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Trophic Specificity of the *Rana arvalis* Population from the Eastern Ural Radioactive Trace in Relation to the State of the Soil Mesofauna

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Abstract—Studies on the population of *Rana arvalis* Nilss. frogs performed in the radioactively contaminated area near Lake Berdanish in 1993 revealed a number of features indicating that the contents of nutrients in the organisms of adults and juveniles is low. The analysis of simultaneously collected data on food supply to this population showed that the structure of food chains in the study area is simplified and the diversity and biomass of soil invertebrates (the main food for amphibians) are sharply reduced. These factors account for food deficiency, which manifests itself in a low level of stomach filling and individual energy reserves of the frogs and is reflected in their population characteristics.

Key words: amphibians, moor frog, trophic relations, soil mesofauna, radionuclides.

INTRODUCTION

The specific role of amphibians in biocenoses is determined by the fact that they are the link connecting the terrestrial and freshwater food chains, thus playing an important role in the transfer of matter and energy between ecosystems with different biological cycles. According to the characteristic features of individual development, they are initially the consumers of the first order that subsequently become predators (Garanin, 1981). In various terrestrial communities, annual consumption of invertebrates by amphibians ranges within 2–5% of total production, i.e., is comparable to or greater than that by birds (Gil'manov, 1987). Compared to birds and mammals, amphibians have a low metabolic level and, hence, require ten times smaller amounts of food for producing the same biomass (Seale, 1982). The ecological efficiency of poikilothermal vertebrates is estimated as approximately 10%, compared to 2% in homoiothermal animals (May, 1983). Simplification and changes in the structure of biocenoses and particular food chains result in an increasing role of animals as destructors of organic matter (Shvarts, 1976). In natural ecosystems, amphibians consume 0.03–0.06% of the primary production; in anthropogenic complexes, where the primary production is low, they consume approximately 0.1% (Leont'eva, 1990). At each stage of their life cycle, amphibians can be used as model objects for assessing the state of natural environment. The same is true of the soil invertebrate fauna. Therefore, the analysis of trophic relationships between these biocenotically important groups under conditions of heavy contamination with radionuclides appears to be of considerable interest.

MATERIALS AND METHODS

We studied the population of *Rana arvalis* Nilss. frogs inhabiting the southwestern shore of Lake Berdanish in an area of the radioactive trace with a contamination density (by ^{90}Sr) of 1000–500 Ci/km^2 (Southern Ural Nature Reserve near the Research Station of the Mayak Production Association, Chelyabinsk oblast). A population of the same species inhabiting a relatively clean area near the Dolgobrodskoe Reservoir (90 km west of the reserve) was used as a control. A total of 114 juveniles and 23 adults were captured. The latter were subsequently analyzed for the contents of the gastrointestinal tract. During the period of field studies, we examined the state of the soil mesofauna. Attention was given to changes in the composition, abundance, and biomass of soil invertebrates caused by strong radioactive contamination in the Southern Ural. Material was collected by the standard method of soil excavations (Gilyarov, 1976) in the spring and summer of 1993. Animals were fixed in 70% alcohol. To determine biomass, animals were weighed on a WT-250 torsion scale.

RESULTS AND DISCUSSION

Morphophysiological State of Rana arvalis Population

The previous studies considered morphological, morphophysiological (Pyastolova *et al.*, 1996), physiological (Vershinin and Tereshin, 1996), cytogenetic, and histological (Pyastolova and Vershinin, 1999) parameters of juvenile and adult frogs from the aforementioned samples examined with the use of conventional zoological, histological, and biophysical tech-

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Table 1. Morphophysiological parameters of adult *Rana arvalis* frogs

Population, sample (*n*)	Body weight, g	Body length, mm	Index, ‰				
			liver	heart	spleen	intestine	kidney
Lake Berdanish (10)	4.838 ± 0.72	38.27 ± 1.84	36.5 ± 1.93	3.49 ± 0.28	1.35 ± 0.24	188.36 ± 12.05	3.85 ± 0.38
Dolgobrodskoe Reservoir (11)	13.92 ± 1.43	52.9 ± 1.9	39.07 ± 3.1	3.55 ± 0.16	3.05 ± 0.61	174.2 ± 9.75	3.39 ± 0.22

Table 2. Mean diameters of *Rana arvalis* eggs in water bodies of contaminated and control areas (numerator is egg diameter, mm, and denominator is number of eggs measured)

Habitat	Stage of egg development		
	11–12	13	16–17
Lake Berdanish	1.68 ± 0.025 / 20	No data	1.799 ± 0.017 / 100
Dolgobrodskoe Reservoir	1.71 ± 0.018 / 60	1.82 ± 0.014 / 60	1.85 ± 0.016 / 60

niques. A number of differences in the population and physiological parameters of *R. arvalis* revealed in these studies indicated that animals from contaminated sites were characterized by substantially lower energy reserves and metabolic level.

