ABSTRACT
Background. The development of effective environmental management programs requires an appropriate assessment of the current state of the environment and contributes to anticipating future changes in the state of the environment. Obtaining such information is one of the main objectives of monitoring the environment, which is subject to anthropogenic stress, including radiological contamination. The distribution of radionuclides and their ability to migrate in ecological chains and concentration in individual parts requires special control in contaminated areas.

Objective. The purpose of the study was to analyze the content of radionuclides ($^{137}$Cs and $^{90}$Sr) in soils near the settlements of the zone of radioactive contamination of the Volyn region and their spatial differentiation. Priority is given to agricultural lands, soils, crop products, which necessitates the organization of targeted monitoring of the agro-industrial complex

Material and methods. Radioactivity from $^{137}$Cs and $^{90}$Sr in the soil originating in the Volyn region was studied from 1996 to 2018. Radiation control was carried out on the area of 59852 ha (arable land - 38897 ha, meadows and pastures – 20955 ha).

Results. A significant part of the study area has elevated levels of radioactive contamination. The density of radionuclide contamination of agricultural soils in the settlements of the region has been determined. Density of pollution of all surveyed agricultural lands $^{137}$Cs ranges from 0.01 to 2.826 Ci/km$^2$, and $^{90}$Sr from 0.01 to 0.048 Ci/km$^2$.

Conclusions. The radiological situation in the Volyn region (Ukraine) remains stable. There are slight fluctuations of $^{137}$Cs and $^{90}$Sr, which is due to changes in weather conditions, which leads to an increase or decrease in groundwater and as a consequence - the migration of radionuclides. The most polluted were the soils of administrative districts of Manevychi and Liubeshiv.

Key words: radionuclides, $^{90}$SR, $^{137}$CS, radioactive contamination, soils, monitoring, settlement

INTRODUCTION
Rational use of agricultural lands in the conditions of technogenic impact on the environment, in particular optimization of nature use in the zone of radioactive contamination is an important task of modern times [13]. One of the most important objects of radiation pollution monitoring is the sphere of agricultural production, especially crop and livestock products. The main source of radionuclides in human food is soil. Radionuclides are absorbed by plants and entered the crop products, and during its use they are absorbed in the human body.

Taking into consideration the behavior of radionuclides in the natural environment and decision-making on measures to reduce radioecological indicators of risks caused by the Chernobyl disaster remain relevant. The Volyn region, in particular the Kamin-Kashyrsky, Lyubeshivskyi and Manevychi administrative districts, also suffered from radioactive contamination. Much of the territory of these areas has elevated levels of radioactive contamination. To solve the problems related to the optimization of agro-landscapes in the conditions of radioactive contamination requires a comprehensive analysis of the ecostates of the study area.

The analysis of stock materials on the contaminated territories of the Volyn region showed the absence of scientific generalizations on radioactive contamination formed on the basis of unified approaches. The available information needs to be overviewed and systematized. It is necessary for the development of these conclusions, proposals for the rational use of agricultural land has been
exposed to radioactive contamination. The content of radionuclides, ecostate of landscapes of the region, the degree of safety of local water and resources use were studied periodically. Many years of research, considerable attention has been paid to the use of water, biotic and land resources. However, there is an urgent need to clarify the state, dynamics, spatial distribution of radiation pollution, which largely determines the environmental safety of residents.

