RÉPUBLIQUE
FRANÇAISE
Liberté
Égalité
Fraternité

IRSN
INSTITUT DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

BRIEFING NOTE

DATE: **21/04/2021**

Effects of the Chernobyl and Fukushima accidents on ecosystems: current knowledge

In the mass media, the public was able to see both reports and works of fiction on the flora and fauna present in areas contaminated by the major nuclear accidents which occurred at the Chernobyl Nuclear Power Plant on 26 April 1986 and the Fukushima Daiichi Nuclear Power Plant on 11 March 2011.

The observations presented in these reports raise questions about the effects of the contamination of these sites on fauna and flora. There has been a lot of research on some wild species in these areas, and this research is helping to better understand the effects of radioactive contamination on ecosystems - radioactive contamination that has been present on these sites for 35 years at Chernobyl and 10 years at Fukushima.

Introduction

The Chernobyl and Fukushima-Daiichi nuclear accidents resulted in significant radioactive releases into the environment. The characteristics of these releases are described and compared in the brief: Fukushima and Chernobyl accidents: Different impacts on the environment published on the IRSN website.

The radionuclides emitted during these nuclear accidents were deposited, then dispersed and redistributed in the environment over the years. The flora and fauna in these areas are exposed to ionizing radiation in two ways: external exposure induced by radiation emitted by radionuclides present in the environment, and internal exposure induced by radionuclides ingested, inhaled, or absorbed by wildlife.

The radionuclides emitted during the accidents led to acute exposure of wildlife immediately after the accident, and this exposure had deleterious effects on certain species in the contaminated areas. Today, the individuals constituting the wildlife in the contaminated areas remain chronically exposed to radionuclides present in the environment every day and come from successive generations which have been produced by individuals that were initially exposed or by those which subsequently migrated to contaminated areas.

These observations raise various questions, such as are the effects observed in the short term still visible? Have new effects, unrelated to short-term effects, appeared?

The work presented below aims to shed light on these questions and is based on recent knowledge (published mainly since 2016) on the effects on the wildlife in the areas contaminated by the Chernobyl and Fukushima nuclear disasters. They supplement the knowledge provided in the brief drafted in 2016 by IRSN which can be consulted here: What have we learned from the ecological studies carried out over the long term on the fauna and flora of the territories contaminated by the Chernobyl and Fukushima accidents?

I - The first sign: the abundance of organisms

To study the populations status, one of the methods frequently used in ecology is the estimation of the abundance of individuals. A variation in abundance makes it possible to quickly integrate and estimate many deleterious effects of ionizing radiation on populations. Numerous studies have been carried out on different groups of organisms since the accidents and show contrasting results depending on the region (Chernobyl, Fukushima) and the group considered (birds, insects, mammals, etc.).

In the Chernobyl region, several research teams have quantified the abundance of large mammals; however, the results obtained are contradictory (see IRSN 2016, Møller and Mousseau, 2013, Deryabina et al., 2015, and Gurung et al., 2015) . More recently, old data, collected by teams that had previously carried out abundance measurements in the field, was re-analysed by integrating a new estimate of the dose absorbed by organisms (Beaugelin-Seiller et al., 2020). Various parameters that could influence abundance were taken into account (human activities in the exclusion zone, time of observation, and type of forest cover). As the abundance estimation method is based on tracks observed in the snow, the time elapsed since the last snowfall was also considered as a parameter. This new study confirms the conclusions of the first analysis carried out in 2013 and shows that the measured abundances actually depend on the estimated dose (the absorbed dose rates being between 0.0066 and 610 µGy/h): in the most contaminated environments, a 60% decrease in the number of mammals is observed for an increase of a factor of 10 in the dose (total dose absorbed during the generation time of the species considered), this decrease being greater for ‘prey’ (66%) than for ‘predators’ (50%).

