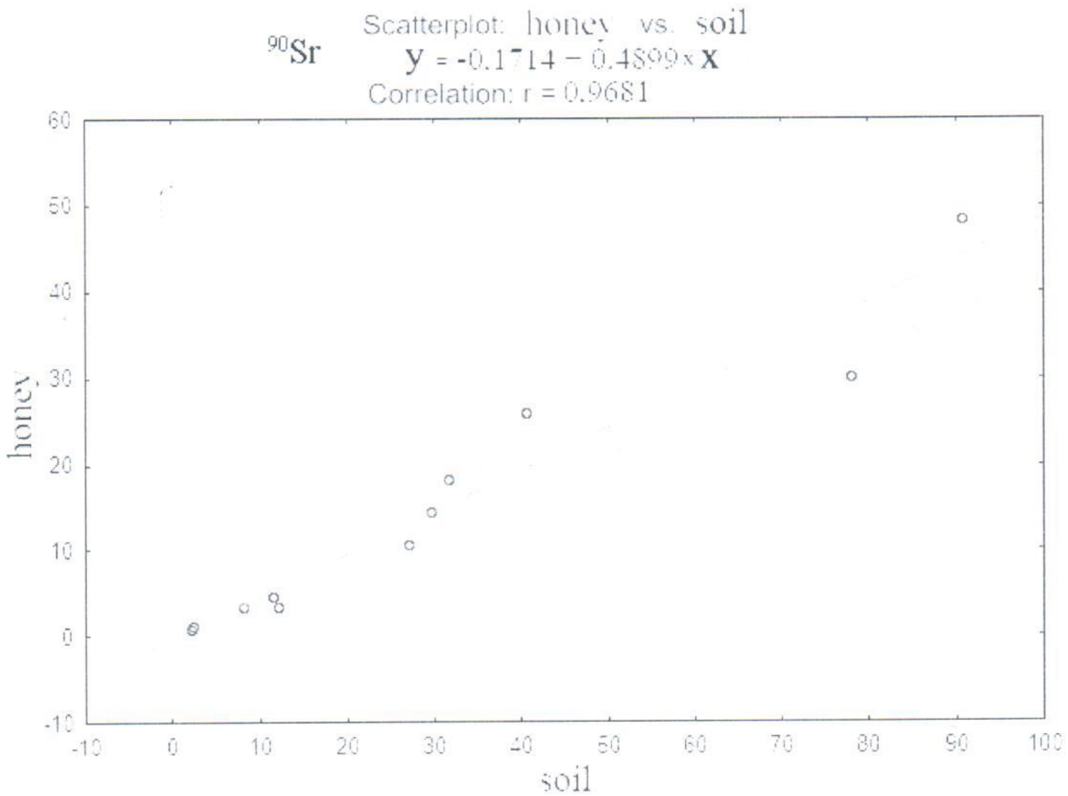

Figure 5. Dependence of the specific activity of ^{90}Sr in the honey on the specific activity of ^{90}Sr in the soil

Based on the actual data on the content of heavy metals in the honey, as well as the *Solidago canadensis* inflorescences and soil from the places of its gathering from 11 sites of the meadow ecosystems of Chernihiv Polesie, the correlations in the honey-plant (Table 5) and honey-soil systems (Table 6) were made, as well as the highest concentrations of metals in the *Solidago canadensis* inflorescences and soil, at which their content in the honey will be at the level of MPC.

Table 5. Dependence of the content of heavy metals (HM) in the honey on the content of heavy metals in the plant

HM	The linear regression equation of dependence	r	p	r^2	The highest content of HM in the plant, at which the content of HM in the honey will be at the level of MPC
Zn	y = -0.1701 + 0.0923×x	0.9693	0.00000	0.9395	34.3
Cd	y = -0.0075 + 0.7222×x	0.9309	0.00003	0.8665	0.08
Pb	y = -0.0132 + 0.7743×x	0.9678	0.00000	0.9367	1.31
Cu	y = 0.0139 + 0.5193×x	0.9788	0.00000	0.9580	1.89

Table 6. Dependence of the content of heavy metals in the honey on the content of heavy metals in the soil

HM	The linear regression equation of dependence	r	p	r^2	The highest content of HM in the soil, at which the content of HM in the honey will be at the level of MPC
Zn	y = -0.2038 + 0.0682×x	0.9784	0.00000	00.9572	46.97
Cd	y = -0.0015 + 0.2086×x	0.9297	0.00003	0.8643	0.247
Pb	y = 0.0303 + 0.2752×x	0.9437	0.00001	0.8907	3.5
Cu	y = -0.0092 + 0.3752×x	0.9858	0.00000	0.9719	2.69

According to the linear regression equations of dependence for the honey-plant and honey-soil systems of each site, the prognostic calculations of the content of heavy metals in the goldenrod honey were performed (Table 7). The graphic representation of the actual and predicted values of heavy metals in the honey is given in Figure 6.

