RESEARCH ARTICLE

BioRisk

Ecocide – global consequences
(pesticides, radionuclides, petroleum products)

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Citation: Metcheva R, Ostoich P, Beltcheva M (2022) Ecocide – global consequences (pesticides, radionuclides, petroleum products). In: Chankova S, Peneva V, Metcheva R, Beltcheva M, Vassilev K, Radeva G, Danova K (Eds) Current trends of ecology. BioRisk 17: 7–18. https://doi.org/10.3897/biorisk.17.77438

Abstract

The problem of environmental pollution is becoming increasingly important on a global scale. Man has oversaturated the environment of his habitat with harmful and most often toxic waste. It is difficult to describe all the toxic substances, as a separate book can be written for each group. The term "ecocide" has been introduced, which reflects large-scale destruction of the natural environment. We will focus only on three classes of pollutants that are of particular concern, creating environmental conflicts. These are:

• Pesticides are extremely toxic and create large amounts of non-degradable waste. It accumulates in tissues and organs of target organisms, becoming toxic and causing serious pathological changes in the body, mainly at the cellular and subcellular levels, causing various diseases and as a result, serious changes in the structure and functions of the populations and the whole ecosystem are increasingly observed.

• Waste from the nuclear industry and radioactive fallout from nuclear explosions. It is especially dangerous that radioactive elements can be concentrated in certain organs.

• Petroleum products - often large quantities end up in the seas and oceans, along with industrial waste of various kinds, impossible to compensate for by nature and they pose a serious threat to ecosystems, many of which have already been destroyed.

At the submolecular level, chemical and physical effects can lead to genetic rearrangements (mutations); destructive ionization in the tissues of every living being, sometimes with completely unexpected consequences for humans.

Introduction

The word "ecocide" combines 'eco', which comes from ancient Greek word 'οικος', meaning house which nowadays means 'habitat' or 'environment' and -cide' comes from the Latin verb 'caedere', meaning 'to cut down' or 'to kill'. Ecocide literally means "to kill the environment", or destruction of large areas of the natural environment as a consequence of human activity.

The problem of environmental pollution is becoming increasingly important on a global scale. Man has oversaturated the environment of his habitat with harmful and often toxic waste. It is difficult to describe all the toxic substances, so the focus will be stressed only on three classes of pollutants that are of particular concern, creating environmental conflicts. These are:

1. Pesticides. Their use is sometimes unavoidable, yet they pose serious hazards to ecosystems due to runoff in freshwater ecosystems and biomagnification along food chains.

2. Radionuclides. Localized anthropogenic contamination can be dangerous to ecosystems due to a tendency of fission products such as ^{131}I, ^{137}Cs, and ^{90}Sr to bioaccumulate in the terrestrial and aquatic biota.

3. Petroleum and petroleum waste products. Large quantities of petroleum and its derivatives have ended up contaminating ocean ecosystems and shorelines, producing damage that is hard to overcome.

Ecocide can be irreversible when an ecosystem is damaged beyond its capacity for self-repair. It is generally associated with damage caused by an organism, which might cause ecocide directly by destroying enough species in an ecosystem to disrupt its structure and function. Ecocide can also result from pollution such as high concentrations of pesticides which decimate the local biodiversity.

Pesticides

Pests are the most serious problem in agricultural production. Since the discovery of DDT, farmers use pesticides as the most effective means against destruction of crop production. Pesticides significantly damage the environment as well as humans, they damage water and soil quality, which has a dangerous effect on animals, birds, plants and humans.

The degree of pesticide toxicity strongly depends on its environmental behaviour. They enter in the ecosystems by two different pathways depending on their solubility. Water-soluble pesticides enter groundwater, streams, rivers and lakes and in this way harm non-target species. Fat-soluble pesticides enter organisms along food chains and have a strong tendency towards biomagnification. They are absorbed in the fatty tissues and result in persistence of pesticides in food chains for very long periods. These persistent pollutants are transferred up the food chain faster than they are broken down or are excreted. Therefore, the higher trophic levels of the food chains will contain higher

pesticide concentration. This disrupts the normal functioning of the whole ecosystem as the species in higher trophic levels will die due to greater toxicity.

