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FREQUENCY DISTRIBUTIONS OF ^{90}SR AND ^{137}CS CONCENTRATIONS IN AN ECOSYSTEM OF THE 'RED FOREST' AREA IN THE CHERNOBYL EXCLUSION ZONE

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Part of the Savannah River National Laboratory
HPJ Special Issue

October 2011

ABSTRACT

In the most highly contaminated region of the Chernobyl Exclusion Zone: the ‘Red Forest’ site, the accumulation of the major dose-affecting radionuclides (^{90}Sr and ^{137}Cs) within the components of an ecological system encompassing 3,000 m^2 were characterized. The sampled components included soils (top 0-10 cm depth), *Molina caerulea* (blue moor grass), *Camponotus vagus* (carpenter ants) and *Pelobates fuscus* (spade-footed toad). In a comparison among the components of this ecosystem, the ^{90}Sr and ^{137}Cs concentrations measured in 40 separate grids exhibited significant differences, while the frequency distribution of the values were close to a logarithmically normal leptokurtic distribution with a significant right-side skew. While it is important to identify localized areas of high contamination or “hot spots,” including these values in the arithmetic mean may overestimate the exposure risk. In component sample sets that exhibited logarithmically normal distribution, the geometrical mean more accurately characterizes a site. Ideally, risk assessment is most confidently achieved when the arithmetic and geometrical means are most similar, meaning the distribution approaches normal. Through bioaccumulation, the highest concentrations of ^{90}Sr and ^{137}Cs were measured in the blue moor grass and spade-footed toad. These components also possessed distribution parameters that shifted toward a normal distribution.

Key words: Chernobyl, bioaccumulation factor, ^{90}Sr, ^{137}Cs

INTRODUCTION

The catastrophic nuclear accident that occurred at the Chernobyl Nuclear Power Plant (ChNPP) near the town of Pripyat, Ukraine (1986), necessitated the assessment of radiological consequences as well as a characterization of the developing radioecological situation. Correct characterizations of ecosystem parameters always entail significant obstacles. The main obstacle encountered is the extreme heterogeneity of spatial distributions both of the radioactive fallout pattern and of other ecological characteristics (e.g. landscape, soil, vegetation, water regime, microclimate, etc.). Most of the radioactive materials released from the ChNPP are concentrated in the central areas of the Chernobyl Exclusion Zone (ChEZ), as well as along the paths of the radioactive plume and in so called "hot spots" (Shestopalov 1996). Additional challenges are introduced by the heterogeneity in distribution of the physical-chemical forms of the fallout resulting from the dynamic changes that occurred within the destroyed reactor and from the weather conditions during the first few weeks following the ChNPP accident (Kashparov et al. 2003). All these factors impact on the current biological availability of the radionuclides and the prospects of its change in the future (Ivanov and Kashparov 2003). As a result, all researchers encounter the same problem: a large uncertainty in the characterization of the contamination level. This problem is applicable not only to land contamination assessments, but to the assessment of contamination in animals and plants as well. Biota samples taken from relatively small areas are known to have a wide range of concentrations of radionuclides (Beresford et al 2008; Bondarkov et al. 2003; Chesser et al. 2000; Gashchak et al. 2008; Jackson et al. 2005; Jagoe et al. 2002; Mietelski et al. 2010; Oleksyk et al. 2002). In this connection the determination of what measurements exceed critical values and what radionuclide concentration ratios are appropriate in the links of the trophic chain, is not trivial.

A normal distribution of concentration values is implicit in the use of arithmetic group averages as a representative value for the assessment of exposure risk. However, for most cases, the contamination of a sample of some ecosystem's component is usually characterized by a distribution that is closer to a logarithmically normal distribution, a Weibull distribution, or other distributions with a significant skew or excess (Pinder and Smith 1975; Oleksyk et al. 2002). Such a pattern of distribution was found for ^{90}Sr and ^{137}Cs in the bodies of small mammals (Oleksyk et al. 2002; Baryakhtar et al. 2003), small birds (Gashchak et al. 2008), chiropterans (Gashchak et al. 2010), and various species of amphibians in the ChEZ (Jagoe et al. 2002; Gashchak et al. 2009). However, various opinions exist on how the trophic level and relationships of a component in an ecosystem, differentially impacted by its own set of environmental and bioaccumulation characteristics, will affect the distribution of values representing an ecosystem. Reconciling this issue requires the accurate identification of the radionuclide concentrations for each individual species sampled in the given area. This is especially problematic in dominant species that are often small in size. The environmental contamination levels that exist in the ChEZ make it possible to easily assess the ^{90}Sr and ^{137}Cs content of species that may be as small as insects. Therefore, contamination concentrations and the distribution of values within the food network of this biocenosis can be evaluated.

The purpose of this study was to assess characteristics of the frequency distribution of ^{90}Sr and ^{137}Cs concentrations with respect to the trophic links of a system within an ecosystem. The soil – plant – insect – amphibian system in the 'Red Forest' site (one of the most contaminated areas of the ChEZ) was selected for this study.

MATERIALS AND METHODS

Links of the trophic chain were sampled in August of 2003 in the area of the ‘Red Forest’ site located 2.5 km south west of the ChNPP. This particular area has been characterized as having the highest contamination levels found outside the ChNPP Industrial Site (Bondarkov et al. 2003, 2006, 2009).

The following elements of the ecological system were sampled for analysis: soil (0 – 10 cm deep upper layer), blue moor grass (*Molinia caerulea*), carpenter ants (*Camponotus vagus*), and spade-footed toads (*Pelobates fuscus*). All of the selected biotic components have established populations in the ‘Red Forest’ area. In addition, both of the animal species do not migrate far and do not move quickly, therefore, they can be defined as conditionally non-migratory. However, it should be noted that there is no direct trophic connection between the blue moor grass and the carpenter ants. Carpenter ants feed on decaying vegetative organics (frequently on wood pulp), making it difficult to identify their actual specific source of food. This selection of species was due to the absence of other animal and plants species that could have both served as links in one trophic chain while also possessing populations that were present in sufficient quantities to support radiological analysis.

The soil samples were taken from the area of approximately 3,000 m^2, using a 40 point square grid sampling method, at a distance of about 10 m between neighboring points. The upper soil layer core (7cm in diameter and 0 – 10 cm deep) was sampled by a soil sampler, immediately next to the point where the blue moor grass had been sampled. The soil in the experimental area was sod podzol with the upper 0 – 10 cm layer density ranging from 764 to 1,668 kg·m^{-3}, averaging 1,319 ± 36 kg·m^{-3}. For radiological analysis, 10 g of the air dried homogenized soil sample was used.

Vegetative parts of the blue moor grass were sampled at a height of at least 5 cm above the soil layer, with the intention of minimizing the amount of soil particles that might have redeposited on the grass surface due to natural factors. For radiological analysis, 2.2 g of the pretreated air-dried homogenized grass sample material was used.

The amphibians were captured over several days by using a pitfall trap (0.3 m wide, 0.5 m deep and 50 m long). Since animals of different ages may differ regarding radionuclide accumulation and excretion, only the toads similar in age (size) were selected, with an average body mass being 5.0 ± 0.2 g. The radionuclide content was measured in the skinless femur of the spade-footed toads (muscle + femoral bone). The average mass of these samples was 2.19 ± 0.04 g.

The stomach contents of the spade-footed toads were assessed; whereby it was determined that they fed primarily on carpenter ants. The ants were collected manually in the same area as the toads. The carpenter ants' body masses ranged from 0.0098 to 0.0651 g and averaged 0.0251 ± 0.0018 g.

