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12-23-2022

Radioecology of Chernobyl: the biological effects of ionizing radiation on natural systems and non-human biota

1 - Introduction

In the era of anthropogenic climate change, we are becoming increasingly aware of natural systems' limited capacity for absorbing waste and contamination created by the modern human world. The atomic age has brought the fear of environmental catastrophe from industrialization and capitalism to a new level of horror. Contamination released by our exploitation of nuclear energy is more or less omnipresent in the terrestrial environments we occupy. During the past 70 years, the field of radioecology has amassed many scientists who are still attempting to understand and predict the behavior of radiation and radionuclides introduced into environmental systems.

Chornobyl has become a paradigm for a post-nuclear world. The word itself has become synonymous with catastrophe. Within radioecology, Chornobyl is the most mentioned release event (Shaw 2007). Chornobyl's infamy is well-earned, as the level of devastation caused by the reactor accident is unmatched by any other. The knowledge that contaminants from a single power plant meltdown could cover half the globe emphasized the importance of radioecological study. There are vast amounts of research surrounding the effects of Chornobyl on non-human life, all of which help to build a better picture of radiation catastrophe on the environment. For an incident of such enormity, many questions about the ramifications of Chornobyl on the environment remain unanswered. This paper serves as a surface-level review of some prominent studies on Chornobyl's effect on the environment.

2 - Radiation

Fundamentally, radiation is energy. Atoms have the most stable isotope when the number of neutrons is close to or slightly larger than the number of protons. Adding or removing neutrons from a nucleus leads to instability.

The ultimate goal of most things in the universe is to reach a level of balance or stability. In order to become stable, an unstable atom must release some of its energy. This release of energy is radiation or radioactive decay. During decay, radiation travels from its atomic source in the form of energy waves or energized particles. These errant particles are essentially drunk drivers on the atomic highway - dangerous road hazards that can careen into your lane without warning and knock off your side mirror. Instead of a mirror, radiation rips electrons off of other atoms.

Not all forms of radiation are damaging. Radiation falls into two general categories: ionizing radiation and non-ionizing radiation. Non-ionizing radiation has enough energy to bump and move atoms in a molecule around or cause them to vibrate, but it doesn't have enough energy to remove electrons. Radio waves, visible light, and microwaves all belong to the non-ionizing radiation family, and we come in contact with them daily.

Ionizing radiation is drunk driving radiation, the kind that can cause severe damage to tissue and DNA. Ionizing radiation is emitted during the radioactive decay. Radioisotopes, or radionuclides, are particles that emit ionizing radiation and can be identified by their proton/neutron counts. These particles can be recognized, measured, and tracked as they pass through ecological systems. Ionizing radiation comes in three forms, alpha decay, beta decay, and gamma decay.

Alpha decay is the release of two protons and two neutrons tightly bound together from a radioactive atom. While alpha decay has enough energy to pierce through our skin cells, it can't get very far. The skin on our eyelids is the thinnest in the entire body but it is thick enough to block alpha particles. Alpha radiation is dangerous when ingested or inhaled. In general, alpha particles are so heavy that they don't travel very far. But their weight, when ingested, makes them more dangerous than other kinds of radiation. The ionizations they cause are closer together. If ingested, alpha particles can cause severe damage to cells and DNA.

When a neutron breaks down into a proton and an electron and gets released from a radioactive source, it is called beta decay. That newly free electron is extremely high energy and can be highly ionizing. Beta decay creates free radicals - unstable atoms that have had their electrons stolen. While beta particles can penetrate tissue better than alpha particles, they carry less energy making the damage they cause less severe. As with alpha particles, beta particles are most dangerous when ingested.

Gamma decay differs from alpha and beta decay in that there's no particle ejected from the nucleus. While alpha and beta particles have mass and energy, gamma rays are photons, meaning they have no mass. Undergoing gamma decay does not change the structure or composition of an atom, only the energy. Gamma rays are a highly ionizing form of electromagnetic radiation. With an energy level thousands to millions of times higher than that of visible light, gamma rays can easily penetrate barriers that stop alpha and beta particles. They pose a great danger, as they can pass easily through the entire human body, damaging tissue and DNA along the way.

Once an atom becomes stable, it can no longer emit radiation. The amount of time it takes for an atom to become stable is, then, of much importance. This time frame is defined by something called a half-life. Half-life is the length of time it takes for half of the radioactive atoms of a specific radioisotope to decay. After one half-life 50% of the atoms will be stable. After two half-lives 25% of the atoms will be stable, and so on. The typical rule of thumb is that, after seven half-lives, less than one percent of the original amount of radioactive atoms will remain (CDC). Depending on the radionuclide, a half-life could be very fast or very short. In general, the most concerning radioisotopes have very long half-lives because they can remain present in natural systems for long periods of time.

The net result of exposure to ionizing radiation is damage to tissue and DNA. The effect of radiation exposure depends on many variables including the kind of exposure (external vs. internal), the type of radiation (gamma vs. beta vs. alpha), the absorbed dose, and the amount of time during absorption.

