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COMPLEX ANALYSIS AND MATHEMATICAL MODELING OF THE INTERNAL EXPOSURE DOSE OF THE UKRAINIAN POLISSYA RURAL POPULATION

The aim of this research is to determine the socio-economic and environmental factors that influence the formation of the internal exposure dose of the rural population of the radioactively contaminated territory of the Ukrainian Polissya. The most important ecological and socio-economic factors influencing the internal exposure dose were established and applied to the Group Average clustering algorithm and the principal component analysis. Based on the analysis results, the authors developed a mathematical model and created the appropriate software to form a proper assessment of the internal exposure dose in the human body many years after the Chornobyl accident.

Keywords: rural Polissya population, internal exposure dose, ^{137}Cs, socio-economic and environmental factors, artificial neural network.

1. Introduction

People living on radioactively contaminated land are inevitably at risk due to internal irradiation because of radionuclides ingested with food [1 - 5]. Recent studies [6] show that the rural population of Ukrainian Polissya, including children, consumes food products which contain ^{137}Cs contamination level several times higher than the permissible one. Milk, edible mushrooms, and berries are most relevant, as they are essential in the region's diet. Therefore, correct estimation of internal exposure doses of a population many years after a large radiation exposure incident is necessary for solving two problems: the determination of "dose-effect" dependence (health consequences) with the subsequent radiation risk assessment, and making decisions on the radiation countermeasures that need to be introduced.

It is well known that almost three-quarters of the total dose burden of the rural population, caused by the Chornobyl nuclear power plant (ChNPP) accident, consists of ^{137}Cs [7 - 9]. ^{137}Cs is rapidly incorporated into biosystems and is an environmentally persistent radionuclide. Thus, ^{137}Cs consumption leads to relatively uniform absorption in almost all human body organs and tissues [10]. That is why for decades, the contamination of territories with this radionuclide has led to the need of removing it from the land through phytoremediation and other countermeasures to reduce exposure [11]. However, in some settlements in the Ukrainian Polissya, the an annual dose of the inhabitants still exceeds 1 mSv/year [6]. The results of several studies have shown a clear specificity of the rural residents' diet in different parts of Ukrainian Polissya, and also revealed trends in changing the consummatory behavior of the local population in recent years. This change can be explained by the current economic rural-specific conditions on radioactively contaminated territories and global climate change. In fact, there are significant differences in the internal exposure dose values in rural areas with both high and low densities of radioactive contamination, and they remain steady over time [12, 13].

Another disadvantage of the traditional ecological approach in the analysis of internal exposure doses [10, 14 - 17] is that it is based on ^{137}Cs incorporation into the human body mainly from the consumption of milk and potatoes. They represent all meat-dairy and plant products, respectively. When calculating the internal exposure dose for certification of settlements, soil and traditional food samples are measured. In this case, the effectiveness of any countermeasures is not estimated. On the contrary, direct body-burden measurements with whole-body counter (WBC) reflect the effect of countermeasures and self-limitations of people. Massive organizational, agrotechnical, agrochemical and technological countermeasures in the private agricultural sector, which have reduced radioactivity in the food eaten by the local residents, have also led to a decrease in dose value in products from private farms. Therefore, existing internal exposure dose model estimates, based mostly on initial radioactive contamination level of milk and potatoes [17], significantly exceed the actual dose values calculated by WBC measurements. Meanwhile, the share of forest products (mushrooms, berries, and game), which are significant components of the rural population's diet, increased [4, 7, 18, 19]. Consequently, in some cases, the internal exposure dose model estimates are diminished due to the lack of consideration of the consumption of forest products. Therefore, no matter how correctly radioactive contamination levels of soil and food are measured, it is impossible to fully determine the exact causes of the rural population exposure doses using only those measurements. Dose exposure varies due to socio-economic instability and environmental changes. Therefore, the objective of this research was to determine the environmental and socio-economic factors which influence the formation of the internal exposure dose of the rural population of the Ukrainian Polissya radioactive contaminated territory.

The subsequent step was to develop a mathematical model and to create appropriate software to obtain a proper assessment of the internal exposure dose of the Ukrainian Polissya population many years after the Chornobyl accident.