The soil and blue moor grass samples were air dried at +90°C for 24 hours, including homogenization and geometry (volume and density) standardization prior to radiological analysis. The samples of amphibian and ant tissues were exposed to "wet" (acidic) ignition with concentrated HNO_3 and H_2O_2 added. The obtained solution was evaporated to generate wet salts, followed by the addition of 1M HNO_3 to standardize the geometry.

The ^{137}Cs concentrations for the samples were measured by a Canberra-Packard gamma-spectrometer with an high-purity germanium (HPGe) detector (GC 3019). A standard source

(OISN-16; Applied Ecology Laboratory of Environmental Safety Centre, Odessa, Ukraine) was used for calibration of the effectiveness of the spectrometer. The standard source contained epoxy granules (<3.0 mm) with the density of 1 g cm^{-3} with a ^{152}Eu concentration of about 158 kBq kg^{-1} (as of 8 October 2001). The effectiveness of recording the 662 keV gamma lines was 0.0206 pulse·Bq^{-1}·s^{-1}. The minimally detectable activity was 0.18 Bq per sample.

The ^{90}Sr concentrations for the soil and blue moor grass samples were measured spectrometrically without any radiochemical pretreatment. The procedure used a β-spectrometer EXPRESS-01 with a thin-filmed (0.1 mm) plastic scintillator detector that was developed by the Institute of Nuclear Research at the National Academy of Science of the Ukraine. The spectrometer and associated software ("Beta+") had been developed to measure ^{90}Sr content in thick-layered samples with a comparable ^{137}Cs content (^{137}Cs/^{90}Sr ratio not exceeding 30:1) (Bondarkov et al. 2002a 2002b). The obtained experimental spectrum was processed by a correlation with the measured spectra from the standard sources, such as: ^{90}Sr+^{90}Y, ^{137}Cs and the ^{90}Sr + ^{90}Y, and ^{137}Cs combinations as well as from background. To assure validity of the measurements, the equipment was calibrated on a daily basis. A more detailed description of this method can be found in Bondarkov et al. (2002a, 2002b).

The ^{90}Sr concentration in carpenter ants and spade-footed toads were measured using the radiochemical oxalate method with ^{90}Y (Marey et al. 1980). The ^{90}Y chemical yield was, at a minimum, 65%. The samples were measured using a low background proportional gas counter: the FPE 770T6 "EBERLINE." The relative error for measuring ^{90}Sr in the samples varied from 12 to 45%, as influenced by the various levels of activity.

The ^{90}Sr and ^{137}Cs concentration measurements were adjusted to account for the fresh weight of the entire body of the carpenter ants, skinless femur of the spade-footed toads, and air dry mass of the soil and blue moor grass.

RESULTS AND DISCUSSION

Concentrations of ^{137}Cs as measured in ecological components

Results characterized the 'Red Forest' area within the ChEZ as having significant heterogeneous spatial distribution of ^{137}Cs and ^{90}Sr. Of particular importance, the values within a sample set (soil – plant – insect – amphibian) indicate that the spatial distribution of the radioactive fallout is a logarithmically normal distribution with a right side skew. This frequency distribution is most evident in the soil samples. Despite the presence of some extremely high soil ^{137}Cs and ^{90}Sr values (exceeding the average soil contamination values by factors of 4 or 5), 90% of all soil values differ from the average values by factors of only 2 or 3. Values exhibit a decreasing degree of dispersion as sampling progressed from the soil toward the upper level of this trophic chain: the amphibians.

The ^{137}Cs activity values for soil, blue moor grass, carpenter ants, and spade-footed toad are characterized in Table 1. As expected, there is a high range in the ^{137}Cs concentration values for each component of the ecosystem (between 1 – 2 orders of magnitude). The highest coefficient of variation (CV) was found in the soil (212%), while the lowest was found in the blue moor grass (68%). The CV for the ants and toads was 107% and 71%, respectively. The highest ^{137}Cs concentration values were measured in the blue moor grass. On average, the blue moor grass ^{137}Cs concentration was significantly higher than the values measured in the soil where it grew ($p<0.001$). The ^{137}Cs concentration also was higher in the tissues of the toads and ants than in the soil ($p<0.001$). No valid differences were found between the ^{137}Cs concentration of the spade-footed toads and the carpenter ants.

A right-side skew frequency distribution of ^{137}Cs concentration values with a positive excess and asymmetry is typical of the results in this studied ecosystem (Fig. 1). The greatest asymmetry in the values were observed among the soil and carpenter ants samples (Table 1). Conditionally, this distribution can be considered close to a logarithmically normal distribution. However, Oleksyk et al. (2002) found that, under the conditions of the ChEZ, the frequency distribution of concentration values for radionuclides in elements of terrestrial ecosystems can correspond to other types of distribution, such as normal, exponential, Weibull, or even mixed types. The proof of this correspondence requires a much larger sampling size (up to 150 – 1000 samples), which is technically challenging and expensive. Therefore, based on the data from this study, we assume that the distribution of the ^{137}Cs concentration values in the components of the tested ecosystem is a logarithmically normal distribution.

Concentrations of ^{90}Sr as measured in ecological components

The ^{90}Sr concentrations also exhibited a large range of values for each component studied in this ecosystem (Table 2). Again, the highest CV value was measured in the soil (279%), while the lowest was again, the blue moor grass (76%). The CV for carpenter ants and spade-footed toads were 133% and 97% respectively. With consideration to the carpenter ants, the potential feeding base consists of trunks of dead pine and birch trees, as well as the fallen foliage and grass sod that contains dead herbaceous plants. Accounting for the various concentrations of contamination among these food components, large variations in the radionuclide intake for the carpenter ants are to be expected. The highest ^{90}Sr concentrations were measured in the toads while the lowest ^{90}Sr were measured in the soil (the difference among these average values is significant, $p < 0.001$). The average ^{90}Sr concentrations in the carpenter ants and the blue moor grass also exhibited bioaccumulation as they possess values that are also higher than those measured in the soil ($p < 0.05$ and $p < 0.001$, respectively).

Similar to the distribution of ^{137}Cs values within a sample set, in all cases, the frequency distribution of the ^{90}Sr concentration values is conditionally logarithmically normal with a right side skew (Fig. 2). The soils and plants have the highest asymmetry values and the toads have the lowest asymmetry values (Table 2).

Distribution parameters associated with trophic position

In general, we observed a regular decrease of the excess and the asymmetry parameters in the following sequence: soil – plant – animal. These contamination parameters decrease as the links become higher in the trophic chain. This trend is especially strong for ^{90}Sr but less strong for ^{137}Cs.

The maximum values measured for the soil are likely to be associated with the presence of “hot” particles of various activities unevenly distributed in the area and in the volume of the samples. This feature is characteristic for the ‘Red Forest’ site (Bondarkov et al. 2003) and for most of the ChEZ (Kashparov et al. 2003). The lower excess and asymmetry values identified for the plants may result from the fact that the root intake of the radionuclides does not originate from the total radionuclide inventory in the root layer but from an accessible mobile fraction that is more homogenously distributed within the area.

Ants and toads have the same capability of equalizing the flow of radionuclides because they pick up their feed from a larger area. The amphibians were found to have especially low indicators of excess and asymmetry and, in this case, they are the upper trophic link. This is in agreement with earlier studies (Pinder and Smith 1975; Oleksyk et al. 2002) that also found logarithmically normal distribution in ecological components, with asymmetry and excess values that approached one as sampling advanced into the upper trophic levels. This was attributed to the ability of the upper level trophic links to accumulate contaminants from larger areas over longer periods of time, allowing for the integration of the contaminant in the body of the animals.