There are many different units of measurement for radiation, helpfully categorized into the R.E.A.D. mnemonic (although it isn't very catchy):

R – Radioactivity: the amount of ionizing radiation released by radioactive material. The units of measurement for radioactivity are the curie (Ci) and the becquerel (Bq).

E - Exposure: the amount of radiation traveling through the air. The units of measurement for exposure are the roentgen (R) and the coulomb/kilogram (C/kg).

A - Absorbed dose: the amount of radiation absorbed. In other words, the amount of energy deposited in materials through which radiation passes. The units for absorbed dose are the radiation absorbed dose (rad) and gray (Gy).

D - Dose equivalent: a combination of the amount of radiation absorbed and the medical effects of that kind of radiation. Units for dose equivalent are the roentgen equivalent man (rem) and sievert (Sv). Biological dose equivalents are commonly measured in 1/1000th of a rem, or millirem (mrem).

For comparison, 1 R (exposure) = 1 rad (absorbed dose) = 1 rem or 1000 mrem (dose equivalent). Fig.1 (below) offers a frame of reference for absorbed dosages and their observed effects.

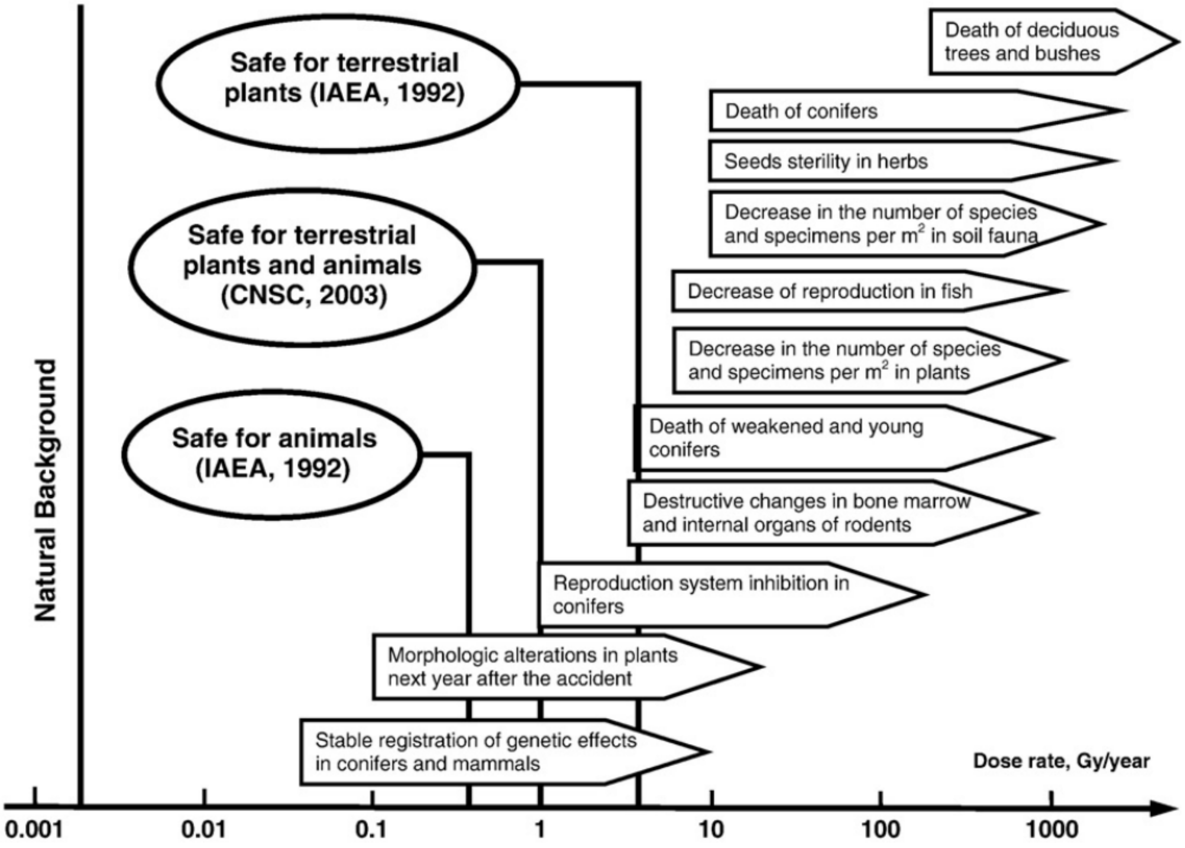

Fig.1 - A reference of effects observed on non-human species within the 30-km Chernobyl Exclusion Zone (Geras'kin et al. 2008).