The threats associated with the use of these toxins cannot be ignored. It is of paramount importance to study the pesticide impact on populations of aquatic and terrestrial ecosystems. Accumulation of pesticides along food chains is of greatest concern as it directly affects terrestrial predators and raptors. Indirectly, pesticides can also reduce the quantity of plants and primary consumers, on which higher orders feed. Spraying with insecticides, herbicides and fungicides has also been associated with reduction in the population of rare species of animals and birds.

Pesticides enter the water via rain, by runoff, leaching through the soil or they may be applied directly to water surfaces, for instance, for the purpose of controlling mosquitoes. Water contaminated with pesticides is a serious threat to aquatic life forms. It can affect aquatic plants, decrease dissolved oxygen in the water and can cause physiological and behavioural changes in fish populations. These pesticides are not only toxic themselves but also interact with stressors which include harmful blooms of algae. Aquatic animals are exposed to pesticides in three ways: direct absorption via skin; uptake via gills during breathing and via drinking contaminated water.

Pesticides in terrestrial ecosystems are able to cause sublethal and lethal effects on plants. As early as 1977 Kelley and South (1977) note that herbicides cause considerable damage to fungal species in soil by inhibiting the growth of symbiotic mycorrhizal fungi that help plant nutrient uptake. Glyphosate, a broad-spectrum herbicide, reduces the growth and activity of nitrogen-fixing bacteria in soil (Kanissery et al. 2019). Even low doses of herbicides have a great impact on the productivity and diversity of the natural plant communities and wildlife. Beneficial insects like bees and beetles can experience significant population decline due to the use of broad-spectrum insecticides (Pisa et al. 2015). Synergistic effects of fungicides and neonicotinoid insecticides are very harmful to bees. Even a low dose of them reflects negatively on their feeding behaviour. Since 2006, each year, honeybee populations have dropped by 29–36% (Pisa et al. 2015).

Some reports have confirmed that only about 10% of pesticides reach the target groups of organisms in crops. (Pisa et al. 2015; WHO 2017) The majority of pesticides react with non-target organisms (WHO 2017). If the toxicity expression of a pesticide is measurable, the non-target organisms can be used as bioindicators. There are various options on the choice of species for pesticide monitoring. They depend mostly on the feeding habitat of the species. The non-targeted part of an applied pesticide moves through the ecosystem and a significant portion of it accumulates in the lower trophic levels. By the mechanisms of bioaccumulation, it reaches higher trophic level organisms and affects normal physiological processes of the organisms, thereby putting the whole ecosystem at risk (EEA 2013).

Gutierrez et al. (2012) reported the response of the copepods and the cladocerans as early bioindicators of endosulfan toxicity. Ecotoxicological risk to the copepods *Acartia margalefi*, *A. latisetosa* and the mysid *Siriella clausi* can be used as early indicators to assess the risk to marine ecosystems.

Due to specific morphological features, bees can carry pesticides which may be brought to the hive. Thus beehives may also be polluted. The spraying of beehives

during honey collection may be the reason for pesticide adulteration of honey and beeswax (Kujawski and Namieśnik 2011). This indicates the use of honey bees as a potential bioindicator to determine the amount of pesticide levels in pollinator communities.

Earthworms are common organisms in the soil ecosystem and play an important role in soil health (Spurgeon et al. 2003). They play a significant role as bioindicators of soil contamination and as models for soil toxicity. Their reduction may alter the nutrient cycling and nutrient availability to plants (Rizhiya et al. 2007). Pesticides produce neurotoxic effects in earthworms and after exposure they are strongly physiologically damaged, with DNA damage, changes on feeding activity and loss of vitality (Zhang et al. 2020).