Elemental behavior of ^{90}Sr and ^{137}Cs within components of the ecosystem

The behavior of ^{90}Sr and ^{137}Cs in an ecosystem also will influence the distribution characteristics of these elements within a sample set. For instance, the ^{90}Sr accumulation and excretion rate in bodies of animals is known to be significantly lower than that of ^{137}Cs. Because the carpenter ants remain geographically connected with their colonies and preferred feeding areas, the high rate of ^{137}Cs metabolism would identify discrete sub-samples that were subjected to “hot spot” exposure in instances of heterogeneous contamination. Conversely, toads do not have such geographical connections, thus they tend to have a more equalized ^{137}Cs intake and accumulation as indicated by lower excess and asymmetry values. Regarding ^{90}Sr concentrations, the distribution of values are similar between carpenter ants and spade-footed toads as ^{90}Sr accumulates and remains with the ant and toads during a much longer period of time. Thus, the concentration of the radionuclides are equalized within the species.

Physiological characteristics of the animals may also affect the radionuclide intake. It is possible that the ^{90}Sr and ^{137}Cs concentrations depended on the mass of the animals as a function of its physiological state. As shown in small birds and rodents, the physiological conditions of animals at a certain state of their life cycle can significantly affect their radionuclide intake (Gashchak et al. 2008; Maklyuk et al. 2007a, 2007b). Despite the extreme live mass values that differed by a factor of 6.6 for the carpenter ants and by a factor of 4.7 for the toads, there was no evidence of this dependence in this study.

Concentration Ratios

This study also made it possible to calculate parameters of the radionuclide transfer from one link of the ecological system to another. Soil samples were taken in close proximity to associated plant samples allowing for the calculation of a concentration ratio. The radionuclide concentration ratio (CR) is a non-dimensional value that represents the accumulated concentrations measured in one component relative to concentrations from another. A value of one indicates equilibrium between species, while values above one suggest the bio-accumulation of a contaminant by a species. Plants accumulated ($\text{mean}_{\text{geom}} \times \text{SD}_{\text{geom}}^{\pm1}$) $9.13 \times 2.62^{\pm1}$ times more ^{137}Cs than was measured in associated soil and $3.28 \times 2.55^{\pm1}$ times more ^{90}Sr. The calculated CR value for the trophic link of toads relative to the ants for ^{90}Sr and ^{137}Cs also possess values that exceed one. The accumulation is much more pronounced in ^{90}Sr for the toads relative to the ants (Table 3).The CR for the carpenter ants also exceed one when compared to the soil. The CR was calculated relative to the soil because the ants did not feed on the studied plant blue moor grass, but on putrescent timber. Therefore, if we exclude the plants data, we observe a rapid increase of the ^{90}Sr concentration and a gradual increase of the ^{137}Cs concentration in the trophic chain.

CONCLUSION

The completed study imparts importance on the characterization of values within sampled components of an ecosystem, including: distribution, symmetry and excess parameters. The use of the arithmetic mean as representative of contamination in an area may not accurately characterize the potential risk of exposure within an area. Sample sets that exhibit logarithmically normal distribution with a significant right-side skew are better represented by the geometric mean value. The concentrations of ^{137}Cs and ^{90}Sr coefficients of variation, asymmetry and excess decreased in blue moor grass samples, relative to soil samples. While concentrations within a sampled species generally increased as trophic levels increased, unique chemical properties of radionuclides also must be taken into consideration when sampling among any one biocenotic group. While neither group is representative of the ecological whole, they are important indicators of the maximal exposure risk.

While it is important to identify areas of high contamination or "hot spots" within any zone, characterization and prediction analysis requires the consideration of the frequency pattern of radionuclide values within a sample set to ensure that assessments are correct. From the results of this study, it is clear that the geometric means as listed in Tables 1 and 2 better characterize the contamination values that are displayed in Fig. 1 and 2. Also, increased concentrations of ^{90}Sr and ^{137}Cs in plants and amphibians corresponded with decreasing differences between arithmetic and geometrical means. Therefore, distribution parameters approached normal as the bioaccumulation processes of flora and fauna were able to equalize the heterogeneity of ^{90}Sr and ^{137}Cs concentrations that were exhibited in the soil.

Acknowledgments - The authors would like to thank Ines Triay, Yvette Collazo, Kurt Gerdes, and Ana Han for their support of the U.S. Department of Energy Office of Environmental Management's International Cooperative Program with IRL. The original idea for this paper belongs to Michael H. Smith and Michelle Wilson (Savannah River Ecological Laboratory). The authors would like to express their appreciation to V.I. Martynenko and A.A. Shulga for performing spectrometric and radiochemical analyses. The authors would also like to express their gratitude to Tatyana Albert (Thomas E. Albert and Associates, Inc.) for translating documents and reports prepared at SRNL and IRL and Valerie Grant and Jennifer Grant for editing this article.

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REFERENCES

Baryakhtar VG, Bondarkov MD, Gaschak SP, Goryanaya JuA, Maximenko AM, Liabik VV, Chesser RK, Baker RG. Problems in small mammals radioecology. Environmental Sciences and Pollution Research. Special Issue No 1. P. 95–106; 2003.

Beresford NA, Gaschak SP, Barnett CL, Howard BJ, Chizhevsky I, Strømann G, Oughton DH, Wright SM, Copplestone D, Maksimenko AM. Estimating the exposure of small mammals at three sites within the Chernobyl exclusion zone – a test application of the ERICA-Tool. Journal of Environmental Radioactivity 99:1496–1502; 2008.

Bondarkov MD, Ivanov YuA, Bondarkov DM, Gaschak SP, Maksimeko AM, Chesser RK, Rodgers B, Zheltonozhskaya M. Half-lives of self-purification for various isotopes in soils of the Chernobyl exclusion zone. Radioprotection, 44 (5): 909-911. – Proceedings of the International congress organized by IRSN: Radioecology and environment radioactivity – ECORAD-2008. 15–20 June, 2008, Bergen, Norway; 2009.

Bondarkov MD, Bondarkov DM, Zheltonozhsky VA, Maksimenko AM, Sadovnikov LV, Strilchuk NV. A method of ^{90}Sr concentration measurement in biological objects and soil samples without radiochemistry. Nuclear Physics and Atomic Energy. 2 (8): 162-167; 2002a. (Russian).

Bondarkov MD, Maximenko AM, Zheltonozhsky VA. Non radiochemical technique for ^{90}Sr measurement // Proc. Vol. 2 of the International Congress 'Ecorad 2001', Aix-en-Provence (France), Radioprotection Colloques. – Vol. 37, C1. – P. 927 – 931; 2002b.

Bondarkov MD, Gaschak SP, Ivanov YuA, Maksimenko AM, Ryabushkin AN, Zheltonozhsky VA, Sadovnikov LV, Chesser RK, Baker RG. Parameters of radiation situation on the territory of the Red Forest site in the Chornobyl exclusion zone as impact factors for wild non-human species. In: Contributed Papers of International Conference on the Protection of the Environment from the Effects of Ionizing Radiation (6-10 October 2003, Stockholm, Sweden). IAEA-CN-109/100. 196–199; 2003.

Bondarkov MD, Zheltonozhska MV, Gaschak SP, Ivanov YuA, Maksimenko AM, Martynenko VI, Rodgers BE, Chesser RK, Bondarkov DM Vertical migration of radioactive nuclides on research sites of Chernobyl zone. Problems of nuclear power plants safety and of Chernobyl. Volume 6. 155–163; 2006. (Russian).

Chesser RK, Derrick W, Sugg, MD, Lomakin, RA, Van Den Bussche J, DeWoody A, Jagoe CH, Cham E, Dallas F, Whicker W, Smith MH, Gaschak SP, Chizhevsky IV, Lyabik VV, Buntova EG, Holloman K, Baker RJ. Concentrations and dose rate estimates of 134Cesium, 137Cesium and 90Strontium in small mammals at Chornobyl // Environmental Toxicology and Chemistry. Vol. 19, No. 2. – PP. 305-312; 2000.