Mature frogs (spawners) from the contaminated zone differed significantly from the control frogs in body weight, length (38.27 ± 1.84 and 52.9 ± 1.9 mm, respectively), and the spleen index (1.35 ± 0.24‰ and 3.05 ± 0.61‰, respectively). A decrease in relative spleen weight (Table 1) probably reflected the suppression of hemopoietic and metabolic functions in animals from the contaminated zone (Pyastolova *et al.*, 1996). Regression coefficients for the dependence of heart, liver, kidney, and spleen weights on body length in adult frogs from the contaminated area distinctly differed from those in the control, indicating changes in the level of metabolic processes and in hemopoietic organs of these frogs (Pyastolova *et al.*, 1996).

At approximately the same relative liver weights, adult and juvenile amphibians from Lake Berdanish differed from the control frogs in having smaller hepatocytes and a lower cytoplasm-to-nucleus ratio (Pyastolova *et al.*, 1996). This provided evidence for a relatively small energy reserve in frogs from the area contaminated by radionuclides.

It appears that the small size of spawners is largely associated with a decrease in the life span of animals forming the reproductive core of the population, as is usually observed in contaminated regions (Ushakov *et al.*, 1982; Pyastolova and Vershinin, 1999). The ratios of body weight to length showed that the nutritional state of frogs from the contaminated zone is inferior to that of control frogs (123.13 ± 11.8 and 256.6 ± 20.4, respectively). This is attributable to a low metabolic level, higher energy expenditures for adaptation to altered environmental conditions, and the reduced number of food objects (insects and some other invertebrates) in the region contaminated by radionuclides.

In the population inhabiting the contaminated area (Table 2), the egg diameter was smaller than in the control population: 1.799 ± 0.017 mm (n = 100) vs. 1.85 ± 0.016 mm (n = 60) (Pyastolova *et al.*, 1996). Similar data were obtained in studies on the *R. arvalis* populations from the region of the Chernobyl Nuclear Power Plant (Cherdantsev *et al.*, 1993). The proportion of clutches containing small embryos also increased. A similar situation was previously recorded in *R. arvalis* populations from urbanized regions (Vershinin and Gatiyatullina, 1994). As egg size is determined by the conditions of vitellogenesis, its final value may eventually depend on feeding conditions and activity of the female; the same concerns the degree of oocyte atresia and, consequently, individual fecundity (Jorgensen, 1982). In the case of retarded development caused by unfavorable environmental factors (temperature fall, starvation, etc.), the ratio between energy expenditures for growth and reproduction can change, and, as a result, egg number and size can change as well.

In *R. arvalis* frogs from the contaminated area of the Eastern Ural Radioactive Trace, oxygen consumption proved to be significantly lower than in frogs of the control population (Vershinin and Tereshin, 1996). In our opinion, this fact is evidence for the actual decrease of metabolic rate in frogs of the former population.

The inhibition of metabolic processes under conditions of radioactive contamination, manifested in a sharp decrease of oxygen consumption, was previously revealed in mammals (Testov, 1993) as well as in amphibians (*R. arvalis*) (Vershinin and Tereshin, 1996).