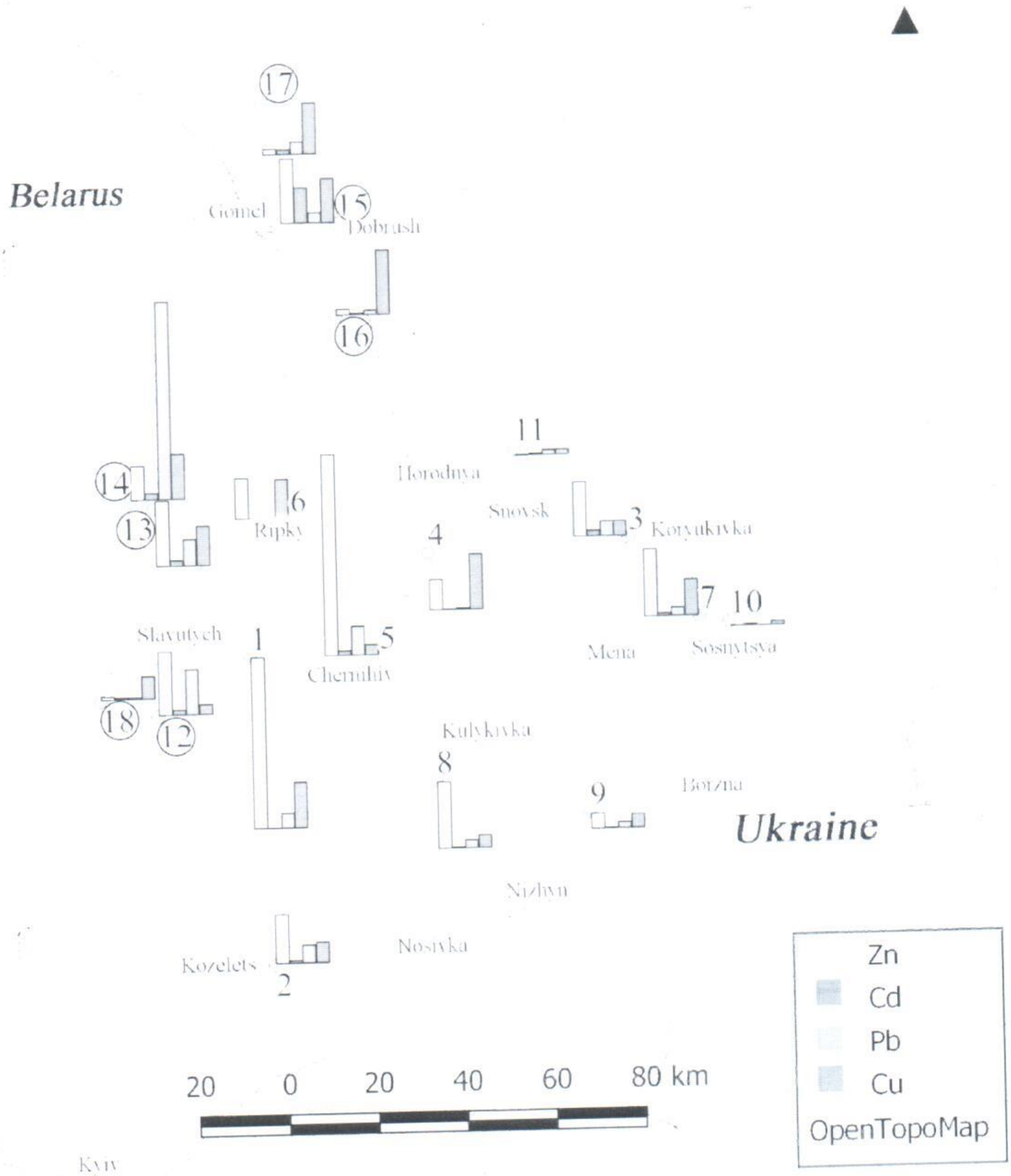

Figure 6. The actual (sites 1-11) and predicted (sites 12-18) content of heavy metals in the *Solidago canadensis* honey