Gaschak SP, Maklyuk YA, Maksimenko AM, Maksimenko VM, Martinenko VI, Chizhevsky IV, Bondarkov MD, Mousseau TA. The features of radioactive contamination of small birds in Chernobyl zone in 2003–2005. Radiation biology. Radioecology. 48 (1): 28–47; 2008. (Russian).

Gashchak SP, Maksimenko AM, Beresford NA, Vlaschenko AS. Strontium-90 and caesium-137 activity concentrations in bats in the Chernobyl exclusion zone. Radiation and Environmental Biophysics. Vol. 49, Issue 4. – PP. 635-644; DOI: 10.1007/s00411-010-0322-0; 2010.

Gashchak SP, Maklyuk YuA, Maksimenko AM, Bondarkov MD. Radioecology of amphibians in Chernobyl zone. Problems of the Chernobyl Exclusion Zone. 9: 76–86; 2009 (Russian).

Ivanov YuA, Kashparov VA. Long-term dynamics of radioecological situation in terrestrial ecosystems on the territory of exclusion zone. Environmental Sciences and Pollution Research. Special Issue No 1. P. 13-20; 2003.

Jackson D, Copplestone D, Stone DM, Smith GM. Terrestrial invertebrate population studies in the Chernobyl exclusion zone, Ukraine. Radioprotection, Suppl. 1, vol. 40, S857–S863; 2005.

Jagoe CH, Majeske AJ, Oleksyk TK, Glenn TC, Smith MH. Radiocesium concentrations and DNA strand breakage in two species of amphibians from the Chornobyl exclusion zone. In: Proceedings Volume 2 of the International Congress “ECORAD 2001”, Aix-en-Provence (France), 3-7 September, 2001. – Radioprotection – Colloques, Vol. 37, C1, PP. 873-878; 2002.

Kashparov VA, Lundin SM, Zvarych SI, Yoshchenko VI, Levchuk SE, Khomutinin YV, Maloshtan IM, Protsak VP. Territory contamination with the radionuclides representing the fuel component of Chernobyl fallout. Sci. Total Environ. 317:105-119; 2003.

Maklyuk YuA, Gashchak SP, Maksimenko AM, Bondarkov MD., Beresford N. Value and structure of dose burdens in small mammals of Chernobyl zone over 19 years after the accident. – Nuclear physics and atomic energy, 3 (21): 81–91; 2007a. (Russian)

Maklyuk YuA., Maksimenko AM, Gashchak SP, Bondarkov MD, Chizhevsky IV Long-term dynamic of radioactive contamination (90Sr, 137Cs) of small mammals in Chernobyl zone. Ecology, 38 (3): 198–206; 2007b (Russian).

Marey AN, Zykova AS eds. Methodological guidance for sanitary control of radioactive substance content in environmental objects. Moscow, Minzdrav 336p. (Russian); 1980.

Mietelski JW, Svetlana Maksimova S, Szwa1ko P, Wnukd K, Zagrodzki P, B1azej S, Gaca P, Tomankiewicz E, Orlov O. Plutonium, ^{137}Cs and ^{90}Sr in selected invertebrates from some areas around Chernobyl nuclear power plant. J. of Environ. Radioact. 101 (6):488-493; 2010.

Oleksyk TK, Gashchak SP, Glenn TC, Jagoe CH, Peles JD, Purdue JR, Tsyusko OV, Zalissky OO, Smith MH. Frequency distributions of ^{137}Cs in fish and mammal populations. J. of Env. Radioact. Vol. 61:55-74; 2002.

Pinder JE III, Smith, MH. Frequency distributions of radiocesium concentrations in soil and biota. In: Mineral Cycling in Southeastern Ecosystems (CONF740513). Howell FG, Smith MH (ed.). Energy Research and Development Agency Symposium Series: 107-121; 1975.

Shestopalov VM. Atlas of Chernobyl exclusion zone. Ukrainian Academy of Science, Kiev, Kartographya. 26p. 1996. (Russian/English).

FIGURES CAPTIONS:

Fig.1. Frequency distribution of ^{137}Cs concentration values in the components of the ecosystem: A) Soil, B) Plants, C) Ants, and D) Amphibians.

Fig.2. Frequency distribution of the ^{90}Sr concentration values in the components of the ecosystem: A) Soil, B) Plants, C) Ants, and D) Amphibians.

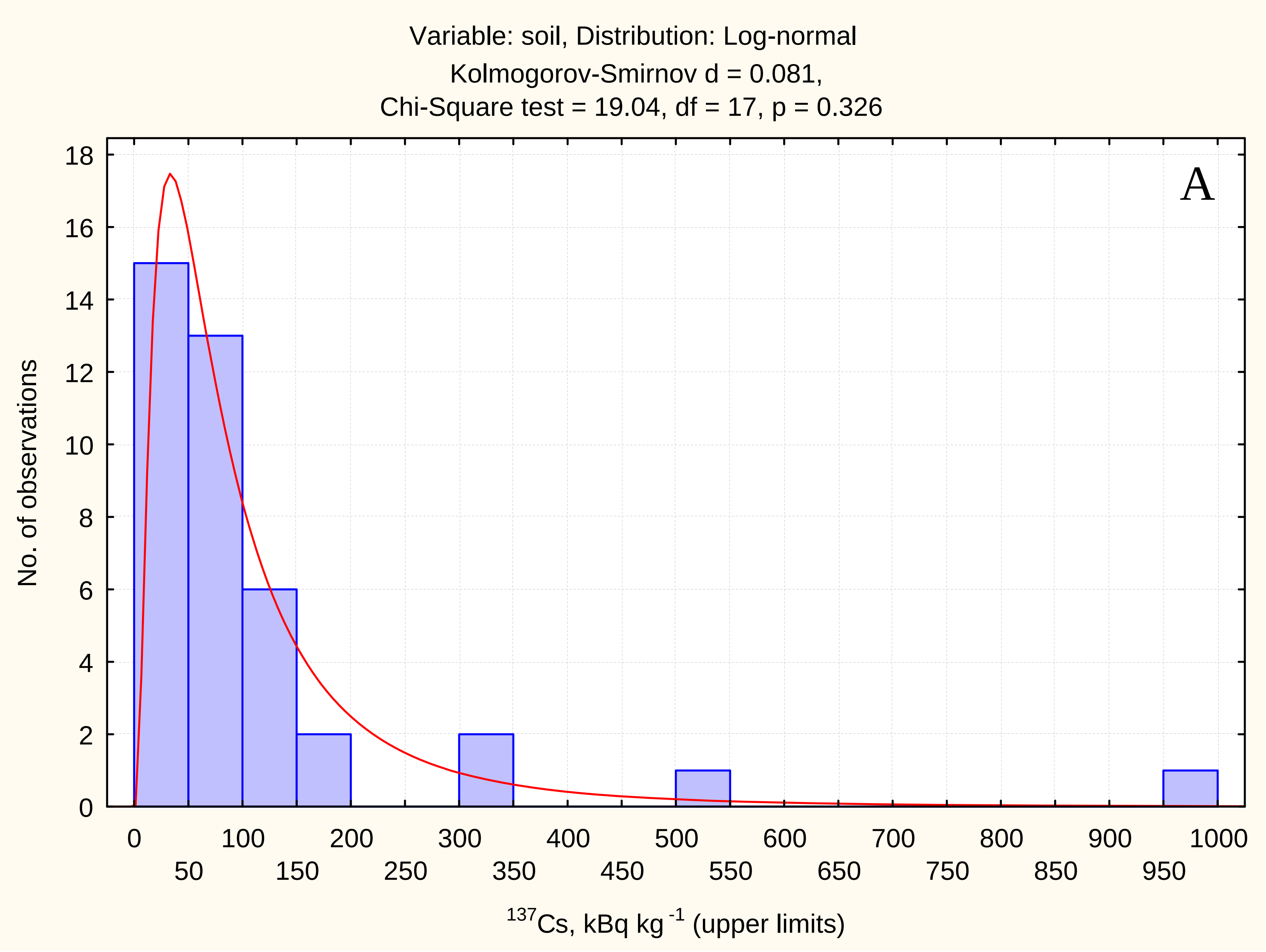

Fig.1. Frequency distribution of ^{137}Cs concentration values in the components of the ecosystem: A) soil.