2.1 - Radiation from Chornobyl

Nuclear power plants create energy by heating water and turning steam turbine generators from fission. The core of the plant contains the fuel, either an isotope of uranium or plutonium. In addition to releasing a huge amount of energy, fission produces radioactive byproducts. In the event of a meltdown, the main issue of concern is the containment of both the core and the fission products. Most nuclear plants use an airtight, steel-reinforced concrete containment structure built to minimize the effects of a potential cooling-system failure (Christodouleas et al. 2007). Chornobyl had no such containment structure.

In order to fully comprehend the intensity of the Chornobyl disaster, it is necessary to understand its scale. The accident involved the largest loss of reactor core materials to the environment in history. Three to four percent of the reactor fuel–6.7 tonnes of core materials–and associated radionuclides were lost to the atmosphere in the steam explosion (Shaw 2007). There are estimates that "clouds" of radiation reached heights between 1,500 and 10,000 meters (10,000 meters is 6.2 miles). Fallout from the explosion covered nearly the entire northern hemisphere (Nesterenko et al 2009). Emissions exceeded one hundred times the radioactive contamination from the bombs dropped on Hiroshima and Nagasaki.

The total magnitude of the Chornobyl release (excluding noble gases) was near 5300 PBq or peta-becquerel (Yoschenko et al. 2017). (Peta-becquerels are equivalent to 10^15 becquerels.) When Chornobyl's fourth reactor exploded, over 100 radioactive elements were released into the atmosphere (IAEA). Some of the most dangerous that were released include iodine, strontium, americium, and cesium. The long half-lives of isotopes from these elements result in long-term contamination of the Chornobyl Exclusion Zone (CEZ) for the foreseeable future: for Cs-137 and Sr-90 at least 300 years, and for Am-241 several thousand years (Yablokov et al. 2009).

2.2 - Spotty contamination and "hot particles"

Besides the spread of radionuclides, the two most important factors in the spread of Chornobyl's radiation are uneven/spotty contamination and "hot particles." Before the 2010s, concern over the evenness of radioactive fallout distribution was very little. Most maps of contamination are based on aerogamma-spectrometric studies, which only give average values of radioactivity. Because of this, localized radioactive “hot spots” can exist without being noted. A distance of even 10 meters can result in a sharp increase in radioactivity. Chornobyl hot spots typically span tens to hundreds of square meters and have levels of radioactivity ten times higher than surrounding areas.

The Chornobyl reactor explosion expelled not only gases and aerosols but also particles of Uranium fuel that melted together with other radionuclides. These firm, “hot particles,” sometimes called “Chernobyl dust” fell in countless amounts all over Europe. “Liquid hot particles” were formed when radionuclides became concentrated in rainfall. Studies on the properties, disintegration, and impact of hot particles are few and far between (Yablokov et al. 2009). The lack of information on hot particles and the general distribution of contamination from Chornobyl is concerning, as it implies a great amount of uncertainty in any studies involving dosage levels across large areas in the CEZ and beyond.

2.3 - Migration of radionuclides

The true environmental impact of a given radionuclide is dependent on the environmental pathways and processes it passes through. Different ecosystems with different nutrient pathways and mechanisms will migrate radionuclides differently. For example, I-131 is one of the most significant radionuclides in the aftermath of a reactor meltdown because of its ability to efficiently incorporate into the environment, especially into the milk of lactating mammals and the thyroid glands of children (Shaw 2007). While I-131 is not a long-lasting radionuclide, it is very damaging for this reason. Human epidemiological studies 20 years after the Chornobyl accident showed that the only cancers that are directly related to the release of radionuclides are thyroid cancers. While I-131 caused these cancers, it wasn’t measurable in the area after only 3 months. This exemplifies the importance of time scale in radioecology. Longer-lived radionuclides pose different environmental hazards than shorter-lived radionuclides.

Understanding the half-lives of radionuclides is vital to determining the residence time within different ecological compartments. Radionuclides with half-lives of thousands or millions of years are a considerable source of concern. It is possible that the true effects of such long-lasting radioisotopes on environmental systems may never be understood.

