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Review

Ionizing radiation effects on soil biota: Application of lessons learned from Chernobyl accident for radioecological monitoring

Andrei S. Zaitsev[a,b,*], Konstantin B. Gongalsky[a], Taizo Nakamori[c], Nobuhiro Kaneko[c]

[a] A.N. Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, Leninsky pr. 33, 119071 Moscow, Russia
[b] Institute of Animal Ecology, Justus-Liebig-University Giessen, Heinrich-Buff-Ring 26, 35392 Giessen, Germany
[c] Soil Ecology Research Group, Faculty of Environment and Information Sciences, Yokohama National University, 79-7 Tokiwadai, Hodogaya, Yokohama 240-8501, Japan

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A B S T R A C T

Russia, Ukraine, Belarus, Kazakhstan and some other neighboring countries bear the heritage of several Soviet era nuclear disasters and the resulting severe radioactive pollution of vast territories. The most famous of them is the Chernobyl catastrophe on April 26, 1986 which resulted in a massive radioisotope fallout (0.185 MBq m^{-2} or higher) over about 25,000 km^2 of the territory of the former USSR alone. Extensive radioecological research around Chernobyl demonstrated that despite high resistance of most of soil-dwelling organisms to ionizing radiation, some soil animals were very vulnerable to radioactive pollution due to low motility, direct contact with hot particles and radioisotope accumulation in soil. These are the reasons that soil organisms are very important organisms for long-term radioecological observations. In this review, we analyze published data on the response of different soil taxa to radioisotope contamination of soil near Chernobyl and other nuclear accident locations. Field results are compared with the available experimental data. Earthworms, millipedes, collembolans and oribatid mites were recognized as the most appropriate biomonitors of different radioactivity levels and types of radioactive pollution. Synthesis of this knowledge allowed us to propose a multilevel system of soil radioecological monitoring, which may be useful for studying the short- and long-term environmental consequences of the recent catastrophe at Fukushima-1 nuclear power plant in Japan, as well as other locations vulnerable to radioactive pollution.

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* Corresponding author at: A.N. Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, Leninsky pr. 33, 119071 Moscow, Russia. Tel.: +7 9637119154; fax: +7 4959545534.
E-mail address: andrey.zaytsev@biogeo.ru (A.S. Zaitsev).

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Introduction

Russia, Ukraine, Belarus, Kazakhstan and some other neighboring countries bear the legacy of numerous Soviet nuclear disasters, accidents and spills, with tens of thousands square kilometers of land polluted by radioactive isotopes. The most famous out of them is the Chernobyl nuclear power station accident on April 26, 1986 which resulted in high radioactive pollution (0.185 MBq m^{-2} – meaning 185,000 radioactive decay events every second per square meter) of about 25,000 km^2 of the territory of the former Soviet Union alone (Vasilenko et al., 1996). Over 1.85×10^{18} Bq of radionuclides were released including 3.7×10^{17} Bq of ^{137}Cs and 8.14×10^{16} Bq of ^{90}Sr (IAEA, 2006). In fact, Belarus is recognized as the most affected territory by the Chernobyl accident (Sushenya et al., 1995; Belyi and Savastenko, 2005). One of the important peculiarities of this accident was associated with the massive release of so-called “hot particles” – highly radioactive microscopic solid objects with a radioactivity of up to 10 kBq (Kashparov, 2003). Less famous but nevertheless hazardous locations include the site of the Mayak nuclear enterprise explosion and spill in the fall of 1957 near the Kyshtym settlement in Eastern Urals (the so-called East-Urals Radioactive Trace – EURT) (Jones, 2008) as well as nuclear weapons testing areas and single explosions locations like Semipalatinsk in Kazakhstan, Northern Urals and Novaya Zemlya Archipelago, and uranium mines and refinery facilities environs in Transbaikal area in Russia (McLaughlin et al., 2000). Due to a variety of radioisotopes deposited and diversity of environmental impacts, Soviet and later Russian, Ukrainian and Belarussian radioecologists accumulated unique knowledge on the response of terrestrial and aquatic ecosystems to radioactive pollution (Krivolutsky and Semyashkina, 1980; Krivolutskii, 1983; Krivolutsky, 1994, 1999, 2003; Maksimova, 1996, 2002; Sokolov and Krivolutsky, 1998; Kryzhanivskij, 2006; Geras’kin et al., 2008b).

Incidents like the long-term radiation exposure in Chernobyl and the recent accident at Fukushima-1 NPP in Japan require effective tools for monitoring and mitigation of adverse effects of ionizing radiation on terrestrial ecosystems (McNamara et al., 2003; Thielen, 2012). Moreover, existing knowledge can greatly expand our understanding of current risk levels and radioecological loads in Japan (Garnier-Laplace et al., 2011).