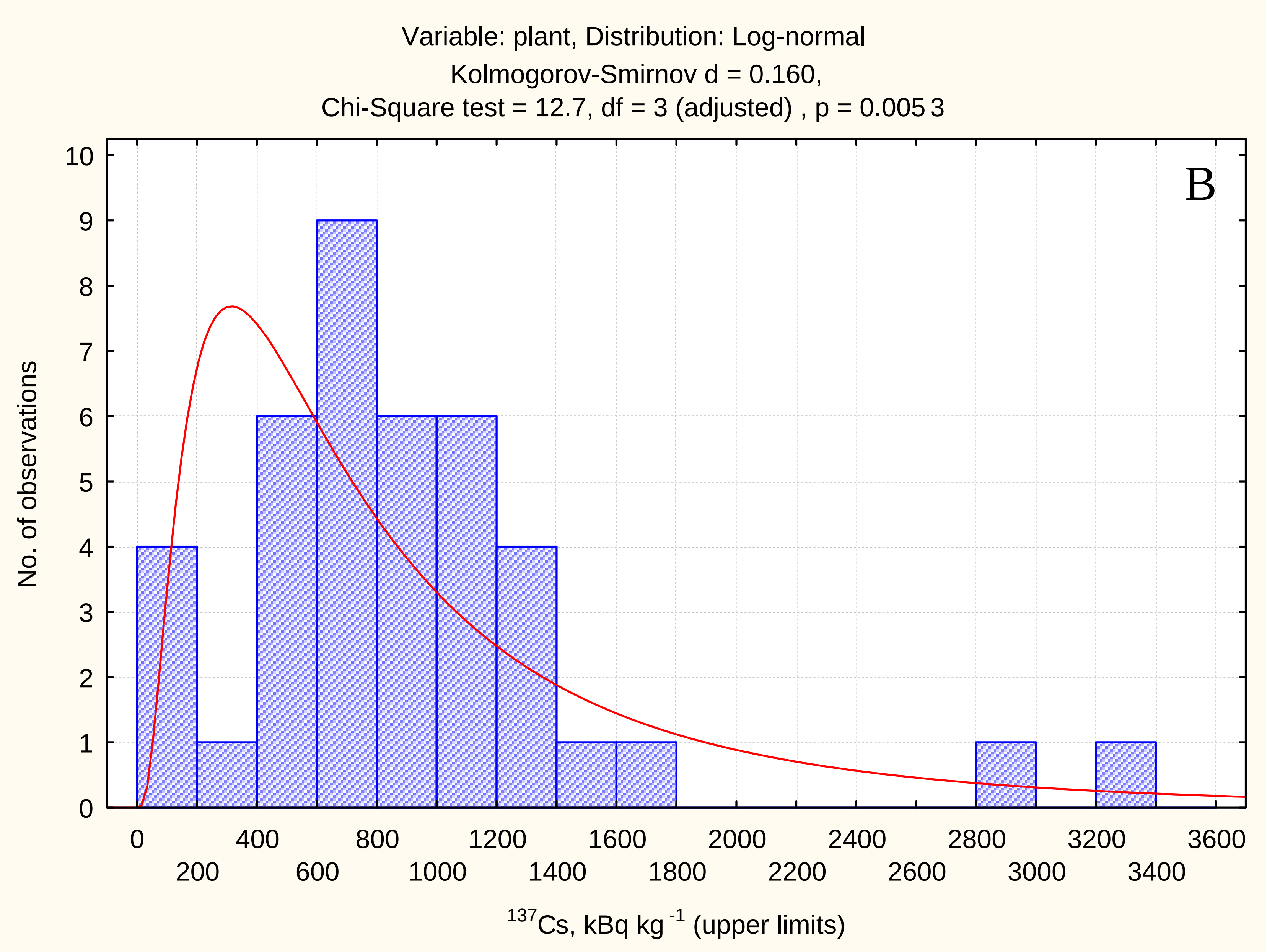

Fig.1. Frequency distribution of ^{137}Cs concentration values in the components of the ecosystem: B) Plants.

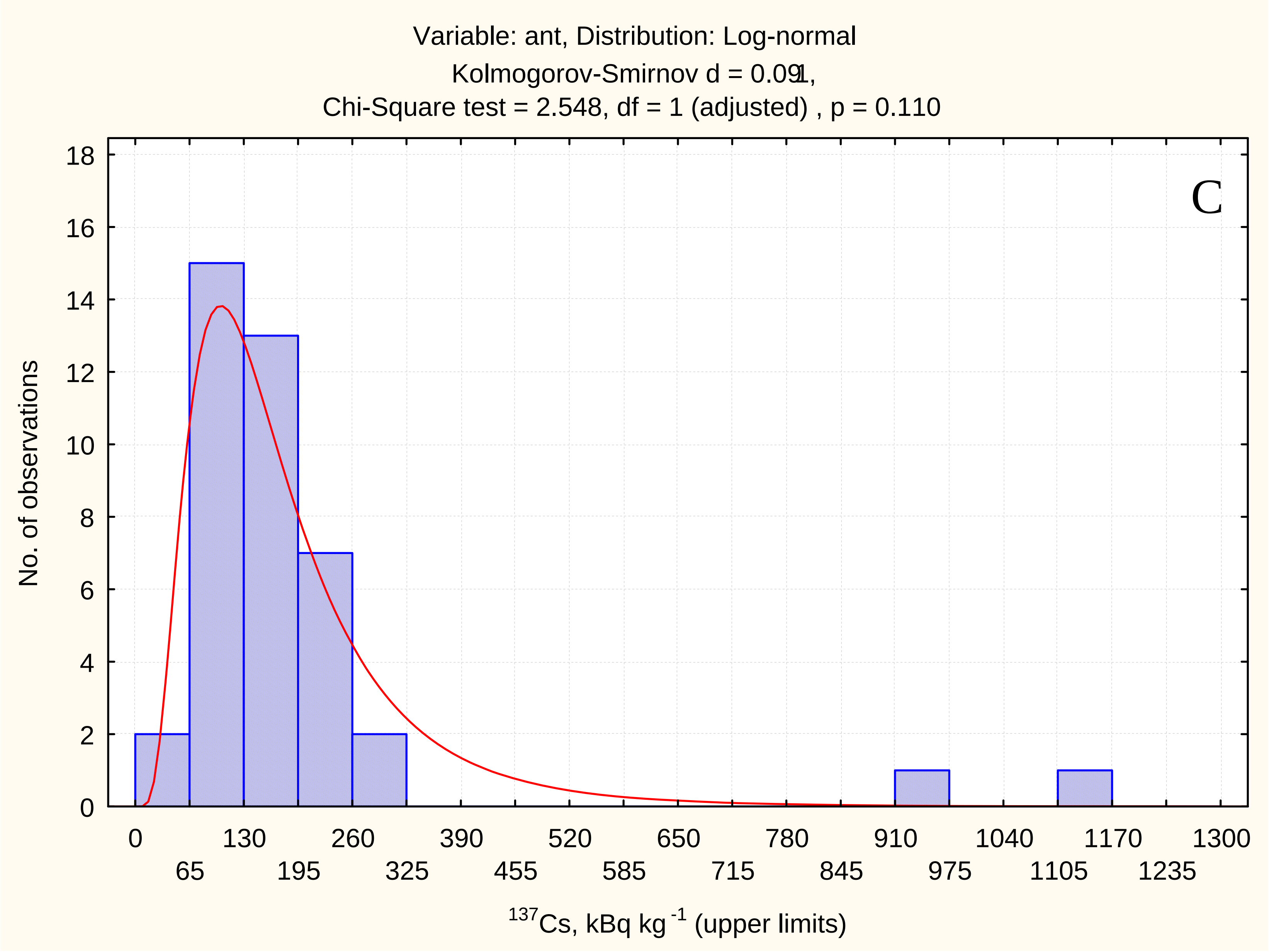

Fig.1. Frequency distribution of ^{137}Cs concentration values in the components of the ecosystem: C) Ants.