Bird feathers are one of the best indicators for the presence of pesticides in the body. Several studies showed a significant correlation between the contamination level in seabirds' food and their feathers. Feather collection is easy and minimally invasive and is very important from the viewpoint of conservation biology. Moreover, feathers indicate toxicant exposure during an annual cycle. There is a wide concentration range of pesticides that can be traced using feathers from birds in Patagonia (6.49 ± 5.95 µg/g) (Martínez-López et al. 2015) to relatively high concentration in birds from Spain (870.48 ± 614.48 ng/g) (Espín et al. 2012). Feathers can be used as bioindicators throughout the wide range of different geographic regions of the world. For biomonitoring of OCPs in Antarctica, penguin feathers are a very good tool (Metcheva et al. 2017).

A lot of studies show that herbivorous mammals, and especially rodents, are one of the best species that fulfil the requirements for a good bioindicator for pesticide contamination due to their large population number, good representation of spatial and ecological niches, sufficient knowledge about their physiology, great reproductive potential, as well as their dietary composition (Tataruch and Kierdorf 2003).

Since use of pesticides is unavoidable, early monitoring is essential to prevent or control the damage caused by pesticides to humans and ecosystems. It is a timely need to integrate the studies of different disciplines including toxicology, environmental chemistry, population biology, community ecology, conservation biology and landscape ecology to understand the direct and indirect effects of pesticides on the environment. In the future, chemical pesticides can be used in combination with natural treatments and remedies, resulting in more sustainable elimination of pests. This combination not only promises environmental health, but also has diverse applications in controlling urban pests and invasive species.

Nowadays, is very important to control the use of pesticides and to find ways to apply appropriate substances; to encourage farmers to reduce pesticide overuse. It is necessary to develop and apply various techniques for remediation of pesticides from the environment. Adsorption and bioremediation have been found to be most suitable as environmentally friendly, cost-effective and less toxic by-products. Environmental protection organisations, farmers, health professionals, producers, and governments have to commit to and adopt joint initiatives to reduce the negative effects of pesticides. Immediate action is needed to effectively control pesticides and to adopt strict laws and regulations in this area. Integrated pest management is very useful for the management and further application of pesticides, as well as for their best control.

Radioactive contamination

Radionuclides are nuclides that have excess nuclear energy, making them unstable. This instability is due to excess energy in the atomic nucleus, leading to the release of particles with different energies in a process called radioactive decay. Natural radionuclides emit alpha (α), beta (β⁻) and gamma (γ). Of these types, α-particles have the strongest biological effects, causing 20 times more biological damage than an equivalent dose of β⁻ or γ radiation (ICRP 2007). While α and β⁻ particles do not penetrate deeply into matter, γ-radiation, especially at the higher end of the energy spectrum, has high penetration. Biologically, α and β⁻ emitters are only relevant if incorporated into living organisms, while γ-emitters are relevant both as internal and external radiation sources. Some technogenic radionuclides emit other types of radiation. Medical PET isotopes such as ^{18}F, ^{11}C, ^{13}N, ^{15}O, are positron (β⁺) emitters. Other radionuclides such as ^{252}Cf are capable of emitting neutrons. Both positron and neutron emitters require special equipment for handling and detection of radiation sources (Hall and Giaccia 2006). Some radionuclides emit multiple radiation types. The technogenic radionuclide ^{137}Cs emits β⁻ particles at two energies: 511 and 1173 kiloelectronvolts (keV), and γ-rays at 661.6 keV.