In Fukushima Prefecture, an a team of American researchers, in cooperation with a Japanese research centre, also investigated the abundance of mammals and galliform birds following the accident, using camera traps (Lyons et al., 2020). As in the previous study, the authors analysed the relationships between radiation levels and the abundances of these organisms and also considered other parameters, such as human activity (distance to the closest trail and its use), vegetation, altitude, and the distance to the nearest waterpoint. This is the first study in Fukushima Prefecture to consider the impact of human activity. This parameter turns out to be very important because the results show that it is the primary factor affecting the abundance of populations, with a majority of species being more abundant in areas where human activity is limited. Among other major parameters, the authors also demonstrated the effect of altitude on population abundance. In contrast, the abundance of wild animals does not generally seem to depend on the ambient dose. Only one species of pheasant is more abundant in the most contaminated areas. This study is constrained by the lack of precise measurements of the dose received by organisms; however, it emphasises the **importance of considering the effect of human activities on wild populations to discern the potential effects induced by exposure to ionizing radiation from those influenced by other factors.**

Marine species present on a wide swath of the east coast of Japan, including Fukushima Prefecture, were monitored in 2012 and 2013. The diversity and abundance of species present in the tidal zone presented a dependence on the distance to the Fukushima Nuclear Power Plant. Specifically, the absence of a common mollusc (*Thais clavigera*) in all of the sites studied near the power plant (Horiguchi et al., 2016) was observed in 2012, while the parts of the coast only affected by the tsunami were not impacted. More recent monitoring has, on the contrary, revealed an increase in the abundance and diversity of organisms in the areas closest to the plant, four to five years after the accident (Horiguchi et al., 2020). These studies show the importance of monitoring the abundance of populations over time, which makes it possible to distinguish the effects resulting from acute exposure (short duration, generally associated with high doses) from those resulting from chronic exposure (longer duration, usually associated with low doses).

The abundance measurement therefore provides a first glimpse of the status of wildlife populations exposed to ionizing radiation; however, the healthof the individuals observed cannot be assessed using this measurement alone. In addition, if the reproduction of individuals inhabiting the most contaminated areas is impacted, a 'source-sink' dynamic falls into place: the weak competition for resources induced due to limited reproduction in the most contaminated areas can promote the migration of individuals towards these areas. This hypothesis has been verified for barn swallows (*Hirundo rustica*) in the Chernobyl region (the ambient dose rate average on the various sites studied is between 0.22 and 3.42 µSv/h) (Møller et al., 2006). Populations estimated to be abundant may thus consist of individuals with different past exposure to ionizing radiation. **It is therefore fundamental to study, more precisely, whether individuals in the most contaminated areas have capacities (survival, reproduction, etc.) identical to those present in the least contaminated areas.**

II - What are the long-term individual effects?

Exposure to ionizing radiation can affect the biological functions of living organisms. Numerous studies carried out *in situ* in the Chernobyl region and, to a lesser extent, in the Fukushima region have shown that radioactive contamination of the environment can generate effects in different species, such as oxidative stress, genetic damage, depression of the immune system, sperm malformations, slowing of the ability of cells to multiply, partial albinism, and cataracts (Møller and Mousseau, 2006; Geras'kin et al., 2008; Aliyu et al., 2015; IRSN 2016; Cannon and Kiang, 2020; and, more specifically, e.g. monkey: Ochiai et al., 2014, Hayama et al. 2017, Urushihara et al. 2018; butterfly: Taira et al., 2014).

However, while these effects are real, in many cases the dose rates described by the authors are often misjudged. Indeed, in many studies only a portion of the exposure of organisms to radiation is taken into account: it is limited to external gamma irradiation, and does not consider internal contamination, the predominant route of exposure for many combinations of organisms and radionuclides (Giraudeau et al. 2018). It should also be noted that some of the studies carried out *in situ* did not reveal any significant negative impacts of ionizing radiation at the individual level (e.g. crustaceans: Fuller et al., 2017, 2018; frog: Giraudeau et al., 2018; fruit fly: Itoh et al., 2018).