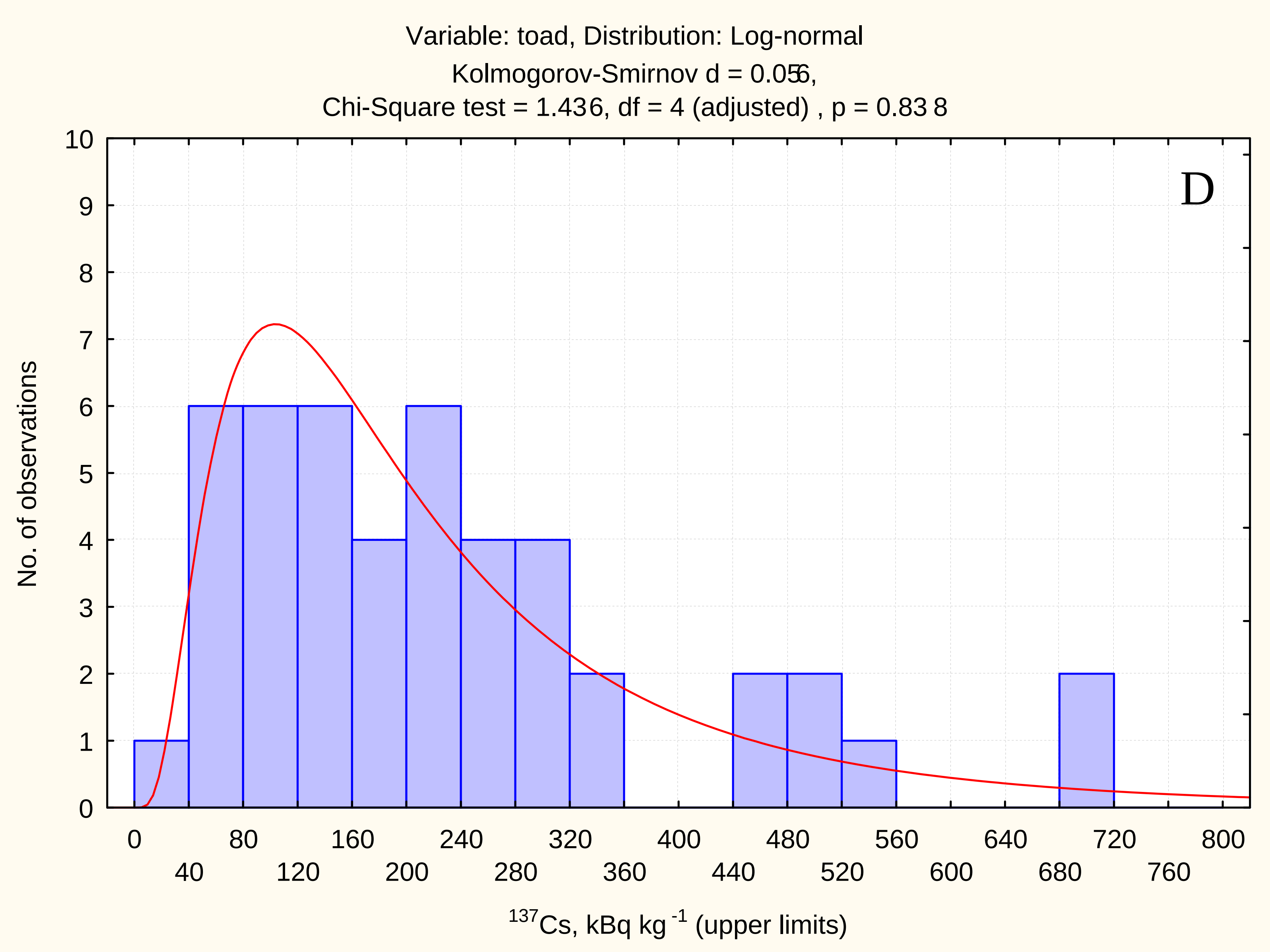

Fig.1. Frequency distribution of ^{137}Cs concentration values in the components of the ecosystem: D) Amphibians.