The biological effects of radionuclides are mainly due to the emitted ionizing radiation (IR). Researchers have elucidated the biological effects of high and medium doses of radiation. However, low-dose effects are still insufficiently understood (Hall and Giaccia 2006; Kosti 2019). Currently, IR risk is extrapolated linearly to the low doses by using the Linear Non-Threshold (LNT) mathematical model (Trott and Rosemann 2000; Hall and Giaccia 2006). Other hypotheses include radiation hormesis, which is the idea that small doses of radiation are beneficial due to the induced protective stress responses (Schirrmacher 2021), and low-dose hypersensitivity, which is the assumption that low doses of radiation are more mutagenic (Joiner 2001). While radiation hormesis has been well researched recently (Shankar et al. 2006; Schirrmacher 2021) it has still not been taken into account in radiation protection calculations, where every minimal dose of radiation is assumed to carry a small but non-negligible risk (ICRP 2007). On the other hand, the low-dose hypersensitivity hypothesis is supported by recent studies, raising questions about the validity of current assumptions in radioprotection (Heuskin et al. 2013). Organisms have different radiosensitivities. The champion of radioresistance is the bacterium *Deinococcus radiodurans*, which can withstand an acute dose of 5000 Gy with almost no loss of viability. Similarly, tardigrades can withstand 5000 Gy with 50% loss in viability (LD_{50}=5000 Gy). For comparison, the LD_{50} for humans is around 6 Gy, for mice around 6.4 Gy, and for goats only around 2.4 Gy (Bond 1963).

A significant concern in radionuclide-contaminated areas arises from the process of bioaccumulation. Similarly to other elements from their respective groups, radio-isotopes are incorporated preferentially into different target organs and tissues. Thus, ^{90}Sr, an analogue of calcium, has a strong affinity for bone and hematopoietic tissue. Some of the properties of the three most significant anthropogenic radionuclides are presented below (Table 1):

Table 1. The most significant anthropogenic radionuclides and their biological effects (data adapted from Besson et al. 2009 and Holm 2006).

Radionuclide	Symbol	Half-life (λ)	Emitted radiation	Target tissue	Biological effects
Cesium-137	^{137}Cs	30.17 years	β- (511, 1173 keV), γ (661.6 keV)	nerve, muscle	different cancers
Strontium-90	^{90}Sr	28.8 years	pure β- (546 keV)	Bone	bone cancer, leukemia
Iodine-131	^{131}I	8.02 days	β- (333.8, 606.3 keV), γ (364.5, 636.9 keV)	thyroid gland	thyroid cancer

As evident from the table, the most significant environmental contaminants of the above are ^{137}Cs and ^{90}Sr due to their long half-lives and persistence in nature. ^{131}I was only a very significant risk in the first year following the Chernobyl accident, causing ~4000 excess thyroid cancers in the most significantly affected populations of the former USSR (Williams 2006).

Natural radioactivity, including external terrestrial γ-radiation, internal α, β- and γ-radiation from terrestrial radionuclides, cosmic radiation, and exposure to radon (^{222}Rn) and thoron (^{220}Rn) and their radioactive progeny molecules accounts for ~95% of the annual radiation dose for the terrestrial biota (Hall and Giaccia 2006; ICRP 2007). Globally, there are areas with high natural radiation, mostly due to thorium (^{232}Th) deposits. Two such areas are Guarapari, Brazil, and Kerala in southern India. The area of Ramsar, Iran, has increased natural radioactivity due to radioactive hot springs containing ^{222}Rn and its progeny. Although annual doses in these areas reach an average of 35–40 mSv/a, compared to 3.6 mSv/a average in Europe, epidemiological studies report no excess cancer risk (Dobrzyński et al. 2015; Kosti 2019).

In contrast, environmental contamination by man-made radionuclides poses serious risks. The Chernobyl accident is the most prominent example of technogenic environmental damage, although it is not the only one; Chernobyl caused significant chronic morbidity and mortality in people and enormous damage to the environment and economies in Europe. This is mostly due to ^{131}I, ^{137}Cs, and ^{90}Sr, and their tendencies for bioaccumulation and biomagnification in terrestrial ecosystems (Chesser et al. 2001, UNSCEAR 2020). Although the Chernobyl accident is the best-known example, there are other significant events in the period 1945–2011. The Fukushima accident in 2011 presents a new precedent – the reactors in the plant were nearing the end of their design life (UNSCEAR 2020). Since this is true for many of the currently operating reactors, crumbling nuclear infrastructure may present a significant radiation hazard in the future.