Table 7. The predicted content of heavy metals (mg / kg) in the *Solidago canadensis* honey

Number of the site*	On the content of the substratum in which the prediction is made	Zn		Cd		Pb		Cu	
		Absolute	Average	Absolute	Average	Absolute	Average	Absolute	Average
12	plant	0.95	1.025	0.070	0.057	0.680	0.655	0.084	0.083
	soil	1.10		0.044		0.630		0.082	
13	plant	0.99	1.025	0.094	0.072	0.404	0.362	0.604	0.608
	soil	1.06		0.050		0.320		0.611	
14	plant	0.50	0.475	0.100	0.085	0.780	1.865	0.681	0.680
	soil	0.45		0.070		2.950		0.678	
15	plant	0.97	0.930	0.530	0.040	0.157	0.141	0.663	0.713
	soil	0.89		0.026		0.124		0.763	
16	plant	0.09	0.085	0.028	0.021	0.072	0.072	0.974	0.962
	soil	0.08		0.013		0.072		0.949	
17	plant	0.08	0.065	0.072	0.050	0.190	0.156	0.766	0.834
	soil	0.05		0.027		0.121		0.902	
18	plant	0.05	0.025	0.028	0.021	0.030	0.041	0.346	0.332
	soil	0.00		0.013		0.051		0.317	
MPC		3.000		0.050		1.000		1.000	

* the name of the site as it is in Table 1.

According to the prognostic calculations, we expect to exceed the MPC of cadmium in the honey from sites 12-15 and 17 and lead from site 14. The possible sources of cadmium in the meadow ecosystems are industrial emissions, agricultural activities (application of phosphorus fertilizers, limestone materials) and vehicles emissions (car tires and lubricants contain cadmium).

We draw the attention to the fact that the values of the predicted (by the content of heavy metal in the plant) concentration of cadmium in the honey differ from the value determined by the prediction made by the content of this heavy metal in the soil. It is known that cadmium is quite actively absorbed by plants. With the aerogenic pollution of ecotopes, high rates of cadmium accumulation by plants was established for tree species (Hryshko, 2014). On the example of the natural and agricultural landscapes of Zhytomyr Polesie it is proved that even on the low cadmium-contaminated soils it is possible to obtain contaminated plant products. The analysis of the seasonal dynamics of the lead and cadmium content shows that the maximum of pollutants, regardless of plant species, is concentrated in their vegetative organs in September, exceeding the content of the latter in May by 2.3 – 6.2 times for Pb and 2.3 – 5.9 times for Cd (Biliavskyi, 2012). The content of heavy metals in different parts of plants is caused by their physiological ability to unequal accumulation of these toxicants in the vegetative and reproductive mass; it also depends on the level of supply and chemical form of these elements and their presence in the soil. Thus, within the meadow ecosystems of the Dobrush urban zone, the high concentration of cadmium in the *Solidago canadensis* inflorescences and the predicted cadmium content in the honey, which exceeds the MPC by more than 10 times, are quite probable even with the MPC of this heavy metal in the soil. That is why when predicting the content of heavy metals, especially cadmium, in bee-keeping products one should take into account the importance of their content not only in soil but also in plants. The values of the highest content of heavy metals in the *Solidago canadensis* inflorescences and soil, at which the content of heavy metals in the honey will be at the MPC level, are given in Tables 5, 6.

5. Conclusions

In the late phase after the Chernobyl disaster, in order to obtain the products with standard contents of heavy metals and radionuclides, it is possible to use *Solidago canadensis* L. as a honey resource invaded by this species of the meadow ecosystems of Polesie, which have been radioactively contaminated.

According to the predicted indicators of the specific activity and the content of heavy metals from 7 studied sites, which in 1986 were exposed to radioactive contamination, only the meadow ecosystems in the floodplain of the Iput river (the Zalissia village, Dobrush district, Gomel region) are suitable for gathering the goldenrod honey.