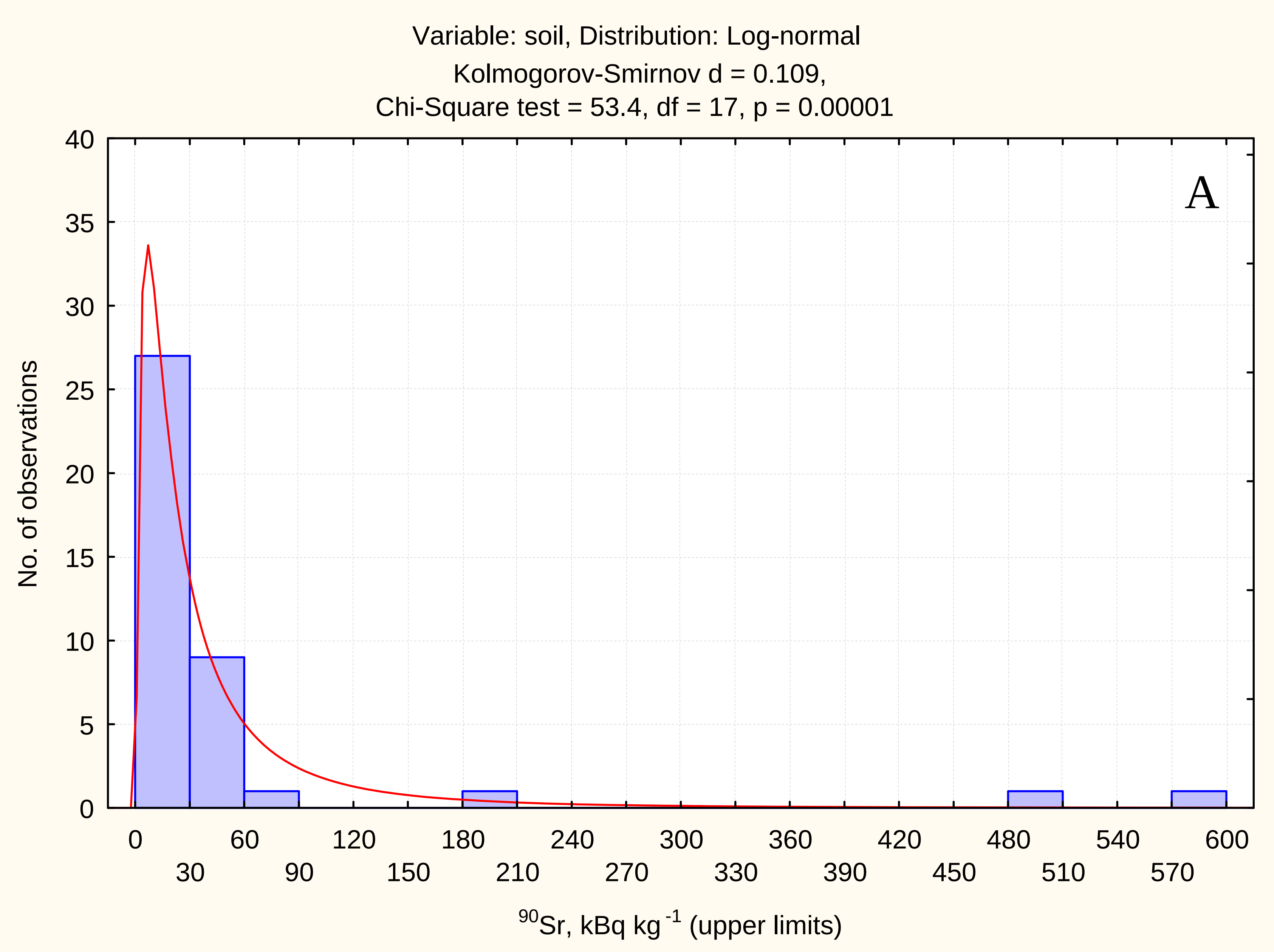

Fig.2. Frequency distribution of the ^{90}Sr concentration values in the components of the ecosystem: A) Soil.

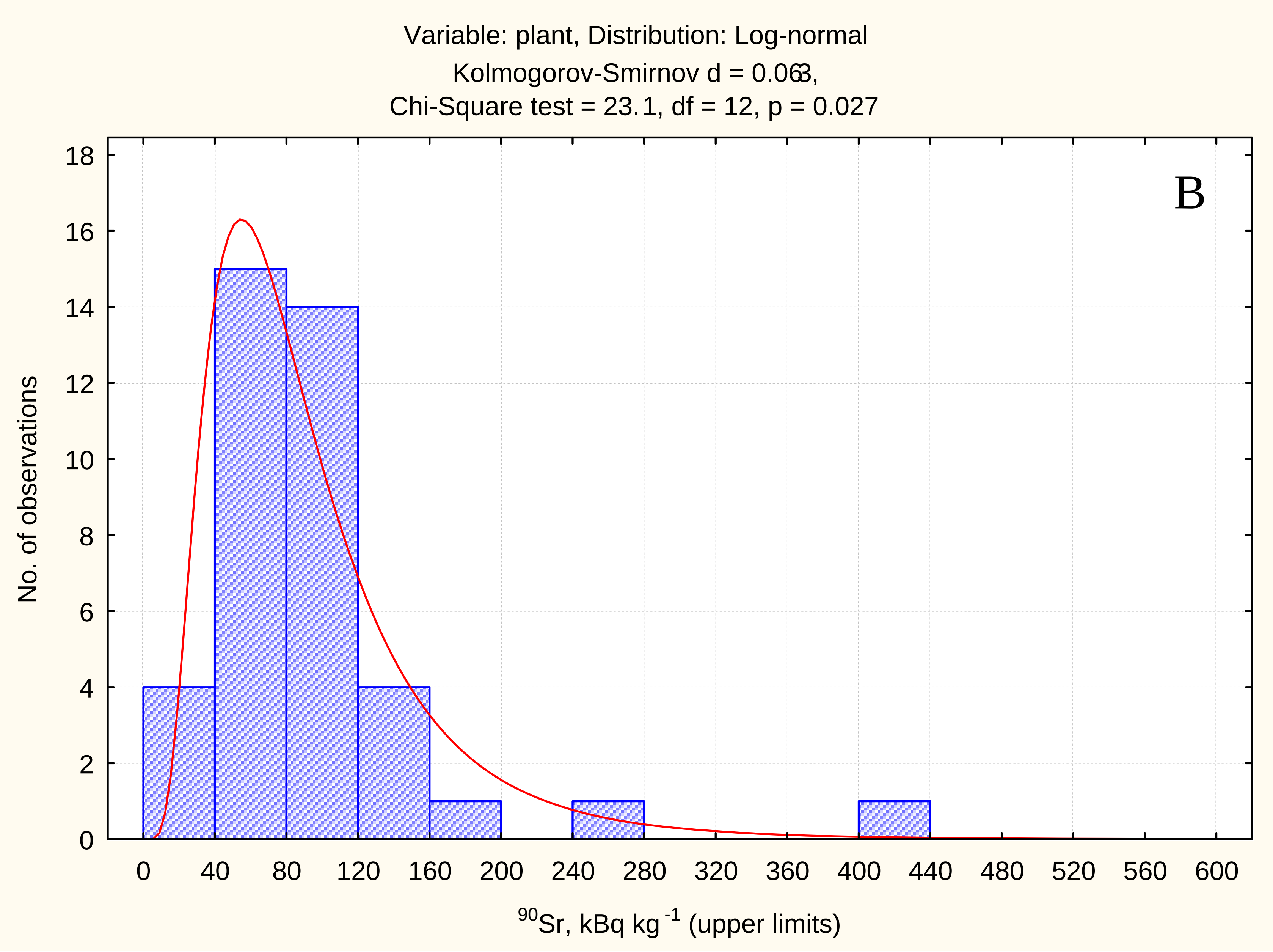

Fig.2. Frequency distribution of the ^{90}Sr concentration values in the components of the ecosystem: B) Plants.