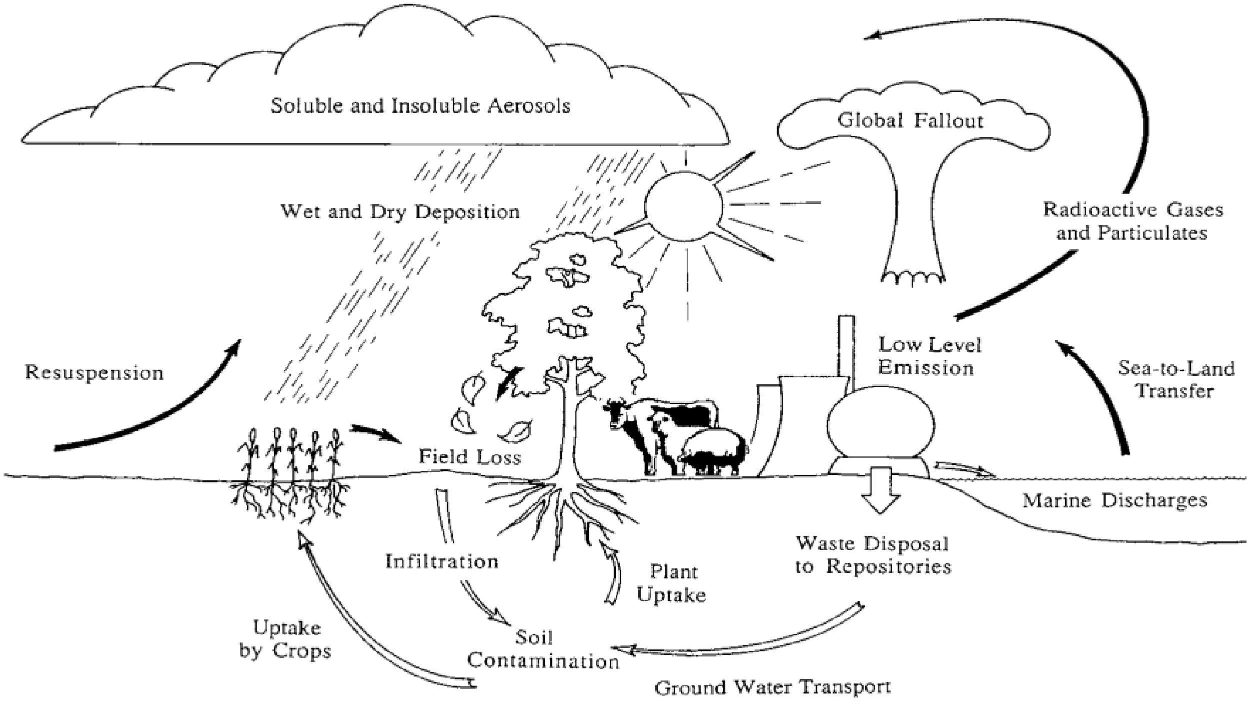

Fig. 2 - "Pathways leading to redistribution throughout the environment of artificial radionuclides from nuclear fuel cycle facilities, atomic weapons and radioactive waste disposal sites." (Shaw 2007)

However, radioecology also must take into account that primordial radionuclides—such as U-238 and K-40 which have half-lives of 4.47 and 1.28 billion years, respectively–have been components of Earth's environment since its formation. All living organisms have evolved with the presence of certain amounts of natural radiation. Every one of these factors serves to emphasize the importance of radioecological study.

2.4 - Ionizing radiation and DNA damage

Ionizing radiation can induce a wide range of DNA damage, including direct and indirect breaks. Ionizing radiation results in radiolysis, which involves particles cleaving associated molecules away from each other, creating a cascade of reactive molecules. Radiolysis causes an indirect form of DNA damage. The radiolysis of water creates reactive oxygen species (ROS), which are unstable molecules that can react easily with other molecules in cells. Besides damage to DNA, ROS can impair proteins, lipids, and other macromolecules (Rowe et al. 2007).

The most direct form of DNA damage occurs when a high-energy particle or photon collides with a DNA strand and breaks its phosphodiester backbone (Cannan and Pederson 2017). More common damage is caused by ionizing radiation splitting water molecules near DNA, creating hydrogen and hydroxyl free radicals that cause single-strand DNA breaks (SSBs) nearby (Barnard et al. 2013). If close enough to each other, SSBs can spontaneously result in double-stranded breaks (DSBs). Both SSBs and DSBs can hinder DNA processing and DNA repair. DNA ligase can only reseal SSBs if the break results in one 3' hydroxyl end and one 5' phosphate end. For instance, if the SSB is "dirty"—meaning not the right combination of ends—it can become virtually unprocessable (Weinfeld and Soderlind 1991).

2.5 - Effects of ionizing radiation on plant biology

Certain unique biological traits lead ionizing radiation to affect plants differently from animals. Unsurprisingly, cancer occurrence in plants is very different from that of animals. Arguments have been made that plants are not particularly susceptible to cancer because of the structure of plant tissue. Plant cells are fixed in place within the cell wall matrix, which constrains neoplastic cells and essentially limits metastasis (Aktipis et al. 2015). Plants also do not contain the same circulatory systems that allow rapid and widespread metastasis in animals.

The dividing cells of multicellular plants are in meristematic tissue, which contains undifferentiated cells that are essentially equivalent to totipotent human stem cells. However, one difference is that meristems do not contain a *p*-53-mediated pathway of apoptosis (Caplin and Willey 2018). While the effects of ionizing radiation on meristems are not well known, it is clear that the function of meristems also acts as a measure of tumor resistance within plants (Doonan and Sablowski 2010). Plants are also more resistant to the negative effects of radiolysis because they are used to the lysis of water already. The light reactions of photosynthesis begin with the photolysis of water, which creates the same products as the radiolysis of water. Photosynthetic plants are therefore accustomed to large amounts of oxidative radicals and can disarm them much more easily than animals (Caplin and Willey 2018).