This problem of contamination of toxic substances is devoted a significant amount of studies. Special attention is paid to works by Samoilenko who proposed a comprehensive zoning of radioactive contaminated areas and the possible ecological consequences of the resource [16], Tavrov [17] who identified the most environmentally hazardous local complexes and forms of the use of water, biological and land resources of geosystems reservoirs of the Polissia and North Forest. Ilyina et al. [8, 9, 10, 11] have studied natural ponds as the environment complexes and accumulation of sediments and established geochemical indicators of the conditions investigated anthropogenic transformation processes and the sources and types of toxic substances in the conditions of Ukrainian Polissia. Korotun [12] analysed the monitoring of radiation pollution in the territory of Rivne region, Romanchuk [15] carried out the evaluation of the radioecological formation of radiation doses to rural residents of Polissia of Ukraine, Hromyk et al. [4, 5, 6, 7] have carried out eco-geographical substantiation of optimisation of agricultural landscapes in the zone of radioactive contamination of the Volyn region, Dutov [1] has considered agroecological aspects of minimize population exposure and Grygus et al. [3] found out the medical and geographical aspects of radioactive contamination. However, important special and temporal aspects of the propagation and accumulation of pollutants especially near settlements require detailed studies. It is part of a wide system of measures on liquidation of consequences of Chernobyl accident.

The purpose of the study was to analyse the content of radionuclides in soils near the settlements of the zone of radioactive contamination of the Volyn region and their spatial differentiation.

**STUDY AREA**

Radiation control was carried out on an area of 59852 ha (arable land - 38897 ha, meadows and pastures - 20955 ha) in seven administrative districts of the Volyn region (Ukraine), including in the area of radioactive contamination (Manevychi, Lyubeshiv and Kamin-Kashyrskyi administrative districts).

**MATERIALS AND METHODS**

To assess the effects of pollution, data on surface contamination of soils with radionuclides $^{137}$Cs and $^{90}$Sr (Ci/km$^2$) were used. All measurements were carried out in the Laboratory of Ecological Land Safety and Product Quality of the Volyn Branch of the State Institution ‘Soil Protection Institute of Ukraine’ (Lutsk). Determination of $^{137}$Cs in soil was performed by the gamma-spectrum method on the AI-1024-95-17 unit, as well as on the PSA 68-01, RUB-01P6 radiometers, SEG-02, SEG-05 gamma spectrometers. The results of internal control over the accuracy of gamma spectrometric work to determine $^{137}$Cs showed that the main relative error of measurements does not exceed 7%, of the allowable 25%. $^{90}$Sr was determined by a radiochemical method with measurement on a modernized DP-100 No A 16-878 installation with PSO 3-4 M 09 [14].

The main types of soils are sod-podzolic, podzolic, chernozem, sod and swamp. The area of radioactive contamination of the region is characterized by a high rate of transfer of radionuclides from the soil to plants, which complicates the radiation situation and can adversely affect the health of residents [16].

**RESULTS AND DISCUSSION**

As a result of the Chernobyl catastrophe, radionuclides that went outside the station were released into the atmosphere, where they accumulated. High migration capacity in the food chain (soil → plant → animal → livestock products) led to their entry into the human body. Internal radiation was added to the external irradiation. The presence of long-lasting radionuclides in the food chain causes internal exposure of humans and animals for many decades after contamination. Radionuclides get into the environment in different ways, but the soil, due to its absorbency, is the main accumulator of radioactive isotopes.

The ability to migrate and concentrate in certain parts of the food chain necessitated the organization of targeted monitoring of the agro-industrial complex. The monitoring system includes: observation and assessment of the level of radioactive contamination of nature components and biota elements in order to prevent possible negative consequences for human health; identification of patterns of spatial and temporal migration of radionuclides in biotic chains and making a forecast on this basis of future levels of radioactive contamination.

The purpose of radiation pollution monitoring is to accumulate the information needed to make decisions on the management and regulation of radioactive contamination of the natural environment.
and to develop measures to reduce the absorption of doses by the population. Taking into account specific tasks and purposes, monitoring programs are developed, which establish the choice of objects of observation, type, frequency and frequency of changes, sampling, their further laboratory analysis, methods of statistical processing of results, principles of collection, accumulation and processing of information.