2. Materials and methods

2.1. Data, study sites, and internal exposure dose-measuring

WBC-measurements carried out by the scientists of the Institute of Agroecology and Environmental Management of National Academy of Agrarian Sciences (NAAS) during 2005 - 2013, as well as the state dosimetry passportization data from 2005 - 2012, have been used as an information base for average annual effective dose estimation for inhabitants living in the radioactively contaminated rural areas [20 - 22]. The ^{137}Cs activity in human bodies was assessed with the whole-body gamma spectrometer "Scrinnner-3M" (WBC) according to the appropriate recommendations [23]. The minimum detectable activity (MDA) for WBC «Screener-3M» is 0.3 kBq of ^{137}Cs for an adult based on 300 s of measurement time. The limit of the permissible relative error of the incorporated ^{137}Cs activity detection in a 3 min exposure does not exceed 30 %, P = 0.95. WBC-measurements were converted automatically using appropriate software, developed in NRCRM into weight-normalized body-burden (Bq/kg) in order to use the internal effect dose by the ICRP dose conversion coefficient for ^{137}Cs of 0.0025 mSv/y/Bq/kg. The ^{137}Cs mode of intake was set to chronic with an intake period of 365 days with measurement occurring one day after the last intake. Model evaluation was performed on the basis of WBC-measurements of rural residents of the Vyshgorod district (Study Site 1, SS1) and the Naroditsky district (Study Site 2, SS2), which are in the Kyiv and Zhytomyr regions, respectively (Table 1), from 39 settlements in total. These districts were chosen because of their somewhat representative nature of the Ukrainian Polissya countryside. This allows one to consider as many characteristics of the region as possible when modeling. In SS1, the population of 32 settlements was surveyed: during the spring and autumn of 2005 (1949 measurements) and the autumn of 2013 (294 measurements). In SS2, 7 settlements were surveyed: during spring and autumn of 2008 (357 measurements) and autumn of 2013 (393 measurements). Among the SS1 population surveyed, the teen group (10 - 20 years old) was predominant (48 %), for SS2 – the group of 30 - 40 years (25 %) was predominant. The proportion of people surveyed over the age of 50 was 10 and 20 % for SS1 and SS2, respectively.

Table 1. **Brief description of countryside settlements of Study Sites**

Indicator		SS1	SS2
Average annual effective internal exposure dose, mSv/year	max	0.64	3.30
	min	MDA[a]	MDA[a]
	mean	0.06	0.18
The average number of people in the village, persons		1575	778
Forest area within of 3 km radius from the settlement[b], km^2		9.44	8.62
^{137}Cs deposition density [19 - 21], kBq/m^2		48.88	230.33
Radioactive contamination zone[c]		-	2, 3
Predominant soil types		sod-podzolic	sod-podzolic, meadow
Average distance to the nearest local center[d], km		1.31	24.35
Average distance to the nearest forest, km		13.35	1.89

[a] MDA – below the minimum detectable activity of WBC, we took the radiation dose as 0 mSv/year.

[b] Forest area is not always located within 3 km around the settlements included in SS1.

[c] According to the Ukrainian legislation, 2 – zone of unconditional (obligatory) resettlement, 3 – zone of guaranteed voluntary resettlement.

[d] Administrative center of a given or neighboring district or a settlement close to its size that is the nearest to a certain settlement.

Information on the ^{137}Cs deposition density was obtained from the State Institution "National Research Center for Radiation Medicine of National Academy of Medical Sciences of Ukraine" (NRCRM) [20 - 22] for the corresponding year of the WBC-measurement for each settlement. For 2013 data from 2012 was used. Information on the number of residents and the predominant soil types were provided by local administrations.

2.2. Data analysis and modeling using neural networks

Experimental data were analyzed using OriginPro 9 and Microsoft Excel 2016.

The assumptions and conclusions about the probable distribution law of internal exposure doses are based on the results of the descriptive statistics of WBC-measurements of the SS1 and SS2 populations and the approximation of distribution types. The similarity of the internal exposure doses of the rural populations was studied by cluster analysis of each settlement of SS1 and SS2. We obtained 5 clusters, each of which was characterized by a certain value of the four most variable indicators: internal exposure dose, specific forest area for 1 person within of 3 km radius from the settlement, ^{137}Cs deposition density, and the distance to the nearest local center. Thus, the first cluster is characterized by the average values of all aforementioned indicators. The second cluster is characterized by a high specific forest area. The third cluster is also characterized by a low specific wooded terrain, but also a comparatively large distance to the local center. The settlements of the fourth cluster have a low distance to the local center and the forested area of the adjoining territory, but a high density of ^{137}Cs surface contamination and dose. The last cluster settlements are characterized by a favorable situation regarding the radiation factor, but they have a relatively large distance to the local center.