Some of the risks to ecosystems posed by radionuclide contamination are well understood. They include, at high doses >1 Gy acute dose, teratogenesis in developing embryos, stunted plant growth, visible damage to the flora and fauna. These are known as deterministic effects, because they occur definitely after exposure to strong doses of ionizing radiation and are dose-dependent. More worrying are the so-called stochastic effects, which occur with a small probability even at low radiation doses. These include radiation mutagenesis and, as a consequence of it, radiation carcinogenesis (Hall and Giaccia 2006; ICRP 2007). Based on data from mouse experiments and results from the monitoring of survivors of Hiroshima and Nagasaki, it is estimated that the

doubling dose of radiation-induced mutagenesis is 1 Gy; an acute exposure to 1 Gy of γ-rays doubles the spontaneously occurring rate of mutation (Russell et al. 1958). However, this perspective is being challenged. For example, Goncharova and Riabokon (1998) observed transmission of chromosomal damage in the progeny of wild rodents from the vicinity of Chernobyl, indicating genomic instability. Another, more recent venue of research with significant progress, is the radiation-induced bystander effect (RIBE**)** phenomenon, in which non-irradiated cells show similar cytotoxicity and genetic damage to their irradiated neighbours (Osterreicher et al. 2003; Wang et al. 2018). The results from bystander effect studies generally support the theory of low-dose hypersensitivity and highlight possible molecular mechanisms for increased radiation risks in the low-dose range (Osterreicher et al. 2003; Wang et al. 2018). Dubrova et al. (1996) report a higher mini- and microsatellite mutation rate in the children of Chernobyl liquidators. The same concern was raised in a more recent study (Bazyka et al. 2020). Both of these findings support the theory that even low doses of radiation can be harmful to the biota. Radiation risk is still to be taken very seriously, and every effort should be made to keep radioactive contamination of ecosystems to a minimum.

Petroleum products

All types of oil differ by their chemical composition, weight, prior refinement, concentration of heavy metals, sulphur, and other impurities. Oil spills involve accidental contamination by oil ranging from various grades of crude oil to different refined products, from heavy fuel oil to light, less persistent, but very toxic fuels. The chemical composition of the spilled oil, and the associated weathering reactions, determine their fate, behaviour, and impact in the marine environments. Oil spills are of great concern due to the long period of oil and gas exploitation and the adverse impacts of the marine environment and these various undesirable repercussions have been documented. (Murawski et al. 2021).

On February 15, 1996 the oil tanker "Sea Empress" lost 72,000 t of crude light oil and 370 t of heavy fuel oil of her cargo in the North Sea. Over 100 km of coastline were affected. Estimates suggest that overall, 200 km of coastline has been affected. A further 25,000 tons of waste were created by the clean-up operation. The "Sea Empress" ranks as one of the world's top 10 oil spills (Johnson and Butt 2006).

The 2010 "Deepwater Horizon" oil spill is considered the largest marine environmental disaster in North America. Over 200 million gallons of oil poured into the Gulf and contaminated the coast. It is estimated that up to 170,000 people worked to clean up the Gulf oil spill. This event is now considered to be the worst environmental disaster in US history, with massive ecotoxic effects on sea life and human habitats. The ecological effects were drastic and longstanding, affecting all biota of all trophic levels ranging from microorganisms and algae to pelagic fish, marine invertebrates, mammals, and seabird populations, marine mammals from whales to otters, and plankton populations (Lee et al. 2015).

Crude oil releases the most harmful toxins into the water and air within a short time. The rest of the toxins are broken down by microorganisms in the sea water, but before this, crabs, shellfish and fish concentrate toxins in their bodies. The toxins are then bioaccumulated in higher trophic levels. It could take decades to understand how oil affects the next generation of whales, coral, sea turtles, birds, fish, and other marine life.