The only source of objective information about the radiation situation is direct observations and measurements. Monitoring of radiation pollution includes: periodic measurements of dose rates of β and γ parts in the field; periodic sampling at specially selected observation sites and control points, determination of the concentration of radionuclides in these samples, radiation contamination and physicochemical forms of radionuclides; calculation of dose loads on biota on the basis of primary data of radiation pollution monitoring; assessment of current conditions and forecasting of possible changes in the radiation situation.

Several authors [8, 16, 17] have studied the radioactivity of soils and other elements of the environment in Ukraine after the Chernobyl disaster, drawing attention to the identification of the most heavily contaminated sites and to the ecological consequences.

According to the results of monitoring (1994–1995) of $^{137}$Cs and $^{90}$Sr soil contamination in settlements, it was established that the maximum content of $^{137}$Cs and $^{90}$Sr is available in the Lyubeshiv administrative district of the village Berezna Volya ($^{137}$Cs-2.83 Ci/km$^2$, $^{90}$Sr-0.04 Ci/km$^2$) and village Lakhvychi ($^{137}$Cs-0.65 Ci/km$^2$, $^{90}$Sr - 0.04 Ci/km$^2$) (Table 1, Figure 1).

According to the level of soil contamination of the territory, settlements with villages Lychyny, Stavyschhe, Kachin (Kamin-Kashyrskiy district), Berezna Volia (Lyubeshiv district), Haluziya, Prylisne (Manevychi district) we attributed to the zone of enhanced radiation control (Table 2).

Table 1. Results on complex monitoring of radiation pollution of soils in the settlements of Kamin-Kashyrskiy, Lyubeshivskiy and Manevychi areas of the Volyn region, Ukraine (1994–1995)

| No  | Settlement        | $^{137}$Cs Ci/km$^2$ | $^{90}$Sr Ci/km$^2$ |
|-----|-------------------|----------------------|---------------------|
|     | Kamin-Kashira district |                      |                     |
| 1994 |                  |                      |                     |
| 1   | Lychyny           | 1.398                | 0.028               |
| 2   | Buzaky            | 0.794                | 0.026               |
| 3   | Cherche           | 0.968                | 0.022               |
| 4   | Stavyschhe        | 1.404                | 0.014               |
| 5   | Nuyne             | 0.614                | 0.024               |
| 1995 |                  |                      |                     |
| 1   | Karasin           | 0.656                | 0.048               |
| 2   | Viderta           | 1.114                | 0.038               |
| 3   | Kachin            | 1.410                | 0.042               |
| 4   | Olshani           | 0.244                | 0.022               |
|     | Lyubeshiv district |                      |                     |
| 1994 |                  |                      |                     |
| 1   | Mala Hlusha        | 0.344                | 0.032               |
| 2   | Mukoshlya         | 0.384                | 0.026               |
| 3   | Lakhvychi         | 0.652                | 0.040               |
| 4   | Berezna Volya     | 2.826                | 0.040               |
| 1995 |                  |                      |                     |
| 1   | Lobna             | 0.868                | 0.028               |
| 2   | Lyubotyn          | 0.44                 | 0.042               |
| 3   | Vetly             | 0.464                | 0.024               |
| 4   | Pozhoh            | 0.612                | 0.034               |
|     | Manevychi district |                      |                     |
| 1994 |                  |                      |                     |
| 1   | Haluziya          | 1.236                | 0.038               |
| 2   | Kulykovychi       | 0.466                | 0.012               |
| 3   | Chornyzh          | 0.810                | 0.024               |
| 1995 |                  |                      |                     |
| 1   | Haluziya          | 1.368                | 0.032               |
| 2   | Komarove          | 0.486                | 0.024               |
| 3   | Prylisne          | 1.182                | 0.030               |