The analysis of the main factors that influence the internal exposure doses of the rural population was performed by principal component analysis (PCA) in order to reduce and interpret data sets with underlying linear structures. The indirect factors include the settlement population, the distance to the nearest forest, and the forest area around the settlement. These factors make the biggest contribution to the internal exposure doses, because of the proximity of the forest. Poorly developed infrastructure forms a certain type of management in small and medium-sized rural settlements. Eventually, all of them affect food behavior.

We analyzed the following indicators:

a) quantitative: age of the person at the time of the WBC-measuring (birth year, BY), years; forest area fraction within of 3 km radius from the settlement (FA), %; specific forest area for 1 person within a 3 km radius from the settlement (SFA), km^2/person; ^{137}Cs deposition density (CsC), kBq/m^2; distance to the nearest local center (DLC), km; distance to the nearest forest (DF), km; year of WBC-measuring (YM); month of WBC-measuring (MM); population (P); internal exposure dose (D);

b) qualitative: predominant soil type in the settlement (ST); profession (Pr); education level (EL); radioactive contamination zone (CZ).

Multilayer recurrent neural network (multilayer perceptron, MLP) was selected for the prediction of the internal exposure dose. The software for the mathematical model of internal exposure dose received by the rural population due to the Chornobyl accident was developed using the Python programming language and the PyQt shell for the graphical user interface.

3. Results and discussion

3.1. Evaluation of the dose forming factors and the modeling indicators

The dose distribution law shows a generalized characteristic of the formation of the internal exposure dose of the rural population of the area of interest. In the many years after the ChNPP accident, a lognormal distribution of doses of internal radiation was observed in the vast majority of inhabited rural areas affected by the accident. Most recently, results on the exponential distribution of internal exposure doses for some settlements that have been obtained are observed [24 - 26]. This indicates a change in the pattern of the formation of the internal exposure dose.

When studying the dose for groups of inhabitants of the same social behavior type in the countryside settlements, the concept of Skryabin [27, 28] was taken as a basis. Its essence lies in the fact that a person or a group of people with a certain person and land socio-economic characteristics interacts with the surrounding living environment, contributing to the dose. The internal exposure dose of a person is formed depending on the public awareness of the radiation danger and the public's socioeconomic status, which is related to professional activity and social status. Therefore, the dose distribution in the settlement is determined by the personal characteristics of each of its inhabitants [12, 13]. Moreover, a direct dose-forming factor such as contaminated food consumption is determined by a number of indirect factors associated with the socio-demographic and economic characteristics of each family [24, 28, 29]. Consequently, each family is characterized by "its" dose. Since the family determines the dose, then the dose is the attribute of the family as a kind of social system [30, 31].

It is well-known that the social and economic living conditions of rural residents in different settlements are variable and diverse. It is necessary to examine the characteristics of the locations of the settlements in each individual case. Thus, numerous studies have established an extremely important role in the “forest” factor in dose formation [4, 15, 18, 25, 29, 32]. It is also clear that the smaller the settlement and the further it is located from the local center, the worse the social and economic conditions of its inhabitants. The demographic composition of the population is also different. There is a dependence of the average internal exposure dose of rural residents on the number of inhabitants in the settlement [33].

This approach explains some of the factors affecting dose, but they involve a laborious collection of indirect data about individuals or their groups with similar behavior. Both selected Study Sites are characterized by a specific set of various environmental and socio-economic factors, which determine the peculiarities of the internal exposure dose of the population and should be taken into account during modeling.

Thus, it is expedient to use model representations that account for both direct and indirect factors affecting the internal exposure doses in order to estimate the population doses where there is a lack or shortage of WBC-measurements data. The direct dose-forming factors include soil types and their surface contamination because they determine the ^{137}Cs transfer intensity from the soil to the main agricultural and forest products.