These studies confirm that, in addition to the dose absorbed by organisms, the radiosensitivity of the species, the biological function studied, the life stage at which the organism is exposed, the transgenerational effects (Taira et al. 2015), and adaptation capacities must be considered to assess the effects of ionizing radiation (Shuryak I., 2020).

Recent methodological advances should be highlighted. They involve carrying out a global analysis without any *a priori* on the biological functions of organisms, based on changes in gene expression (transcriptomic analysis). This is how Lerebours et al. (2020) studied, thirty years after the Chernobyl nuclear accident, the effects of radioactive contamination of six Ukrainian and Belarusian lakes on a species of fish, the perch (*Perca fluviatilis*); the total dose rate to which the perch were exposed varied from 0 to 15.7 µGy/h. However, the analysis should be treated with caution, as it was only carried out on three individuals per lake. However, it highlights disturbances in the expression of genes involved in biological processes, such as reproduction, the regulation of DNA damage, and lipid metabolism, consistent with effects on the maturation of oocytes which have been demonstrated in a companion study on a larger number of fish (Lerebours et al. 2018). Another study without any *a priori* on the spleen and liver of bank voles, *Myodes glareolus*, (Kesäniemi et al. 2019) collected in the Chernobyl Exclusion Zone and around Kiev, demonstrated effects on the immune system and lipid metabolism. A dose estimate was performed on each animal. Once again, the importance of these changes on the survival of the animals remains difficult to assess but indicates a modification of certain biological functions linked either to the adaptation of these individuals or to the deterioration of their health status.

However, these global analyses, without any a priori, present a methodological challenge because the numbers studied are often limited, inter-individual variations can mask the desired effects, and the databases necessary for data analysis are often non-existent for the wild species studied. The conclusions that can be drawn at this stage should therefore be treated with caution and cross-referenced with the results and observations obtained by means of approaches deployed at a larger scale for the study of radiation effects on ecosystems.

III - Do the effects on individuals induce persistent changes within the population?

Within the same population, not all individuals have the same characteristics (morphology, behaviour, physiology, etc.). Certain characteristics can be favoured by a selection effect if they allow individuals to be better able to survive and reproduce in contaminated environments. These individuals are selected, they have more offsprings and/or a better survival rate. Over the generations, these offsprings can come to constitute the majority within the population. Such characteristics are called adaptations. Since the Chernobyl and Fukushima accidents, several generations of organisms have succeeded one another and it is probable that such adaptations have taken place. Numerous studies have thus focused on the adaptation of organisms to ionizing radiation, particularly in the case of the Chernobyl accident, and have been compiled in a literature review (Møller et al., 2016). **This adaptation process is often mentioned in the interpretation of certain results obtained in the field but remains very difficult to demonstrate.** To identify an adaptation, it is necessary, in particular, to demonstrate that it persists even after several generations placed in an uncontaminated environment. This review concluded that, in 2016, only one study could demonstrate this. After irradiating bacteria present on swallow feathers from different contaminated sites in the Chernobyl region and from a control site in Denmark, the authors of this study (Ruiz-Gonzalez et al., 2016) found evidence of better bacteria survival and multiplication capacities in those from more contaminated areas (compared to those from less contaminated areas, ambient dose rates being between 0.03 and 2.9 µGy/h).

Since 2016, new studies seeking to test this adaptation hypothesis have been carried out in the Chernobyl region. In one of the most recent studies (Arnaise et al., 2020), the authors studied a potential adaptation of fungi infecting the reproductive parts of a flowering plant. By experimentally irradiating fungi taken from more or less contaminated areas (with ambient dose rates of between 0.03 and 21.03 µSv/h), they demonstrated that fungi from the most contaminated areas are less resistant to effects of acute and strong experimental irradiation. These results contradict what would have been expected if the fungi from the most contaminated areas had acquired radiation adaptation since the accident.