1 Ci/km$^2$ = 37 kBq/m$^2$
The results of radioecological monitoring of soils conducted in 1996–1998 in Kamin-Kashirsky, Lyubeshivsky and Manevychi districts are summarized in Table 3. Analysis of the results of the study of $^{137}$Cs content in soils showed that the maximum content of radionuclides was recorded in 1997 in the village. Borovno (0.27 Ci/km$^2$) Kamin-Kashirskiy district, village Volya Lyubeshivska (0.34 Ci/km$^2$) of Lyubeshiv district and village Yablunka (0.46 Ci/km$^2$) of Manevychi districts. The main $^{90}$Sr batteries were soils in 1997 Rakiv Lis (0.02 Ci/km$^2$) and village Borovno (0.02 Ci/km$^2$) of Kamin-Kashirsky district. The maximum content of radionuclides in the soils of Lyubeshiv district is concentrated in the village Volia Lyubeshivska (0.03 Ci/km$^2$) in 1996. The soils of the village Lyshnivka (0.03 Ci/km$^2$) in 1996 and the village Komarovo (0.03 Ci/km$^2$) in 1998, Manevychi district.

In 2011–2018, radiological control was carried out in seven administrative districts (Lyuboml, Shatsk, Starovyzhiv, Ratniv, Kivertsiv, Manevychi and Lutsk). The content of radionuclides was controlled on the area of 59852 ha (arable land - 38897 ha, meadows and pastures - 20955 ha). The density of contamination of the surveyed agricultural soils at $^{137}$Cs was up to 1 Ci/km$^2$, and at $^{90}$Sr up to 0.02 Ci/km$^2$.

The highest indicators of density of $^{137}$Cs contamination of soils are in the areas included in the zone of radioactive contamination, village Yablunka - 0.15 Ci/km$^2$, village Kostyukhnivka - 0.24 Ci/km$^2$, village Lyshnivka - 0.31 Ci/km$^2$, village Prilisne - 0.27 Ci/km$^2$, village Sytntysia - 0.09 Ci/km$^2$, village Komarovo - 0.08 Ci/km$^2$ Manevychi district; with village Seat - 0.18 Ci/km$^2$, village Velyka Hlusha - 0.11 Ci/km$^2$, village Volya Lyubeshivska - 0.12 Ci/km$^2$ Lyubeshiv district (Table 4, Figure 2).

According to toxicological indicators the soils of the experimental plots do not exceed the maximum allowable concentrations.

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### Table 2. Scale for assessing the level of radioactive soil contamination $^{137}$Cs

| Contamination of the territory, Ci/km$^2$ | Soil contamination | Possibility of human habitation |
|------------------------------------------|---------------------|---------------------------------|
| 0 – 1                                    | Clean soil          | Ordinary residence              |
| 1 – 5                                    | Zone of enhanced radiation control | Accommodation is allowed         |
| 5 – 15                                   | Contaminated soil   | Zone guaranteed voluntary resettlement |

### Table 3. Results on the complex monitoring of radiation pollution of soils in the settlements of Kamin-Kashirskyi, Lyubeshivskyi and Manevychi areas of the Volyn region, Ukraine (1996–1998)

| No | Settlement       | Year of research | $^{137}$Cs Ci/km$^2$ | $^{90}$Sr Ci/km$^2$ |
|----|------------------|------------------|----------------------|---------------------|
|    | Kamin-Kashirskiy |                  |                      |                     |
| 1  | Rakiv Lis        | 1996             | 0.12                 | 0.01                |
|    |                  | 1997             | 0.15                 | 0.02                |
|    |                  | 1998             | 0.06                 | 0.02                |
| 2  | Borovno          | 1996             | 0.25                 | 0.01                |
|    |                  | 1997             | 0.27                 | 0.02                |
|    |                  | 1998             | 0.18                 | 0.01                |
|    | Lyubeshivskiy    |                  |                      |                     |
| 1  | Velyka Hlusha    | 1996             | 0.236                | 0.02                |
|    |                  | 1997             | 0.25                 | 0.01                |
|    |                  | 1998             | 0.40                 | 0.01                |
| 2  | Volya Lyubeshivska | 1996           | 0.20                 | 0.03                |
|    |                  | 1997             | 0.34                 | 0.01                |
|    |                  | 1998             | 0.23                 | 0.01                |
|    | Manevychi        |                  |                      |                     |
| 1  | Lyshnivka        | 1996             | 0.34                 | 0.03                |
|    |                  | 1997             | 0.41                 | 0.02                |
|    |                  | 1998             | 0.27                 | 0.02                |
| 2  | Yablunka         | 1996             | 0.30                 | 0.02                |
|    |                  | 1997             | 0.46                 | 0.01                |
|    |                  | 1998             | 0.36                 | 0.01                |
| 3  | Komarovo         | 1996             | 0.14                 | 0.01                |
|    |                  | 1997             | 0.26                 | 0.01                |
|    |                  | 1998             | 0.17                 | 0.03                |