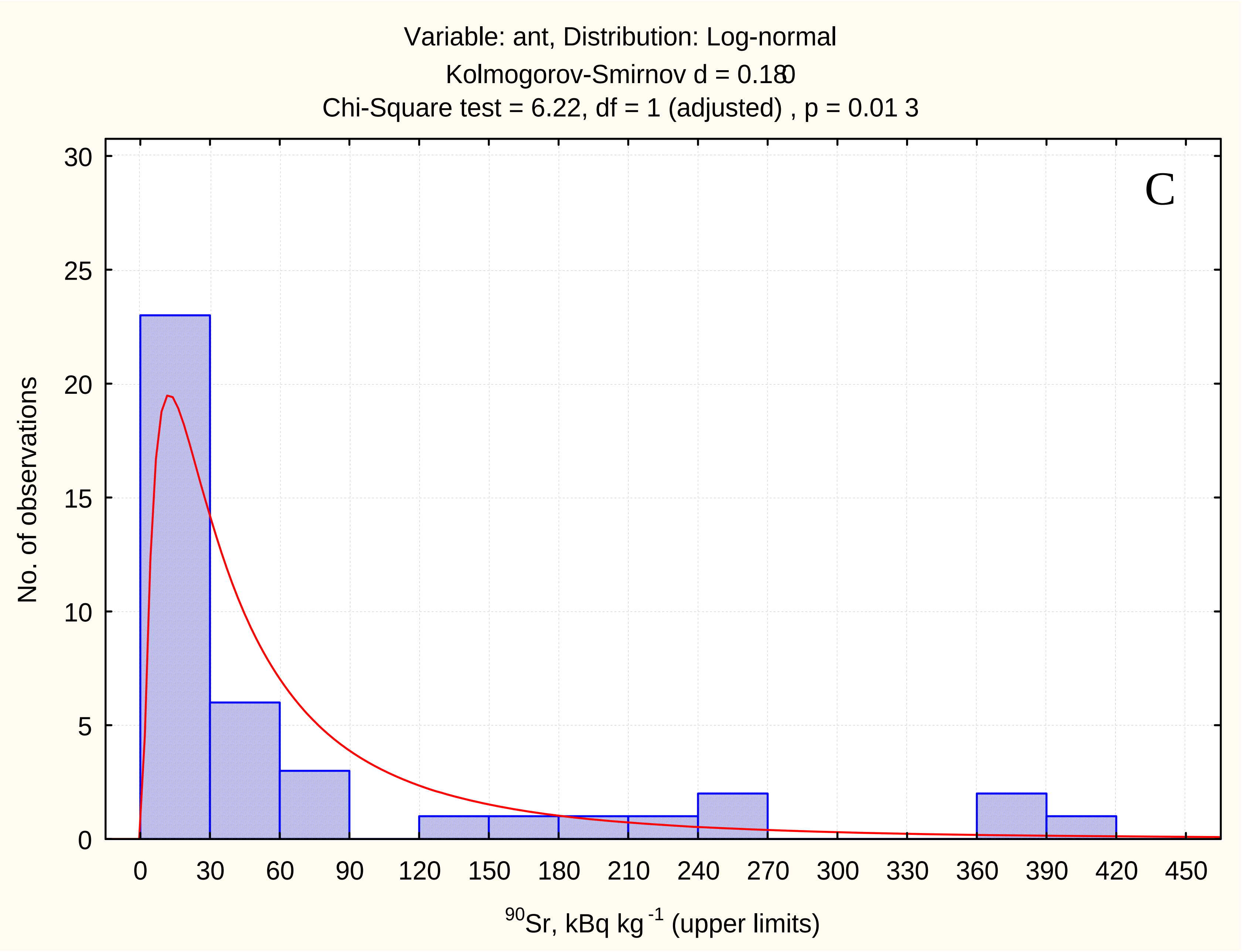

Fig.2. Frequency distribution of the ^{90}Sr concentration values in the components of the ecosystem: C) Ants.

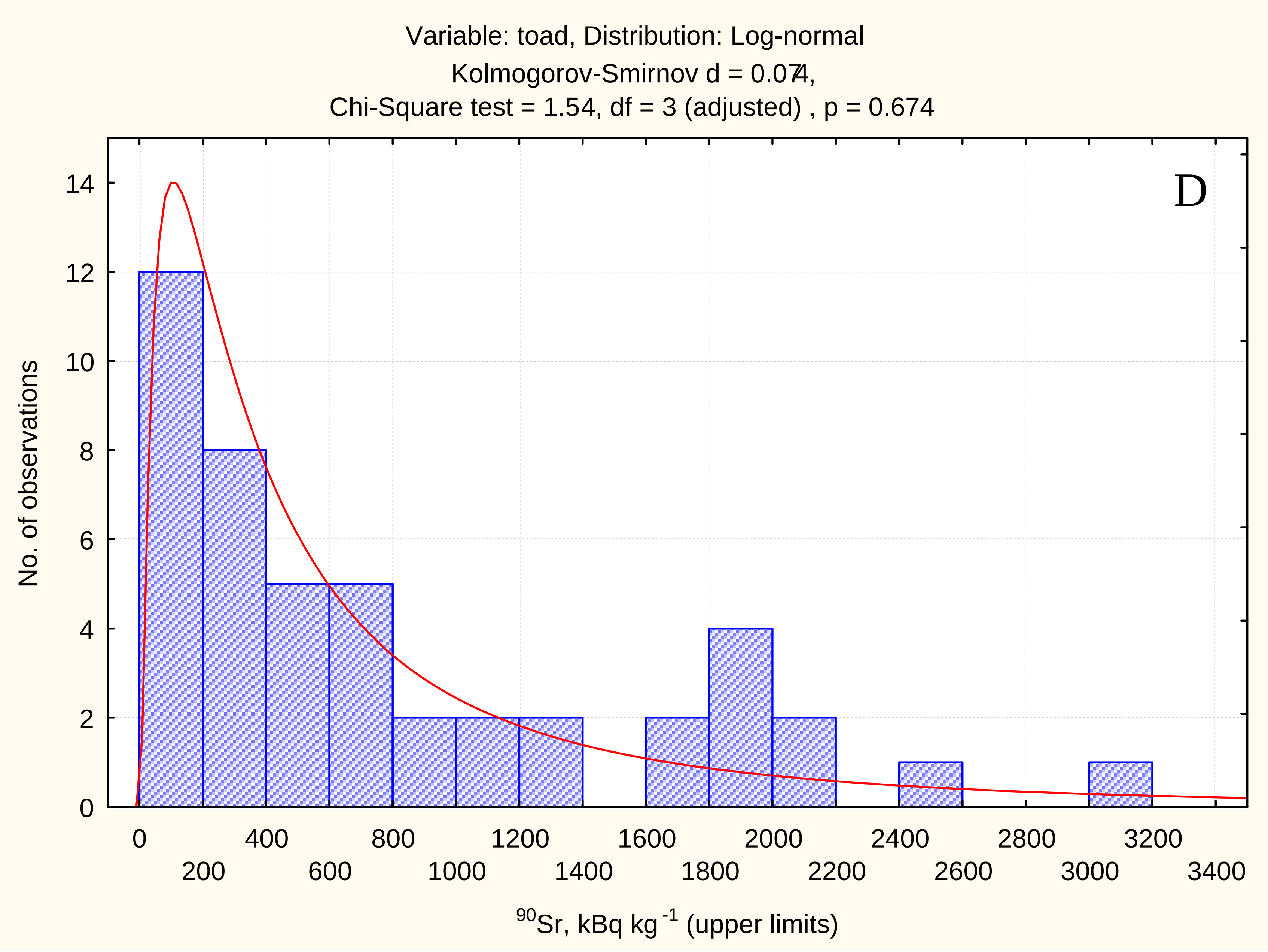

Fig.2. Frequency distribution of the ^{90}Sr concentration values in the components of the ecosystem: D) Amphibians.

Table 1. ^{137}Cs Specific Activity in Components of the Red Forest Ecosystem, kBq kg^{-1}.

Parameter	Soil	Blue moor grass	Carpenter ant	Spade-footed toad
Arithmetic mean	141	903	193	231
Median value	60.4	790	143	192
Standard deviation	299	616	206	164
Geometrical mean	76.0	694	150	180
Standard geo. deviation	2.5	2.4	1.9	2.1
Excess	31.0	5.8	15.3	1.5
Asymmetry	5.4	2.0	3.8	1.3
Range of values	15.9– 880	21.2–3200	43.5–1140	36.4–718
Quartiles (25–75%)	38.9–123	586–1097	103–204	113–291
Percentiles (10–90%)	32.6–240	286–1450	73.7–244	52.1–487
Sampling size	40	40	41	46

Table 2. ^{90}Sr specific activity in the components of the Red Forest ecosystem, kBq kg^{-1}.

Parameter	**Soil**	**Blue moor grass**	**Carpenter ant**	**Spade-footed toad**
Arithmetical mean	67.8	94.5	81.0	796
Median value	22.5	87.4	28.5	507
Standard deviation	189	71.3	108	772
Geometrical mean	23.8	78.3	41.9	448
Standard geo. deviation	3.1	1.8	3.0	3.3
Excess	26.6	12.9	2.5	0.5
Asymmetry	5.0	3.1	1.9	1.1
Range of values	4.9–1120	23.1–432	4.1–392	49.9–3090
Quartiles (25–75%)	10.3–36.7	50.8–107	22.6–73.1	176.5–1340
Percentiles (10–90%)	6.7–72.3	39.0–150	16.3–256	76.7–1890
Sampling size	40	40	41	46

Table 3. Radionuclides concentration ratios in links of the trophic chain calculated using geometric mean values. (non-dimensional ratio values).

Radionuclide	**Soil – plant***	**Soil – carpenter ant**	**Soil – spade-footed toad**	**Carpenter ant - spade-footed toad**[a]
^{90}Sr	3.28	1.76	18.77	10.69
^{137}Cs	9.13	1.98	2.37	1.20

[a] Calculated for sequential links of the trophic chain