When it comes to DNA repair, plants generally have a much higher capacity than animals although the systems they use are similar to other eukaryotes. Plant cells have a greater resistance to the production of DSBs by ionizing radiation and repair them faster than animal cells. At any given dose, plants carry about one-third of the DSBs that animal cells do (Yokota et al. 2005). Interestingly, mutations of DSB repair proteins in plants reduce biomass more than they change aspects of development. This is the opposite of multicellular animals. The majority of detailed molecular mechanisms of plant adaptation to chronic radiation exposure are unknown and remain to be discovered (Volkova et al. 2018).

3 - Contamination of flora

Accumulation of radionuclides by plants and mushrooms is dependent on a variety of factors including soil, climate, season, spotty radioactive contamination, and the specific species and population. Within plant and mushroom species, each radionuclide has its own individual accumulation rate and characteristics. Coefficients of accumulation vary so much that it is incredibly difficult, if not impossible, to predict levels of radioisotopes (Cs-137, Sr-90, Pu-238, Pu-239, and Am-241) for each individual plant or fungus (Yablokov et al. 2009). There is an extensive body of literature on the contamination of plants and mushrooms following the Chornobyl accident and on their consequential genetic and morphological changes. Chornobyl radiation exposure caused structural anomalies and tumor-like changes in many plant species. Several diseases have been identified that are unique to Chornobyl, mostly involving mutated pollen grains and spores. Chornobyl radiation has also caused a variety of inheritable genetic disorders that appear to have awakened genes that had been silent for a very long time in plant evolution.

3.1 - The “red forests” of Chornobyl

The Chornobyl accident stimulated the development of forest radioecology. This field of ecological study is of great importance, as forests cover over 60% of the CEZ and will remain as long-term environmental repositories of radionuclides (Yoschenko et al. 2017). Forests are particularly vulnerable ecosystems due to their ability to scavenge atmospheric pollutants with greater efficiency than vegetation types such as grasslands or farmlands. They also stand in a unique position as both a source and a sink for radiation

(Tikhomirov 1993). Large amounts of data on radionuclide transfer in forests were compiled in the Chornobyl Forum Report (IAEA).

Before the accident, Scots pine trees (*Pinus sylvestris* L.) dominated the forests of Chornobyl's exclusion zone (Geras'kin et al. 2008). These pine trees experienced extreme acute radiation impacts. After the first reactor explosion, a radioactive cloud that contained short-lived radionuclides passed over Scots pine trees living close to the reactor. Detailed information about dose rates in that period is absent. There are estimates that initial exposure dose traits in the cloud may have reached 8,000-10,000 R (Yoschenko et al. 2017). In addition to the radioactive cloud, these trees in close proximity experienced a shower of fallout, intercepted by their crowns. Within the fallout were isotopes of Sr, Zr, Nb, Y, Pm, Pu, Am, and Cm, which are beta and alpha emitters. Within 2-3 weeks of the accident, pines exhibited the first signs of radiation injury. Needles on trees within 100 ha of the plant yellowed, and then died. In an area of such proximity, the absorbed dose to needles and apical meristems exceeded 500 Gy (Geras'kin et al. 2008). Almost all pine trees that received doses higher than 60 Gy died quickly, and their red/orange color inspired a new name: "the Red Forest." The Red Forest of dead trees spanned an area of about 4.5 km^2. Later, the dead trees were bulldozed and, along with heavily contaminated forest litter and topsoil, deposited into trenches for radioactive waste disposal. Officials covered the Red Forest with clean sand and newly planted Scots pine, birch, oak, and shrub species (Kashparov et al. 2012).

Typically, coniferous woody plants have the highest sensitivity to radioactive contamination. This is partially a result of the high capacity of conifer crowns for interception and retention of fallout year-round. Deciduous woody species are more resistant to radiation by—when comparing the value of the lethal dose—an order of magnitude (Tikchomirov & Shcheglov 1994). Radiation damage to deciduous trees was observed only in the immediate vicinity of the destroyed reactor, with dose levels several times higher than conifers with similar damage (Geras'kin et al. 2008). Deciduous stands in the CEZ mainly consist of birch (*genus*: *Betula*), aspen (*Populus tremula* L.), black alder (*Alnus glutinosa*), and oak (*Quercus robur* L.) species. Damage to birch and black locust was recorded in areas where gamma radiation exceeded 105 mGy/day. Radiation resistance became an emphasized selective pressure for the forests of Chornobyl, which resulted in the succession of coniferous trees over deciduous trees.

3.2 - Radionuclide migration from the forest canopy

The canopy of a forest contains a high capacity for the retention of radioactive fallout. This high retention resulted in tree crowns intercepting 60-90% of radionuclides that fell on the forest. High doses of mainly beta-radiation were absorbed by apical and leaf meristems (Tikhomirov and Shcheglov 1994). The rate of crown self-clearing exemplifies the intensity and duration of radiation exposure of forest trees. In only two months, more than 95% of the total radionuclide amount had migrated from the forest canopy to the forest litter. By 1988, in the forest litter of pine stands, 80% of the total C-137 deposition was found in the soil (Ipatyev et al. 1999). In forest systems, litter is an extremely important component in nutrient cycling. Radionuclides migrated to the litter by the shedding of epidermal leaves, buds, and bark from pines. This transfer of radionuclides was accelerated during spring and diminished during autumn and winter, which are stages of physiological rest.