1 Ci/km$^2$ = 37 kBq/m$^2$

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Figure 2. Dynamics of changes of $^{137}$Cs content in soils in the surveyed areas of Volyn region, Ukraine (2011-2018)
Table 4. Contamination of $^{137}$Cs in soils on the surveyed areas of the Volyn region, Ukraine (2011-2018)

| No | Districts                          | Settlement     | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|----|-----------------------------------|----------------|------|------|------|------|------|------|------|------|
| 1  | Volodymyr-Volynskyi               | Ovadne         | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 |
| 2  | Gorokhivsky                       | Zhuravnyky     | 0.03 | 0.04 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 |
| 3  | Gorokhivsky                       | Uhryniv        | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| 4  | Lutsk (Rokyni Res. Farm)          | Sokolyk        | 0.06 | 0.06 | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 |
| 5  | Ivanyivivsky                      | Hryady         | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 |
| 6  | Kamin-Kashirsky                   | Olenine        | 0.12 | 0.15 | 0.09 | 0.12 | 0.09 | 0.07 | 0.05 | 0.07 |
| 7  | Kamin-Kashirsky                   | Rakiv Lis      | 0.07 | 0.07 | 0.08 | 0.08 | 0.06 | 0.05 | 0.04 | 0.05 |
| 8  | Kiyevtsivsky                      | Hrempycha      | 0.12 | 0.11 | 0.08 | 0.04 | 0.02 | 0.02 | 0.02 | 0.03 |
| 9  | Kiyevtsivsky                      | Omelene        | 0.11 | 0.12 | 0.09 | 0.04 | 0.03 | 0.03 | 0.04 | 0.03 |
| 10 | Kiyevtsivsky                      | Koziynychi     | 0.17 | 0.18 | 0.15 | 0.12 | 0.08 | 0.07 | 0.06 | 0.05 |
| 11 | Kiyevtsivsky                      | Stari Koshary  | 0.05 | 0.05 | 0.03 | 0.01 | 0.03 | 0.02 | 0.02 | 0.02 |
| 12 | Kiyevtsivsky                      | Ukholetska     | 0.08 | 0.09 | 0.10 | 0.11 | 0.07 | 0.07 | 0.08 | 0.09 |
| 13 | Lohachinsky                       | Hubyn          | 0.03 | 0.04 | 0.03 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 |
| 14 | Lohachinsky                       | Pryvitne       | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 0.02 | 0.01 | 0.01 |
| 15 | Lutsk                             | Vesele         | 0.03 | 0.04 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 |
| 16 | Lutsk                             | Khyihtsi       | 0.04 | 0.04 | 0.02 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 |
| 17 | Lutsk                             | Krupa          | 0.04 | 0.05 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 |
| 18 | Lyubeshivsky                      | Velika Hlusa   | 0.18 | 0.18 | 0.19 | 0.18 | 0.14 | 0.14 | 0.12 | 0.11 |
| 19 | Lyubeshivsky                      | Volicky Lyubeshivska | 0.24 | 0.24 | 0.21 | 0.19 | 0.17 | 0.15 | 0.13 | 0.12 |
| 20 | Lyubeshivsky                      | Sedlyshche     | 0.22 | 0.23 | 0.18 | 0.18 | 0.16 | 0.16 | 0.17 | 0.18 |
| 21 | Lubomlsky                         | Kusnszhche     | 0.05 | 0.06 | 0.03 | 0.02 | 0.03 | 0.02 | 0.02 | 0.01 |
| 22 | Manevychi                         | Komarovo       | 0.13 | 0.16 | 0.11 | 0.09 | 0.06 | 0.04 | 0.05 | 0.08 |