In the case of honey gather on the meadows invaded with the Canadian goldenrod in the floodplains of the Dnieper river (the Novoselky village, Ripky district, Chernihiv region), the Iput river (the city of Dobrush, Gomel region) and the Sozh river (the Sherstyn village, Vetka district, Gomel region) the excess of the MPC of cadmium in the products is possible. According to the prognostic calculations, we expect the exceeding of the maximum permissible concentration of lead in the honey from the floodplain ecosystems of the Dnieper river near the village of Byvalki (the Loev district, Gomel region). The honey gathered from *Solidago canadensis* in the floodplains of the Dnieper river (the village of Byvalki, Loev district and the village of Komaryn, Bragin district, Gomel region) and the Pakulka river (the village of Pakul, Chernihiv district, Chernihiv region), will not meet the norm in terms of the specific activity of ^{137}Cs and ^{90}Sr.

To assess the possibility of obtaining the environmentally friendly goldenrod honey, it is advisable to predict the content of radionuclides and heavy metals in both plants and soil. To do this, we should also take into account the calculated values of the highest content of heavy metals and the specific activity of radionuclides in soil and plants, at which the content of metals in the honey will be at the level of MPC.

References

Aghamirlou H.M., Khadem M., Rahmani A., Sadeghian M., Mahvil A., Akbarzadeh A. & Nazmara S., 2015, Heavy metals determination in honey samples using inductively coupled plasma-optical emission spectrometry. Journal of Environmental Health Science & Engineering 13: 1–8. DOI: https://doi.org/ 10.1186/s40201-015-0189-8

Aleksenitser M.L., Bondarchuk L.I. & Kubaichuk V.P., 1996, Contamination of bee products with radionuclides and the requirements for their radiometric control. Bulletin of Agrarian Science 4: 32–36. [in Ukrainian].

Biliavskyi Yu.A., 2012, Lead and cadmium content in medicinal plants of Zhytomyr Polesie. Bulletin of Zhytomyr National Agroecological University 2 (1): 44–155 [in Ukrainian].

Burda R.I., Pashkevich N.A., Boyko G.V. & Fitsaylo T.V., 2015, Alien species of natural flora of the Forest-Steppe and Steppe. Scientific Opinion of the National Academy of Sciences of Ukraine, Kyiv. [in Ukrainian].

Dayneko N.M. & Timofeev S.F., 2015, Technogenic pollution of the meadow ecosystems of the Belarusian Polesie. Desna Polygraph, Chernigov. [in Russian].

Dayneko N.M., Timofeev S.F., 2018, State of the meadow ecosystems of the Sozh river in the post-Chernobyl period. Desna Polygraph, Chernigov. [in Russian].

Dayneko N.M., Timofeev S.F., 2020, Composition and structure of the Sozh river floodplain meadows in the post-Chernobyl period. Desna Polygraph, Chernigov. [in Russian].

GOST RB 27262–87, 1987, Method for sampling green forage (grass). Gosstandart, Minsk [in Russian].

Handbook for radiological services of the Ministry of Agriculture of Ukraine, 1997. Ed. by S.X. Poplavska, Kyiv. [in Ukrainian].

Hryshko V.M., 2014, Peculiarities of accumulation of heavy metals in the leaves of woody plants during aerogenic pollution of ecotopes. Introduction of plants 1: 93–100 [in Ukrainian]. URL: http://nbuv.gov.ua/UJRN/IR_2014_1_15

Khalafyan A.A., 2010, Statistica 6. Statistical data analysis. Binom-Press, Moscow. [in Russian].

Kopecky K. & Hejny S., 1974, A new approach to the classification of anthropogenic plant communities. Vegetatio 29 (1): 17–20.

Kopecky K. & Hejny S., 1978, Die Anwendung einer deduktiven methode syntaxonomischer Klassifikation bei der Bearbeitung der strassenbegleitenden Pflanzengesellschaften Nordostböhmens. Vegetatio 36(1): 43–51.

Kovalchuk I.I. & Fedoruk R.S., 2013, Content of heavy metals in the bee tissues and products depending on agroecological conditions of the Carpathians region. The Animal Biology 15(4): 54–65 [in Ukrainian]. URL: http://nbuv.gov.ua/UJRN/bitv_2013_15_4_8

Kupchyk O., 2017, Stripping voltamperometric determination of heavy metals in honey samples. Chemistry & Chemical Technology 11(3): 285–290. https://doi.org/10.23939/chcht11.03.285

Kymakovska N.O., 2015, Radiological justification of permissible levels of soil contamination with ^{137}Cs for running a private holding on the contaminated territories in the remote period: dissertation abstract for the PhD degree (Agricultural Sciences: Ecology). Zhytomyr National Agroecological University, Zhytomyr. [in Ukrainian].