The process of radionuclide migration in forest ecosystems can be divided into two stages. The first stage, which lasts 2-4 years, involves contamination mainly from aerosol precipitation of radionuclides on the forest canopy, which mostly affects surface-level components of the trees–branches, bark, needles, etc. Anything sheltered by the canopy during this stage suffers much lower contamination levels. The second stage begins with radionuclide transfer into the forest litter and eventually into the root-inhabited soil layer, and root pathways begin radionuclide uptake (Tikchomirov and Shcheglov 1994).

3.3 - Genetic effects on Scots pine

Studies of genetic effects in Scotch pine trees began in May, 1986. Genetic effects were estimated by studying the mutation rate of enzyme loci in seed endosperm and the rate of chromosome aberrations in seedlings and needles (Geras'kin et al. 2008). In the most contaminated plots, the frequency of enzyme loci mutations was 4-17 times that of the control, and the frequency of aberrant cells was 1.5-7.2 times higher. These plots experienced an absorbed dose of external gamma radiation at levels of 10-20 Gy (Fedotov et al. 2006). Between 1987-1990, the number of cytogenetic (chromosomal) abnormalities declined more slowly than the contamination in the area (Geras'kin et al. 2008).

Genomic DNA of exposed Scots pine trees in the accident zone was considerably hypermethylated (Kovalchuck et al. 2003). Not only that, the rate of hypermethylation was dependent on the dose absorbed by trees. Results from this study suggested that plants use epigenetic mechanisms in response to radiation exposure. Hypermethylation can be viewed as a stress response or defense strategy in order to avoid genomic instability and/or reshuffling of hereditary material. In the 2003 study, genomes from young trees planted in contaminated soil of radioactive burial sites were the most methylated. However, genomic methylation levels in exposed seeds grown in clean soil were not significantly different than that of the control. This implies that radiation exposure during somatic development and not during the seed stage is the key driver of DNA methylation. Results on the connection between methylation level and dose level are logical—methylation is a resource-heavy, complex process and must therefore be used by the plan in an efficient manner. As radiation pressure decreases, DNA methylation also decreases to normal levels.

3.4 - Anomalies and genetic changes in other species

In Chornobyl-contaminated territories (throughout Europe), radiation-induced changes include aberrations in shape, intercepts, twists, wrinkling, bifurcations, abnormal flattening of stems, and more. In 1986, swelling growths were observed on leaves, stems, roots, flowers, and other organs on plants within the 30-km zone. Reduced numbers of plants per meter squared and species diversity were observed starting at doses of 17 mGy/day. Gigantism of some plant species was observed at external dose rates of more than 36 mGy/day. In the years following, the number of these abnormalities increased and were mainly observed on coniferous trees (Yablokov et al. 2009). Chornobyl radiation caused morphogenic breaks that provoked the development of tumors caused by the bacterium *Agrobacterium tumefaciens*. This pathogenic bacterium causes Crown Gall diseases (tumorogenesis) in a host species by integrating its DNA into the host plant genome (Gohlke et al. 2014).

Thale cress (arabidopsis) is a common model organism for plant biology research and was studied within the Chornobyl exclusion zone starting in 1986. The frequency of lethal embryonic and chlorophyll mutations increased in arabidopsis plants over the first 2-3 years after the accident, despite dose decline. Later, although very slowly, the rate of these mutations declined. In 1992 the mutation rate was still 4-8 times higher than the typical level. Studies of the arabidopsis population's genetic structure have shown that radiation causes a decrease in genetic diversity over time. Progeny of Chornobyl plants showed a lowered frequency of extrachromosomal homologous recombination by 10-fold, significantly higher levels of gene expression for radical scavengers and DNA-repair molecules as well as a higher level of genome methylation (Kovalchuck et al. 2004). Radical scavengers (encoded by genes CAT1 and FSD3) protect cells from damage caused by free radicals by either preventing the creation of radical oxygen species or removing them before they cause damage to vital parts of the cell. Arabidopsis plants have, presumably, developed these efficient mechanisms in order to better tolerate chronic radiation exposure. Another major finding was that Chornobyl plants showed extremely low recombination levels. This could be a sign of adaptation, as a low frequency of recombination could prevent unnecessary genomic arrangements. It has also been suggested that plants grown in contaminated areas adjust their method of DNA repair to a more efficient but error-prone mechanism (Kovalchuck et al. 2004).