| 23 | Manevychi                         | Kotyukhnivka   | 0.14 | 0.39 | 0.35 | 0.28 | 0.27 | 0.24 | 0.22 | 0.24 |
| 24 | Manevychi                         | Lyshnivka      | 0.39 | 0.43 | 0.36 | 0.37 | 0.36 | 0.35 | 0.32 | 0.31 |
| 25 | Manevychi                         | Prylisne       | 0.51 | 0.52 | 0.48 | 0.36 | 0.32 | 0.29 | 0.22 | 0.27 |
| 26 | Manevychi                         | Shtynysya      | 0.27 | 0.27 | 0.22 | 0.13 | 0.11 | 0.10 | 0.11 | 0.09 |
| 27 | Manevychi                         | Tsnyny         | 0.25 | 0.30 | 0.20 | 0.18 | 0.11 | 0.01 | 0.03 | 0.03 |
| 28 | Manevychi                         | Ybliun'ka      | 0.23 | 0.24 | 0.19 | 0.15 | 0.12 | 0.13 | 0.11 | 0.15 |
| 29 | Ratnivsky                         | Hirnyky        | 0.04 | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| 30 | Rozhyschensky                     | Pozharky       | 0.10 | 0.11 | 0.06 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 |
| 31 | Rozhyschensky                     | Peshpa         | 0.10 | 0.13 | 0.04 | 0.03 | 0.03 | 0.02 | 0.02 | 0.01 |
| 32 | Starovyzhivsky                    | Krymne         | 0.12 | 0.08 | 0.06 | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 |
| 33 | Starovyzhivsky                    | Synove         | 0.10 | 0.11 | 0.07 | 0.04 | 0.03 | 0.02 | 0.02 | 0.01 |
| 34 | Turian                            | Kupychiv       | 0.03 | 0.04 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 |
| 35 | Kiyevtsivsky                      | Tuman forestry | 0.16 | 0.19 | 0.12 | 0.11 | 0.08 | 0.08 | 0.07 | 0.09 |
| 36 | Shatsky                           | Pulmo          | 0.07 | 0.07 | 0.05 | 0.02 | 0.03 | 0.02 | 0.01 | 0.01 |

CONCLUSIONS

The radiological situation in the Volyn region of Ukraine remains stable. There are slight fluctuations of $^{137}$Cs and $^{90}$Sr, which is due to changes in weather conditions, which leads to an increase or decrease in groundwater and as a consequence - the migration of radionuclides.

In order to preserve the natural resource potential of the radioactive contamination zone of the region, it is necessary to carry out a set of agrotechnical and agrochemical measures aimed at reducing radioactive contamination. The main measures include the method of tillage, crop placement and liming of acid soils. Application of organic, mineral fertilizers and sorbents with obligatory liming of acid soils is one of the main ways that can most effectively affect the blocking of radionuclides by the soil absorption complex.

Elucidation of the features of spatial differentiation of radionuclides, establishment of levels of contamination with radioactive elements $^{137}$Cs, $^{90}$Sr soils of the studied area requires further study of
their migration and accumulation. The problem of radionuclide contamination has serious socio-economic consequences. The territory needs a long process of socio-economic rehabilitation, which involves the restoration of lost natural resource potential and safe living conditions and the introduction of advanced technologies for the production of environmentally friendly agricultural products.

Conflict of interest
None declared.

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