These indicators were chosen in terms of the degree of their influence on the internal exposure dose value and the availability of such data without additional research. Each selected indicators influence the population’s diet and level of radioactive contamination of the diet’s products. For example, the forest area around the settlement and the distance to the nearest forest affects the probable amount of available mushrooms and berries which are known to have high specific radioactive contamination. The person's age determines the diet as well. Children consume more milk and dairy products, while potatoes and locally produced vegetables and forest products prevail in adults’ diets [17, 24, 25]. The distance to the nearest local center determines the availability of products outside the radioactive contamination area for local residents. The profession is an indicator of particular interest, because it is determined somewhat by education, and therefore, defines the individual’s attitude towards the dangers of radiation. Research [31] has shown that the internal exposure dose of the rural population is influenced not only by the level of each individual’s education but also by the heads of each individual family. Finally, indicators such as the density of ^{137}Cs surface contamination; the radioactive contamination zone, the predominant soil type, and the time that has passed since the Chornobyl accident determine the probable contamination of local food products.

We constructed clusters on the base of the similarities between the studied indicators using the Group Average clustering algorithm (Fig. 1).

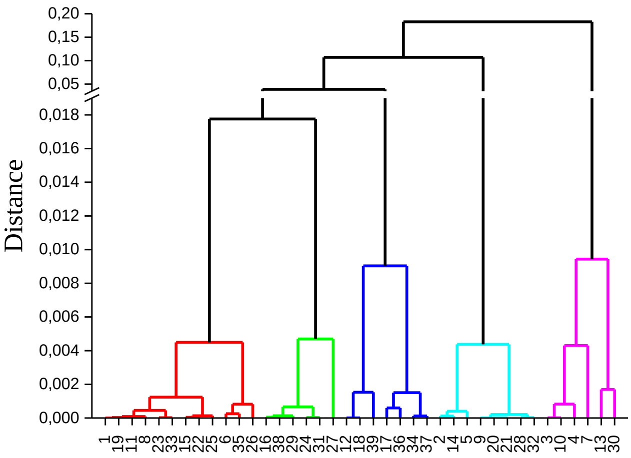

Fig. 1. Clustering Dendrogram of rural settlements similarities for the internal exposure doses.

According to the analysis results, we obtained 5 clusters, each of which differed in several indicators (Fig. 2).

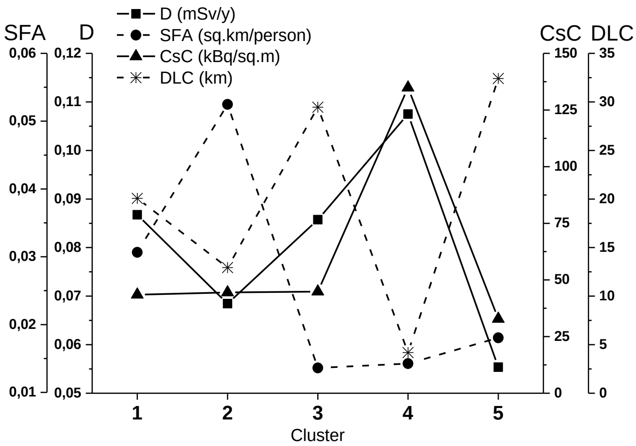

Fig. 2. Similarities of rural settlements with the characteristics of the main clusters.

The PCA method was used to clarify the relationships between the selected factors and their influence on the internal exposure dose. This method describes the dataset variance by linearly independent variables (Fig. 3).

It was found that the internal exposure dose (see Fig. 3) mostly depends on the density of ^{137}Cs surface contamination (r = 0.51) and the specific forest area for 1 person (r = 0.60). Dependence on the radioactive contamination zone (r = –0.42), the age of the person (r = –0.32), and the soil type (r = 0.30)

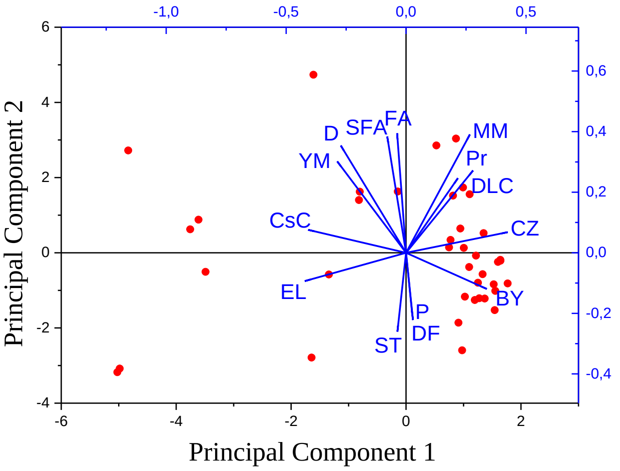

Fig. 3. Biplot of principal components by the main radio-ecological and socio-economic factors and their influence on the internal exposure dose.

was also observed, as well as the year of measurement (r = 0.49), which can be explained by the radionuclide half-life and the specific weather conditions and yield of crops. Age dependence can be explained by the diet peculiarities for people of all ages.