While these adaptations are often seen as beneficial for the viability of wild organisms in contaminated areas, this specialisation can, however, be a handicap in the face of other stresses. In the event that environmental changes, modifying the living environment of these organisms, appear in contaminated areas, it is possible that organisms adapted to ionizing radiation are less likely to withstand new environmental changes (for example, those induced by drought and the more frequent forest fires in the Chernobyl exclusion zone). As such, the destruction of bird nests in the spring by fires is likely to affect the dynamics of bird populations specifically adapted to organisms in the Chernobyl exclusion zone (Beresford et al., 2021).

A major direction of research today is therefore to characterise the potential of populations to withstand future changes in the environment.

The adaptation potential of populations is dependent on evolutionary processes involving a persistent modification of populations over time. This potential can be assessed by measuring genetic diversity.

In the case of the Chernobyl accident, several studies have considered this genetic diversity. A first study, carried out on bank voles (*Myodes glareolus*) (Baker et al, 2017), revealed the existence of a greater genetic diversity in the most contaminated areas (the absorbed dose rates are between 0.29 and 277.92 µGy/h). The authors conclude that there is a greater number of mutations in the most contaminated areas but the effect of migration of individuals towards these areas would also make it possible to obtain such diversity (see ‘source-sink’ dynamics discussed above, Kesäniemi et al., 2018). On the contrary, recent studies on aquatic crustaceans (*Asellus aquaticus*) (for absorbed dose rates between 0.064 and 27.1 µGy/h) and earthworms (for absorbed dose rates between 0.096 and 53 µGy/h) do not show a difference in diversity depending on the contamination level (Fuller et al., 2019 and Newbold et al., 2019).

Based on an analysis of the genetic diversity of populations of tree frogs, Eastern tree frogs (*Hyla orientalis*), a study led by IRSN recently showed, in a similar way to bank voles, an increase in genetic diversity in the Chernobyl exclusion zone compared to other populations located in less contaminated areas (absorbed dose rates between 0.007 and 22.4 µGy/h) (Car et al., submitted). By taking into account the known variations in the genetic diversity of this species in Europe, this study shows that mutations appear more frequently in the populations in the Chernobyl exclusion zone (an occurrence frequency approximately one hundred times higher than that known). It is accepted that when a large number of mutations appear, only a minority allow adaptation to the environment. Indeed, the majority of mutations do not modify the characteristics of individuals or induce deleterious effects. This high genetic diversity in populations of tree frogs in the Chernobyl exclusion zone has been modelled. The models show that this diversity could only be established in populations comprising a small number of individuals. This study found that among the initial population, only this small number of individuals, which have the genetic diversity observable today, have adapted to the irradiating environment. The others have probably disappeared due to the deleterious effects of the mutations generated by the radiation.

Depending on different characteristics (number of offspring per litter, lifespan, etc.), organisms, such as large mammals, could be more sensitive than tree frogs to such deleterious mutations. A meta-analysis of studies using various methods and on many groups of organisms was carried out by Møller and Mousseau (2015) and shows a significant effect of ionizing radiation on the increase in mutations following the Chernobyl accident. However, they do not show a downward trend in mutations over time, which could have been expected due to the reduced exposure of the organisms. If this effect of ionizing radiation seems applicable to many groups of organisms, **the detailed study of the impact on genetic diversity concerns, for the moment, only a few of these groups which does not allow us, today, to have a precise view of the effects of nuclear accidents on the long-term evolution of populations.**

IV - Considering interactions between organisms: what are the consequences on ecosystem functioning?

The effects of nuclear accidents are generally studied at the scale of an individual or populations of the same species; however, an ecosystem is not just a juxtaposition of organisms. Indeed, interactions shape these ecosystems, ranging from the predation of certain mammals to mutualisms between bacteria and plant roots, including the reproduction of flowering plants through pollinators. A particularly interesting direction of current research aims to consider these interactions when studying the effects of ionizing radiation.