The toxic effects of oil spills to wildlife can be categorized as lethal and sublethal. Basically, assessments of environmental impacts of oil spills are based on evaluating concentrations of pollutants required to kill 50% of individuals in test animals' toxicological experiments to estimate lethal concentrations or other effective concentrations (Bejarano et al. 2014). In this way considerable research was conducted to assess traditional biomarkers of biological endpoints (Mitchelmore et al. 2020) and to develop and apply suites of sublethal indicators of aquatic biota health in order to understand the induction of health effects involving immune system function, genomic changes, reproductive success, growth effects, and impairment of various organ systems in affected species (Sherwood et al. 2017; Grosell and Pasparakis 2021; Rodgers et al. 2021). Most often, research on pollutant effects on gene expression is conducted with model organisms. At the sub-molecular level, chemical and physical effects can lead to genetic rearrangements (mutations); destructive ionization in the tissues of every living being, sometimes with completely unexpected consequences for humans.

Ten years after it happened, the "Deepwater Horizon" oil spill continues to harm wildlife. The spill affected 320 miles of shoreline and affected the rich and complex ecosystem of the Gulf. The future duration and magnitude of that impact is uncertain, principally because scientists do not know how the pollutants will affect the Gulf ecosystem in the long term. Observations of damaged corals indicate impact at a depth of 1,370 m, 11 km from the site of the blowout.

Deep-water colonial corals together with ophiuroid symbionts may provide a more sensitive indicator of the impact from petroleum hydrocarbons. They are important habitats for shrimp, crabs and other marine life. Coral colonies presented widespread signs of stress, including varying degrees of tissue loss, sclerite enlargement, excess mucus production, bleached commensal ophiuroids, and are covered by brown flocculent material (floc).

Shellfish can digest oil, which could cause changes in reproduction, growth rates or even death. Fish in oil spill areas show reduced reproduction even years after the spill, because oil remaining in the environment is still toxic to fish larvae. Oil exposure in fish can lead to cancer and eventually to death, but it can also result in reproductive changes. Particularly the nesting habitats of sea turtles are affected. At least 402,000 were exposed to oil during the spill. Sea turtles are extremely sensitive to the effects of contact with oil. Young and juvenile turtles have been found to starve to death when their beak and oesophagus have become blocked with petroleum residue. Birds were among the hardest-hit animals immediately after the spill. The oil coating their feathers had reduced their ability to regulate their body temperatures due to feather damage. Marine mammals face a more expansive threat than most other coastal biota due to their large geographical range. Physical contact with oil has shown to have substantial negative and lethal effects on many varieties of marine mammals, although

the cumulative long-term effects of consumption of petroleum-laden food sources are ongoing (Geraci 2012). Thousands of dolphins died in the months following the spill, after they ingested toxins. They are important indicators of the overall health of the ocean. Humans suffer from oil-related cancers. For many other species, the damage is not clear. Many species have been difficult to study. That's because scientists knew little about the habits of many deepwater marine mammals before the spill, so have trouble detecting changes from current data (Lee et al. 2015).

China, the United States, India and Russia are four of the world's top polluters. At least 10 countries have national ecocide laws, including Vietnam, which enacted the law in 1990. Oil spills in remote high-energy locations will quickly disperse, and are difficult to reach or remediate through dispersal methods. The removal methods are expensive, labour-intensive, cause further environmental degradation, and are overall ineffective (Lee et al. 2015).

Conclusions

The complete destruction of an ecosystem due to human activities may result from exploitation of resources, nuclear warfare or the dumping of harmful chemicals. Ecocide includes all major environmental disasters which would have severe consequences on the Earth's ecological system. Even years after the accidents it is still much too early to assess the full impact. Decontamination will continue for a long period, probably more than 40 years.

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