Principal component analysis of the clusters showed some differences in the rural settlements (Table 2).

There was no significant professional effect on the internal exposure dose. The education level influence on the dose value for cluster 2 is logical. The education level determines the awareness of the risk associated with the consumption of the most contaminated products, such as wild mushrooms and berries.

Table 2. **Comparison of clusters by the correlation between the investigated factors and the internal exposure dose of the rural population (r)**

Cluster	Factor										
	BY	YM	MM	P	FA	SFA	EL	CsC	CZ	ST[a]	DLC	DF
1	–	–	–	–0.51	0.58	0.65	–	0.80	–0.55	|0.59|	0.64	-
2	–	0.59	0.77	–0.79	0.81	0.83	0.59	0.77	–	|0.54|	0.51	-0.52
3	–	–	–	–	–	–	–	0.50	–	|0.85|	0.63	0.65
4	–	–	–	–0,54	–	–	–	0,57	–0,53	–	–	-
5	–0.55	0.80	0.99	–0.58	–	0.84	–	0.72	–	|0.89|	0.71	-

[a] Is given in absolute value because ST is a qualitative indicator, therefore the correlation direction is not important.

The high availability of these products is common for the population of settlements of cluster 2, due to the large area of the forest nearby. For clusters 3 and 5, the effect of soil type is significant, since the distance to the nearest local center (DLC) value is relatively high and the population in these settlements consumes mostly local food. The lack of a significant radioactive contamination zone (CZ) effect for the 2nd, 3rd, and 5th clusters is obvious. The inhabitants of the settlements included in these clusters consume a significant proportion of food products of non-local origin (cluster 2), or the level of soil surface contamination with ^{137}Cs is low (clusters 2, 3, 5). The probability of consumption of the most contaminated products (forest mushrooms and berries) is also low (clusters 3 and 5). The effect of the month of WBC-measurement is probably determined by the consumption of local plant products depending on the season for the 5th cluster, and the fraction of forest mushrooms and berries in the local inhabitant's diet for the 2nd cluster. Confirmation of the 2nd cluster is also the correlation between the dose burden and the distance to the nearest forest. However, this same correlation for the 3rd cluster is not as obvious. For this group of settlements, the distance to the nearest forest (the source of the most contaminated food products – mushrooms, berries, and game), as well as to the nearest local center (the source of radiologically safe food products), is relatively high. Consequently, vegetables and milk are the main source of radionuclides for the local population. Therefore, in this case, the correlation coefficient reflects not only the effect of the distance to the forest on the dose burden but also the combination of the influence of the other aforementioned factors. For assessment of the soil type effect on the internal irradiation dose level only the tightness of the link, but not its direction, matters because this is a qualitative indicator rather than a quantitative one.

Thus, we used all the above factors in further internal exposure dose modeling in order to increase the accuracy of the results, because each of these factors is important for one or more of the rural settlements.

3.2. Modeling of the internal exposure dose

It is expedient to use approaches based on the artificial neural network (ANN) generation. This article refers to Multilayer Recurrent Neural Networks (Multilayer Perceptron, MLP).

The generated system was trained on a sample of 2687 data rows with cross-validation and tested on the 299 data rows sample. The hidden ANN layer contains 12 neurons. The next hidden layer has a dropout rate of 0.5, in order to form the unique subsets of the dataset. The training was held for 16 epochs, and the data was packet-transmitted with 8 data rows.

The appropriate software was developed both to create a mathematical model of the internal exposure dose obtained for a population due to the Chornobyl accident using current data, and to predict the dose value using data that will be collected in the future. It enables the user to train the ANN and save the received weights, predict the internal exposure dose value using an existing file with ANN weights, and display the corresponding plots.

Testing of the developed software was conducted on a file containing 200 (Fig. 4) datasets rows, which were not used in the ANN training. The data are presorted by age in descending order. There are outliers in the set that are significantly different from the others. In this case, the ANN smooths out the value.