One of the first studies on the effects of ionizing radiation on ecosystems and the interactions that constitute them was carried out by Møller et al. (2012). After observing a decrease in the abundance of birds and pollinating insects in the most contaminated areas, the authors studied the abundance of young fruit trees. Since these trees are dependent on pollinating insects, which allow the exchange of pollen to take place, and on birds, which allow the dispersal of seeds, the authors hypothesised that these decreases in animal abundance could induce a decrease in young fruit trees. The results of this study actually show a decrease in the abundance of young fruit trees depending on the contamination of the environment (ambient dose rates are between 0.01 and 379.70 µSv/h) and highlight the dependence of this abundance of young fruit trees to the decrease in pollinating insects and fruit-eating birds. Thus, in addition to the potential deleterious effects of ionizing radiation on these fruit trees, inter-species interactions can induce effects, which are termed '**indirect effects**'.

A particularly interesting and well-documented example of an indirect effect induced by ionizing radiation is that of pale grass blue butterflies (*Zizeeria maha*) in Fukushima Prefecture. Since the Fukushima accident, many studies have focused on this butterfly, demonstrating, for example, an increase in abnormalities in the wings, eyes, antennae, legs, and mouth parts of the butterflies sampled in the most contaminated areas (ambient dose rates between 0.08 and 3.09 µSv/h) (Hiyama et al. 2012). To understand the mechanisms behind this effect, researchers reared caterpillars in the laboratory by feeding them with their host plant, yellow sorrel (*Oxalis corniculata*). By feeding caterpillars with yellow sorrel from environments contaminated by the accident, the authors observed effects (e.g. morphological anomalies) identical to those observed in the field. However, when the caterpillars are directly contaminated with radionuclides, without going through contamination by yellow sorrel, such effects are no longer observed (Gurung, 2018). The authors of this study therefore suspected an indirect effect of ionizing radiation linked to yellow sorrel and to the modification of the plant's composition after contamination. The most recent study on this butterfly-yellow sorrel interaction indeed shows a change in the nutrient composition of sorrel leaves after contamination, with, in particular, a decrease in sodium concentration (Sakauchi et al., 2021). The link between the modification of the nutrients present in the leaves and malformations still needs to be studied, but this example shows to what extent the **very specific effects of contamination by radionuclides on certain organisms can potentially induce a set of modifications on other organisms, in a cascade, and therefore on the entire associated ecosystem.**

A recent question addressed by Mappes et al. (2019) was to ask if the impact of contamination on organisms can be modulated by indirect effects. More precisely, can the effects of ionizing radiation on voles (*Myodes glareolus*) inhabiting the Chernobyl contaminated zone be modulated by food supplementation? Without food supplementation, the authors observed that the abundance of voles decreased with an increase in exposure to ionizing radiation (ambient dose rates between 0.01 to 95.55 µSv/h). Food supplementation only led to an increase in the abundance of populations in locations where radioactive contamination was low (<1 µSv/h); in areas with higher contamination, food supplementation showed no detectable effects. The authors therefore conclude that food supplementation can, to a certain extent, mitigate the harmful effects of an environment contaminated by radionuclides. Once again, this study highlights **the importance of considering the interactions between organisms in the field which can profoundly influence the relationships between exposure to ionizing radiation and its effects.** Since interactions between organisms can be impacted by exposure to ionizing radiation, this can ultimately affect the functioning of the contaminated ecosystem. To study these effects, the major functions structuring ecosystem functioning, such as the decomposition of organic matter (dead plant material, commonly known as 'litter'), were studied in the Chernobyl region.