The frequency of plant mutations in contaminated territories sharply increased after the accident and remained at a high level for several years. Effects on plant species included the enhanced rate of mutagenesis, altered species composition, loss of biodiversity, to damage at the ecosystem level (Geras'kin et al 2008). The severity of these effects was dose-dependent. The decline in background radiation rate was faster than the decline in the mutation rate of plants, meaning that the effects of such large radiation exposure last much longer than the radiation itself. Both woody (scots pine) and herbaceous species of plants showed signs of adaptation. From this, radiation exposure can be viewed as an ecological factor that heightens the action of natural selection. Although the full picture of plant adaptation is incomplete, it is clear that epigenetic regulation is a key factor in maintaining genomic stability.

4 - Contamination of fauna

Studies and data on radiation effects in free-living animals after the Chornobyl accident are fragmentary, and generally not as accurate as those for plants (Geras'kin et al 2008). This can be attributed to the mobility of animals, which both complicates the study and affects the accuracy of radiation dose measurement. Insects in particular are complex to study in radioecology because they occupy different environmental niches at different stages in their life cycles.

4.1 - Entomofauna

Soil animal populations are very suitable for radioecology indicator studies because of their high density and taxonomic diversity. As radionuclides migrated down vertically from the forest canopy, dwellers of forest litter in particular were most severely affected. Overall, population size of soil animals was more greatly affected than species composition. Doses of 29 Gy induced catastrophic changes in population density, and doses of about 9 Gy induced noticeable changes as well (Krivolutskii and Pokarzhevskii 1992).

The most radiosensitive period of development for soil inhabitants is the stage of reproduction and molting after the warming of soil during spring. The Chornobyl accident coincided with this sensitive period for invertebrates and disturbed their normal process of reproduction. The first instar is the stage in the development of arthropods between hatching from the egg and insect form. Among the forest litter inhabitants, first instar larvae and nymphs were not detected (Geras'kin et al. 2008). Earthworms near the Chornobyl NPP (Nuclear Power Plant) did not survive or hatch from cocoons in the fall of 1986. While adult earthworms are rather radioresistant, juveniles are not.

Asymmetry of morphological structures due to contamination was noted in several species such as the Colorado beetle (*Leptinotarsa decemlineata* L.), leaf beetle (*Chrysomela vigintipunctata*), stag beetle (*Lucanus cervus* L.), and species of dragonfly (*Odonata*). Radioactive contamination of different levels resulted in the fluctuation of wing venation. Stag beetles showed asymmetry in the length of their horns, which is a secondary sex characteristic. 10 years later, a study found that mated stag beetles had significantly lower horn asymmetry than unwanted males, meaning that morphological changes due to radiation exposure impacted the mating status and processes of invertebrates.

After 2-2.5 years, population size of soil mesofauna was almost completely restored in size but had a large difference in species diversity, as population rise was mostly due to migration. Even 10 years after the accident, species diversity was only 80% of that compared to before the disaster (Geras'kin et al. 2008).

4.2 - Mammals

When it comes to terrestrial animals, mammals are the most radiosensitive. In the vicinity of the Chornobyl NPP, the most abundant group of mammals are rodents. Due to their large numbers, rapid generations, and habitat within the uppermost soil horizon (where the highest doses are located), rodents are a suitable model species for radioecological study. Acquiring data on radioecological effects on mammals is important so we can better understand how environmental radiation catastrophes could affect humans.

Radioactive contamination interfered with the reproduction processes of mouse-like rodents through two mechanisms; a decrease in embryonic survival and an increase in the fertility potential of females (Geras'kin et al. 2008). The increase in fertility was due to an increase in ovulating ovicells. Over time, external exposure levels dropped and incorporated radionuclides contributed more to dosage. Mean values of Cs-134, Cs-137, and Sr-90 concentrations measured in mammals from the most affected and non-remediated habitats were some of the highest ever recorded for free-ranging animals (Chesser et al. 2009). Despite visibly appearing healthy, these animals expressed many atypical alterations in their haematogenic systems and internal organs. Noticeable differences in the blood system were first observed 6 months after the accident and worsened in subsequent generations (Geras'kin et al. 2008).

Chromosome aberrations and embryonic lethality increased as a result of exposure and stayed at constant high levels for about 22 animal generations in the first 10 years. During those 10 years, absorbed dose decreased exponentially. The longevity of genetic effects in mammalian populations compared to the decrease in dosage shows that the consequences of radiation exposure last much longer than the exposure itself. Before the accident, cells never contained this kind of aberration, only chromatid-type aberrations. Bank voles also demonstrated high frequencies of polyploid cells within their bone marrow. Polyploid cells contain more than two genome copies. Levels of polyploid cells within bone marrow were 1-3 times greater than before the accident.

5 - Contamination of microbiota

Microorganisms are essential to study within the field of radioecology because of their potential ability as bioreducers of uranium from a soluble to an insoluble form (Hoyos-Hernandez et al. 2019). Some members of the bacterial family *Desulfovibrionaceae* can tolerate high radiation levels and have potential for bioremediation of radionuclides, which means they could potentially fill a role as detoxifying bacteria within the microbiome of voles or other species.