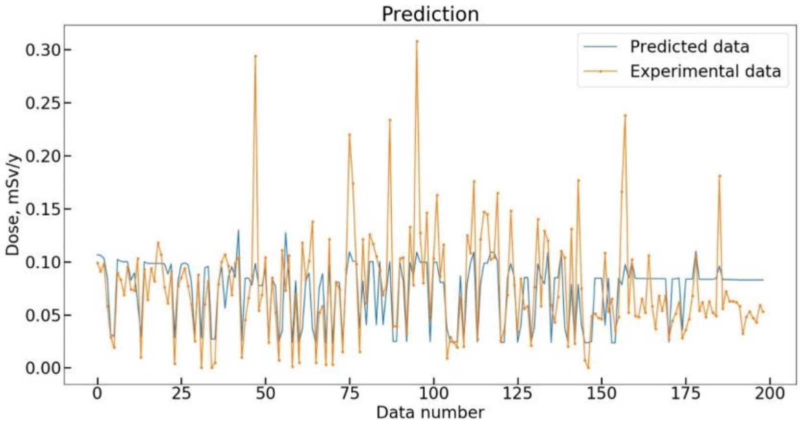

Fig. 4. Comparison of the predicted and real internal exposure dose values.

The ANN has trained better to predict the internal exposure dose for elderly people. This is because the food and behavioral habits of older people are more stable than those of younger people. The prediction accuracy on the test datasets was 89 %. The developed software is unique for the subject domain in question.

4. Conclusions

This means that the inherent socio-economic factors in the Ukrainian Polissya countryside are becoming increasingly important in generating a dose burden for the rural population. It was established that currently rural settlements can be differentiated by dose. This can be explained by the socio-demographic, ecological, and economic factors inherent in each settlement. Using cluster analysis, the settlements were grouped into 5 clusters. The PCA results showed that the most important factors influencing the internal exposure dose were the density of ^{137}Cs surface contamination and the specific forest area for one person. However, the influence of factors varies for different clusters. The mathematical model developed in this paper and software adapted to the subject domain in question provides an opportunity to reduce the time and finances required for the correct assessment of the internal exposure dose of the population. The software allows the user to adjust the ANN parameters and provides a graphical representation of the error values at each stage.

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КОМПЛЕКСНИЙ АНАЛІЗ ТА МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ДОЗИ ВНУТРІШНЬОГО ОПРОМІНЕННЯ СІЛЬСЬКОГО НАСЕЛЕННЯ ПОЛІССЯ УКРАЇНИ

Метою дослідження було визначення соціально-економічних та екологічних чинників, що впливають на формування дози внутрішнього опромінення сільського населення радіоактивно забрудненої території Українського Полісся. Було встановлено найважливіші екологічні та соціально-економічні чинники, що впливають на формування дози внутрішнього опромінення, які було проаналізовано за допомогою кластерного аналізу за методом середнього зв’язку та аналізу основних компонент. На основі результатів аналізу було створено математичну модель та відповідне програмне забезпечення для формування коректної оцінки дози внутрішнього опромінення населення на віддаленому етапі ліквідації наслідків аварії на Чорнобильській АЕС.

Ключові слова: сільське населення Полісся, доза внутрішнього опромінення, ^{137}Cs, соціально-економічні та екологічні чинники, штучна нейронна мережа.

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КОМПЛЕКСНЫЙ АНАЛИЗ И МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ДОЗЫ ВНУТРЕННЕГО ОБЛУЧЕНИЯ СЕЛЬСКОГО НАСЕЛЕНИЯ ПОЛЕСЬЯ УКРАИНЫ

Целью работы было определение социально-экономических и экологических факторов, влияющих на формирование дозы внутреннего облучения сельского населения радиоактивно загрязненной территории Украинского Полесья. Были установлены важнейшие экологические и социально-экономические факторы, влияющие на формирование дозы внутреннего облучения, которые были проанализированы с помощью кластерного анализа по методу средней связи и анализа основных компонент. На основе результатов анализа была создана математическая модель и соответствующее программное обеспечение для формирования корректной оценки дозы внутреннего облучения населения на отдаленном этапе ликвидации последствий аварии на Чернобыльской АЭС.

Ключевые слова: сельское население Полесья, доза внутреннего облучения, ^{137}Cs, социально-экономические и экологические факторы, искусственная нейронная сеть.

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