Mousseau et al. (2014) demonstrated a decrease in the rate of leaf litter decomposition and an increase in the thickness of the litter on the ground related to an increase in ambient radioactivity (the absorbed dose rate is between 0.09 and 240 µGy/h). These results suggest slower recycling of organic matter in response to a higher level of ambient radioactivity, possibly due to a negative impact on communities of decomposers (bacteria, fungi, invertebrates). Conversely, after conducting the same type of experiment, a study led by IRSN showed that the leaf litter decomposition rate increased with an increase in the level of radiation absorbed (the absorbed dose rate is between 0.3 and 150 µGy/h) by decomposers (Bonzom et al., 2016). The authors propose two non-exclusive mechanisms to explain this result: (i) under the effect of moderate stress (here radiological stress) decomposers were able to respond to this disturbance by increasing their survival and reproductive success leading to a greater abundance of decomposers in radioactively contaminated areas. This phenomenon is known as “hormetic effect” (Calabrese and Baldwin, 2002); (ii) the decomposers communities preferentially consumed the litter from uncontaminated areas rather than the contaminated litter which may have a lower quality that was initially in their habitat (for the purposes of the experiment, the uncontaminated litter was in fact deposited above the contaminated litter in the area chosen for the study). Certain parameters, such as the contamination gradient, dose estimate, nature of the leaves used, etc., can explain the contradictory results of these two studies.

The effect of environmental contamination following nuclear accidents on the functioning of ecosystems is only very marginally considered. However, this is an essential research perspective, especially due to the fact that the proper functioning of these ecosystems depends on a set of services these ecosystems provide to human populations (Millennium Ecosystem Assessment, 2005; IPBES, 2019). These ‘ecosystem services’ are of primary importance in the more general study of the effects of global changes and deserves to be more widely integrated into the study of the consequences of nuclear accidents.

References

Aliyu, A., Evangeliou, N., Mousseau, T., et al. 2015. An overview of current knowledge concerning the health and environmental consequences of the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident. Environ. Int. 85:213-28. Epub PMID: 26425805. https://doi.org/10.1016/j.envint.2015.09.020

Arnaise, S, Shykoff, JA, Møller, AP, Mousseau, TA, Giraud, T. 2020. Anther-smut fungi from more contaminated sites in Chernobyl show lower infection ability and lower viability following experimental irradiation. Ecol. Evol. 10: 6409-6420. https://doi.org/10.1002/ece3.6376

Baker, R.J., Dickins, B., Wickliffe, J.K., et al. 2017. Elevated mitochondrial genome variation after 50 generations of radiation exposure in a wild rodent. Evol. Appl. 10: 784– 791 https://doi.org/10.1111/eva.12475

Beaugelin-Seiller, K., Garnier-Laplace, J., Della-Vedova, C. et al. 2020. Dose reconstruction supports the interpretation of decreased abundance of mammals in the Chernobyl Exclusion Zone. Sci. Rep. 10, 1408. https://doi.org/10.1038/s41598-020-70699-3

Beresford, N.A., Barnett, C.L., Gashchak, S., Kashparov, V., Kirieiev, S. I., Levchuk, S., Wood, M.D. 2021. Wildfires in the Chornobyl Exclusion Zone–risks and consequences. Integrated Environmental Assessment and Management. https://doi.org/10.1002/ieam.4424

Bonzom, J-M., Hättenschwiler, S., Lecomte-Pradines, C., et al. 2016. Effects of radionuclide contamination on leaf litter decomposition in the Chernobyl exclusion zone. Sci. Tot. Env., 562 : 596-603. https://doi.org/10.1016/j.scitotenv.2016.04.006

Calabrese, E., Baldwin, L. 2002. Defining hormesis human and experimental. Toxicology, 21, 91–97. https://doi.org/10.1191/0960327102ht217oa

Cannon, G., Kiang, J. 2020. A review of the impact on the ecosystem after ionizing irradiation: wildlife population, International Journal of Radiation Biology, https://doi.org/10.1191/0960327102ht217oa

Car, C., Gilles, A., Armant, A., et al. Unusual evolution of tree frog populations in the Chernobyl exclusion zone. https://doi.org/10.1101/2020.12.04.412114

Deryabina, T., Kuchmel, S., Nagorskaya, L., et al. 2015. Long-term census data reveal abundant wildlife populations at Chernobyl. Current biology. 25(19): 824-826. https://doi.org/10.1016/j.cub.2015.08.017