Another important incentive for developing soil radioecological monitoring is related to investigations of soil communities and mechanisms of their adaptation in areas with elevated natural radioactivity levels (Abumurad and Al-Tamimi, 2001). Numerous such areas exist worldwide and are normally associated with radon springs, uranium ore outcrops and areas of high tectonic activity (United Nations Scientific Committee, 2010). Soil fauna and vegetation in these areas are chronically exposed to unusually high doses of radiation and develop specific physiological or genetic adaptations, which increase their radioresistance (Møller and Mousseau, 2013). Increased radioresistance in turn helps increase survival and fitness of soil organisms, and thus secures the provision of ecosystem services in stressed environments (von Wehrden et al., 2012).

Since soil-living animals comprise up to 95% of the total terrestrial ecosystem diversity and zoomass, it is vital to understand the responses of soil communities to elevated radioactivity levels (Wilson, 1999). Soil animals are also responsible, to a great extent, for biological turnover and biogenic migration of radioisotopes, their mobilization and immobilization in the soil profile (Krivolutsky, 1987b; Müller-Lemans, 1996; Bunnenberg and Taeschner, 2000). As soil usually tends to accumulate released radionuclides with time, implementing soil radioecological monitoring is very important to general radioecological research. For example, monitoring may provide important insights into the biogeochemical traits of radionuclides in terrestrial ecosystems and indicate critical points in their concentration (Pokarzhevsky et al., 1999). Initially the progressive action of radioactivity on soil animals is observed as a reduction of their motility; sometimes radiation burns of tissues in larger animals; and ultimately their death. Functionally, there is a reduction of feeding activity and metabolism culminating in the cessation of reproduction.

In the USSR and later in Russia, soil radioecological research was widely supported from 1963 to 1995 by targeted state programs on research and mitigation of consequences of nuclear accidents, and after 1994 by the State Scientific-Technical Program “Biological diversity”. The results of this work were compiled in a series of extensive reports (e.g. Krivolutsky et al., 1992; Krivolutsky, 1994, 1999; Sokolov and Krivolutsky, 1998). However interest in this topic has subsided in the XXI century, with hardly any active work devoted to soil fauna around Chernobyl performed since 2005. Only a few papers dealing with soil fauna in radio-polluted areas have appeared recently. They deal with issues of dose estimation; with developing a strategy of biota conservation in so-called radioactivity reserves; and, to a smaller extent, with soil fauna groups’ long-term response to radioactive pollution (Maksimova, 2002; Kolesnikova et al., 2005; Kryzhanivskij, 2006; Ulanovsky and Prohl, 2008). It is notable that among thousands of literature sources collected in the FREDERICA database on dose–response relationships of different living organisms, only 30 publications were devoted to belowground fauna. Out of over 30,000 records in that database about 300 discuss soil animal response to radioactive pollution (http://www.frederica-online.org/mainpage.asp). The same ratio was evient in the earlier EPIC database (https://wiki.ceh.ac.uk/display/rpemain/EPIC) where only 54 dose–response records dealing with soil animals were found. Thus, incorporation and further inventory of this knowledge into the systems of radioecological monitoring and risk assessment is rather important in light of the emerging risks of repeated nuclear disasters (Jones et al., 2003).

There are, for example, good precedents for the rapid transfer of experience in soil radioecological monitoring to the area of Fukushima-1 NPP. The soil fauna of Central Japan is relatively well studied (e.g. Aoki, 1999; Harada and Ito, 2006; Kaneko et al., 2012). It consists of mainly palaearctic species with a smaller proportion of tropical and Asian representatives. Moreover, many of Japan’s soil taxa tend to demonstrate high diversity and abundance of species (Aoki, 2009). Interestingly, all major groups of soil organisms monitored around Chernobyl are also present in Central Japan (Aoki, 1999). Thus, the system of soil radioecological monitoring developed in Russia could be applied in the vicinity of the Fukushima-1 NPP with minor adaptations. Several centers of soil-zoological expertise exist in Japan which are potentially capable of organizing a full-scale soil radioecological monitoring process.

The aim of this paper is to review the impact of radioactive pollution on soil fauna on the territory of Chernobyl and other nuclear accidents in the former USSR, and to discuss application of the lessons learned to other regions of the world, especially Japan. In this review we also consider major peculiarities and bottlenecks during the organization of soil radioecological monitoring in areas of nuclear accidents.

Soil fauna as a bioindicator of radioactive pollution

After the initial fallout from nuclear accidents, radionuclides migrate from the ground surface into the soil profile both by means of physico-chemical leaching and via the biological activity in the soil (Rafferty et al., 2000). Soil biota actively contributes to this process through bioturbation (Jarvis et al., 2010) and microbial immobilization (Brückmann and Wolters, 1994). After a certain period of time most of the radioactive isotopes are buried in the soil and are harder to detect from the surface (Krivolutsky, 1999).