Differences in energy resources and expenditures, metabolic level, and the age and size structure of

Table 3. Specific biomass and population density of the main groups of the soil mesofauna

Taxon;	Lake Berdanish		Dolgobrodskoe Reservoir	
	specific biomass, mg/m^2	population density, ind./m^2	specific biomass, mg/m^2	population density, ind./m^2
Enchytraeidae			23.7	9.6
Lumbricidae	1621.3	46.4	5136.5	112.0
Chylopodidae			91.8	22.4
Hemiptera			16.0	3.2
Carabidae	145.0	3.2	180.8	12.8
Staphylinidae	6.1	3.2	85.8	16.0
Elateridae			216.0	32.0
Curculionidae			313.3	28.8
Byrrhidae			64.0	3.2
Rhagionidae	15.4	3.2	12.8	3.2
Dolichopodidae			5.1	3.2
Empididae			11.8	6.4
Asilidae	18.9	3.2	38.1	6.4
Tipulidae	348.5	3.2		
Pamphilidae	101.1	3.2	64.0	3.2
Aranea	132.5	3.2	142.2	6.4
Total	2388.8	68.8	6401.9	268.8

R. arvalis population in the region contaminated by radionuclides provided a stimulus to the analysis of trophic relationships of these frogs.

Basic Characteristics of the Soil Mesofauna

Data characterizing the structure of the soil mesofauna at two study sites are shown in Table 3. We recorded 17 invertebrate families belonging to eight orders. The abundance and biomass of the mesofauna in the contaminated area were 3.9 and 2.6 times as low as in the control, respectively. Some animal groups strongly decreased in number or even disappeared, e.g., the Enchytraeidae (small earthworms playing an important role in organic debris decomposition and soil formation). The number and biomass of Lumbricidae earthworms in the region of Lake Berdanish were also reduced substantially. These earthworms play an essential role in soil formation: loosening the soil, they promote its aeration and moistening, and mucus secreted by them aids in preventing the soil from erosion by wind and water. Their disappearance or decreasing population density are evidence for adverse changes in the ecosystem, which are sometimes irreversible. In the contaminated area, the abundance and biomass of earthworms were only 41 and 32% of those in the control, respectively. Differences were also revealed in their species composition: of four species recorded in the control [*Aporectodea caliginosa* (Sav.), *Octolasium lacteum* (Derley), *Eisenia nordenskioldi* (Eisein), and *Dendrobaena octaedra* (Sav.)], only two were found near Lake Berdanish. These were *D. octaedra,* a typical litter species, and *E. nordenskioldi*, a species inhabiting both litter and soil. Their presence in the most contaminated area and the ability to restore their population are probably attributable to ecogenetic factors, i.e., specific features of their ecological niche, the size and structure of the genome, and differences in radiosensitivity of cocoons and adult worms (Viktorov, 1993). These data agree well with the results of studies on the soil mesofauna performed by Krivolutskii in this region between 1987 and 1989, i.e., 30 years after the nuclear accident. According to this author, permanent disturbances in the soil fauna are explained by its continuous exposure to the direct action of ionizing radiation (Krivolutskii, 1994).

Myriapods (Lithobiidae and Geophilidae), which accounted for approximately 9% of the soil fauna in the control, were not recorded in the contaminated area. As these myriapods are characterized by food preference for lumbricids and enchytraeids, the absence of the latter leads to the reduction of food supply to myriapods and, hence, the decrease of their abundance. In addition, because of certain genetic features (amphimictic reproduction), the myriapod populations cannot recover as rapidly as those of parthenogenetic lumbricids, such as *D. octaedra*: populations of the latter can originate from only one individual, whereas reproduction in geophilids cannot occur without mating, and the probability of finding a partner under conditions of population decline is low (Viktorov, 1993).

Table 4. Specific biomass of the main trophic groups of the soil mesofauna

Group	Lake Berdanish		Dolgobrodskoe Reservoir		Proportion of control, %
	g/m^2	%	g/m^2	%	
Saprophages	1621.3	67.8	5241.1	81.9	30.9
Phytophages	449.6	18.8	609.3	9.5	73.8
Predators	317.9	13.3	551.5	8.6	57.6

Table 5. Food spectrum of adult *Rana arvalis* frogs and frequencies of food objects in their stomachs