5.1 - Gut microbiota in voles

Understanding of the role of gut microbiota has grown immensely in recent years. Gut microbiota composition depends on many factors, and the impact of environmental radiation on gut microbiomes remains largely unknown. In 2018, a study used amplicon sequencing of bacterial 16S rRNA genes to quantify the effect of anthropogenic radionuclides on bank vole gut microbial diversity (Lavrinienko et al. 2018). Environmental radiation had a strong effect on both bacterial function and gut microbial composition.

5.2 - Prokaryotes

Prokaryotes fill an important niche within natural systems as regulators of both carbon and nitrogen. An interesting study from 2019 showed the effects of radionuclide exposure change prokaryotic community structure (Hoyos-Hernandez et al. 2019). The authors proposed that different genes and mechanisms within the prokaryotic community are influenced by radionuclide exposure. Certain genes within radio-resistant bacteria (*Deinococcus geothermis*, *Deinococcccus radidurans*, *Kineococcus radiotolerans, and Rubrobacter xylanophilus*) are highly expressed, implying that they are key factors for radioresistance. These genes include those involved with information storage and processing, amino acid transport and metabolism, and translation factors. The results from the 2019 study suggest that prokaryotic communities in soils with high radionuclide concentrations have functional profiles that would allow them to cope with radiation exposure. However, the authors called for replicate studies to confirm their findings, and to explore the effects of radiation on community structure and function similarly in a laboratory setting.

5.3 - Pathogen expansion

Radiation exposure results in a loss of immune resistance for many species including plants, and the increased virulence of some pathogens. Accelerated development of parasitic species such as tularemia, encephalitis, and fungal pathogens was observed in the Chornobyl NPP. Other pathogens showed the development of new phytopathogenic forms and accelerated horizontal transfer of genes. These findings suggest that the Chornobyl exclusion zone is a territory of increased risk of pathogen spread. Pathogens with increased virulence pose a threat as they could easily be transported out of the exclusion zone and into non-contaminated areas. Research on the potential outcomes of mutated pathogens as a result of anthropogenic ionizing radiation exposure is not nearly as populated as it should be, especially for a field of such importance.

6 - Discussion & conclusions

For the ecological systems at Chornobyl, effects of radiation can be divided into primary and secondary effects. The primary effect of the Chornobyl accident was the irradiation of plants and animals. The secondary effect was the disruption of ecological relations between components of the CEZ forest ecosystem. These secondary disturbances offer the big picture for the Chornobyl ecosystem as a whole. Secondary disturbances were caused by the following:

1. Changes in microclimatic and soil conditions under a radiation-damaged forest canopy. This resulted in variations of heat, light, and water entering the soil.
2. Changes in seasonal phases and development of ecologically connected organisms.
3. Changes in food supply between consumers and producers, mainly a decrease in food sources due to irradiation.

4. Changes in biological pressures as a result of some species being more radioresistant than others. Examples include a succession of deciduous trees over coniferous and the increased prevalence of parasites.
5. The opening of ecological niches for the immigration of new species into the damaged area.

Following this, the effects of radiation in natural and agricultural ecosystems are dependent on the radiosensitivity of the dominant species. For the forest ecosystems of Chornobyl, coniferous trees such as Scotch pine should be mentioned as some of the most radiosensitive.

Radiation levels in the 30-km zone are still at unsafe levels for human habitation. Due to the decrease in human activity, many species have migrated, or returned, to habituate the area. The absence of human disturbance from agriculture, forestry, hunting, fishing, light pollution, noise pollution, and so on has resulted in the considerable growth of wild animal populations. Only two years after the accident, populations of wild boars exceeded pre-accident levels by 8 times. The populations of elk, deer, storks, wolves, and foxes increased similarly. Because of this, the narrative of Chornobyl as a wildlife haven has grown popular. While it holds true that some wildlife is more populated than before, this kind of narrative tends to ignore that this isn't a direct result of a severe nuclear disaster but rather the simple absence of humans. As mentioned in this paper, plant and animal populations in the 30-km zone still show high levels of mutagenesis and morphological anomalies. Most mammals reside in areas that have maintained high enough doses to interfere with reproductive success. The full genetic consequences for life within these dangerous animals are still unknown. The 30-km Chornobyl plant zone contains uniquely developing ecosystems, where normal anthropogenic effects are not felt. Human absence from such an affected area can act as both a focus and a confounding factor in radioecological studies. One request remained consistent across all radioecological studies from Chornobyl: the need for further study.

The biological importance of assessing the systems ecology of Chornobyl cannot be understated. Only this kind of information from natural settings can improve our evaluation of both the consequences of climate change and human-caused radiation disasters. Studies that follow the biological effect of radioactive catastrophes on non-human species are perhaps more important than most realize. Despite our continued attempt at separation from "nature," we will always be reliant on the systems ecology of our environment. As nuclear catastrophe falls to the back of our collective imagination in the years since 1986, radioecological research continues to be paramount.

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