Lisohurska D.V., 2017, Regularities of the ^{137}Cs migration in the chain of soil-plant for rapeseeds in conditions of radioactive contamination of the Zhytomyr Polesie. Bulletin of Sumy National Agrarian University. Series: Livestock 5/2 (32): 61–66. [in Ukrainian].

Lukash O, Melnyk V., Danko H., Rak O., Karpenko Yu. & Buzunko P., 2020 Phytocenotic features of *Calluna vulgaris* (L.) Hill. in Ukrainian Polesie. Ecological Questions. 31(3): 73–107. DOI: http://dx.doi.org/10.12775/EQ.2020.024

Lukash O., Yakovenko O. & Miroshnyk I., 2018, The mechanical degradation of the land surface and the present state of the loess "islands" plant cover of Chernihiv Polesie (Ukraine). Ecological Questions 29(4): 23–34. DOI: http://dx.doi.org/10.12775/EQ.2018.027

Mahmoudi R., Mardani K. & Rahimi B., 2015, Analysis of heavy metals in honey from NorthWestern regions of Iran. Journal of Chemical Health Risks 5(4): 251–256. DOI: https://dx.doi.org/10.22034/jchr.2018.544114

Matuszkiewicz W., 2019, Przewodnik do oznaczania zbiorowisk roślinnych Polski [Guide to the determination of Polish plant communities]. Wydawnictwo Naukowe PWN, Warszawa.

Melnychuk H.V., 2015, Growing strawberries on radioactively contaminated sod-podzolic soils. Agroindustrial production of Polesie 8: 48–51. [in Ukrainian].

Mucina L., Büultmann H., Dierßen K., Theurillat J.-P., Raus T., Čarni A., Šumberová K., Willner W., Dengler J., García R. G., Chytrý M., Hájek M., Di Pietro R., Iakushenko D., Pallas J., Daniëls F. J. A., Bergmeier E., Guerra A. S., Ermakov N., Valachovič M., Schaminée J. H. J., Lysenko T., Didukh Y. P., Pignatti S., Rodwell J. S., Capelo J., Weber H. E., Solomeshch A., Dimopoulos P., Aguiar C., Hennekens S. M. & Tichý L., 2016, Vegetation of Europe: hierarchical floristic classification system of vascular plant, bryophyte, lichen, and algal communities. Applied Vegetation Science 19(S1): 3-264. https://onlinelibrary.wiley.com/doi/epdf/10.1111/avsc.12257

Naccari C., Macaluso A., Giangrosso G., Naccari F. & Ferrantelli V., 2014, Risk assessment of heavy metals and pesticides in honey from Sicily (Italy). Journal of Food Research 2: 107–117. DOI: https://doi.org/10.5539/jfr.v3n2p107

Natural honey. Specifications. DSTU 4497: 2005, 2007. Derzhspozhyvstandart of Ukraine, Kyiv [in Ukrainian].

Permissible levels of the ^{137}Cs and ^{90}Sr radionuclides in food and drinking water (DR-2006): state hygiene standards, 2006. The Ministry of Health of Ukraine, Kyiv. [in Ukrainian]. URL: https://regulation.gov.ua/documents/id238199]/

Republican permissible level of cesium-137 content in medicinal and technical raw materials (RDU / LTS2004), 2004. Minsk [in Russian].

Razanov S.F., 2009, Content of radionuclide and heavy metals in bee-keeping products. Agroecological journal 1: 9–11. [in Ukrainian].

Slavov V.P. & Furman S.V., 1999, Peculiarities of accumulation of some radionuclides in bee honey. Bulletin of the SAAU 1–2: 183–187.
Vasenkov H.I., Kryvyi M.M. & Verbelchuk S.P., 2016, Radioecological aspects of bee-keeping in Polesie. Biodiversity after the Chernobyl disaster: part I. Slovak University of Agriculture in Nitra, Nitra: 261–267.
Yakushev B.I., Efremov A.L., Matusov G.D. & Sak, M.M., 2004, Soil sampling method for radioecological monitoring in natural phytocenoses. Reports of the NAS of Belarus 48(1): 69–71. [in Russian].