Group	Lake Berdanish				Dolgobrodskoe Reservoir			
	N_s	%	N_{iv}	%	N_s	%	N_{iv}	%
Oligocheta		0		0	2	18.18	3	2.041
Aranei	3	27.27	3	16.67	6	54.55	8	5.44
Homoptera	1	9.09	1	5.56	4	36.36	7	4.76
Hemiptera	2	18.18	2	11.11	3	27.27	6	4.08
Carabidae	4	36.36	5	27.78	10	90.91	37	25.17
Histeridae		0		0	2	18.18	4	2.72
Nitidulidae		0		0	2	18.18	2	1.36
Cerambycidae		0		0	1	9.09	1	0.68
Coccinellidae		0		0	1	9.09	1	0.68
Alleculidae		0		0	1	9.09	1	0.68
Curculionidae		0		0	8	72.73	16	10.88
Chrysomelidae		0		0	4	36.36	5	3.40
Staphylinidae	2	18.18	2	11.11	2	18.18	2	1.36
Hymenoptera	1	9.09	1	5.56	4	36.36	6	4.08
Diptera	4	36.36	4	22.22	11	100	48	32.65
Total	11		18		11		147	

Note: (N_s) number of stomachs, (N_{iv}) number of invertebrates.

Representatives of 12 insect families found in the two biotopes included mainly larval beetles and dipterans developing in the soil. In the control sample, larval click beetles (Elateridae), weevils (Curculionidae), and predatory beetles (Staphylinidae) were more numerous. In the region of Lake Berdanish, beetles were represented only by larval ground (Carabidae) and predatory beetles. Out of 17 families collected in this study, only eight occurred in the contaminated area. Moreover, they penetrated the soil to a depth of only 5–6 cm, whereas most animals in the control area occupied the upper 20-cm soil layer.

The communities of soil invertebrates in the contaminated and control areas sharply differed in their trophic structure (Table 4). In the region of Lake Berdanish, the biomass of saprophages was only 30.9% of that in the control. This is attributable to a relatively low mobility of saprophages living under conditions of enhanced background radiation (Krivolutskii, 1983). The biomass of other trophic groups of soil invertebrates in the contaminated area was also substantially lower, reaching 57.6% of the control value in predators and 73.8% in phytophagous organisms. Such changes in the ratio of trophic groups obviously affect the processes of decomposition in ecosystems of the contaminated region.

Apparently, the functions of saprophages in the contaminated ecosystems are mainly performed by the soil microfauna, i.e., by springtails and mites (Krivolutskii *et al.*, 1993). A decrease in the proportion of saprophages and an increase in the proportion of phytophagous organisms in the contaminated area are evidence for the simplified structure of trophic relationships in the biocenosis and, consequently, more intensive matter and energy turnover in the disturbed ecosystems.

Thus, the soil mesofauna of the contaminated area is in a poor state, as follows from a sharp decrease in animal density and biomass, the loss of some species, simplification of ecosystems, and changes in the trophic structure. Soil biogeocenoses of this zone underwent a strong structural and functional transformation.

The Analysis of Contents of the Gastrointestinal Tract

Adult *R. arvalis* frogs captured in the contaminated and control areas sharply differed from each other in the degree of stomach filling, which was noticeable even during visual examination. The mean numbers of food objects per stomach in these samples differed by a factor of 8.14.

The lists of invertebrate groups found in the stomachs of frogs from compared populations were fairly similar, coinciding by 93.9% (Table 5), but the mean number of objects per stomach in frogs from the contaminated site (1.63) was almost ten times lower than in the control (13.36). The overlap of food spectra was estimated on the basis of modified Morisita index (Hurlbert, 1978).

The spectrum of animals found in the gastrointestinal tract of frogs and the spectrum of invertebrates in the local faunas overlapped by 18.3% in the region of Lake Berdanish and by 60.9% near the Dolgobrodskoe Reservoir. This difference is probably associated with size- and age-related differences between the local frog populations. The lists of soil mesofaunas of the contaminated and control areas overlapped by 81.2%; however, as mentioned above, animal abundance, biomass, and the number of families in the contaminated site were substantially lower. The overlap with respect to the ratios between biomasses of different invertebrate groups was only 0.0695%, which is explained by the absence of several taxonomic groups (enchytraeids, millipeds, and hemipterans), a substantial decrease in the biomass of earthworms, and an increase in the proportion of arachnids in the mesofauna of the contaminated area. Hence, potential prey for frogs of this population is scarce, and they have to expend substantially greater amount of energy than "normal" frogs for filling the stomach even by 10%. This factor contributes to the formation of specific features associated with a limited energy supply.

Consequently, amphibians inhabiting the radionuclide-contaminated area live under conditions characterized by the altered structure of trophic relationships, reduced food supply, and increased energy expenditures. These factors affect general stability of such populations and make them more vulnerable to the natural environmental factors.

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