Fuller, N., Ford, A.T., Lerebours, A., et al. 2019. Chronic radiation exposure at Chernobyl shows no effect on genetic diversity in the freshwater crustacean, *Asellus aquaticus* thirty years on. *Ecol. Evol*. 9: 10135– 10144. https://doi.org/10.1002/ece3.5478

Fuller, N., Ford, A., Nagorskaya L., et al. 2018. Reproduction in the freshwater crustacean *Asellus aquaticus* along a gradient of radionuclide contamination at Chernobyl. Sci. Total Environ. 628-629:11-17. https://doi.org/10.1016/j.scitotenv.2018.01.309

Fuller, N., Smith, J., Nagorskaya, L., et al. 2017. Does Chernobyl-derived radiation impact the developmental stability of *Asellus aquaticus* 30 years on? Sci Total Environ. 576:242-250. https://doi.org/10.1016/j.scitotenv.2016.10.097

Geras' Kin, S.A., Fesenko, S.V., Alexakhin, R.M. 2008. Effects of non-human species irradiation after the Chernobyl NPP accident. Environment International, 34(6), 880-897. https://doi.org/10.1016/j.envint.2007.12.012

Giraudeau, M., Bonzom, J-M., Ducatez, S., et al. 2018. Carotenoid distribution in wild Japanese tree frogs (*Hyla japonica*) exposed to ionizing radiation in Fukushima. Scientific Reports. 8(1) : 7438. https://doi.org/10.1038/s41598-018-25495-5

Gurung, R., Taira, W., Sakauchi, K., et al. 2019. Tolerance of High Oral Doses of Nonradioactive and Radioactive Caesium Chloride in the Pale Grass Blue Butterfly *Zizeeria maha*. Insects 10, 290. https://doi.org/10.3390/insects10090290

Hayama, S., Tsuchiya, M., Ochiai, K. et al. 2017. Small head size and delayed body weight growth in wild Japanese monkey fetuses after the Fukushima Daiichi nuclear disaster. Sci. Rep. 14; 7(1):3528. https://doi.org/10.1038/s41598-017-03866-8

Hiyama, A., Nohara, C., Kinjo, S. *et al.* 2012. The biological impacts of the Fukushima nuclear accident on the pale grass blue butterfly. Sci Rep 2, 570 https://doi.org/10.1038/srep00570

Horiguchi T., Kodama K., Kume G., Kang I.J. 2020. Delayed Recovery from Declines in the Population Densities and Species Richness of Intertidal Invertebrates Near Fukushima Daiichi Nuclear Power Plant. In: Fukumoto M. (eds) Low-Dose Radiation Effects on Animals and Ecosystems. Springer, Singapore. https://doi.org/10.1007/978-981-13-8218-5_6

Horiguchi, T., Yoshii, H., Mizuno, S. et al. 2016. Decline in intertidal biota after the 2011 Great East Japan Earthquake and Tsunami and the Fukushima nuclear disaster: field observations. Sci Rep. 6, 20416. https://doi.org/10.1038/srep20416

IPBES, 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. https://ipbes.net/global-assessment

IRSN 2016. Adam-Guillermin C, Armant O, Bonzom J-M, Henner P, Lecomte C. 2016. Conséquences écologiques des accidents nucléaires de Tchernobyl et Fukushima. Rapport n° IRSN/PRP-ENV/SERIS/2016-006

Itoh, M., Kajihara, R., Kato, Y. et al. 2018. Frequencies of chromosomal inversions in Drosophila melanogaster in Fukushima after the nuclear power plant accident. PLoS One. 13(2):e0192096. DOI: 10.1371/journal.pone.0192096

Kesäniemi, J, Boratyński, Z, Danforth, J, et al. 2018. Analysis of heteroplasmy in bank voles inhabiting the Chernobyl exclusion zone: A commentary on Baker et al. (2017) "Elevated mitochondrial genome variation after 50 generations of radiation exposure in a wild rodent". Evol. Appl. 11: 820– 826. https://doi.org/10.1111/eva.12578

Kesäniemi, J., Jernfors, T., Lavrinienko, A. et al. 2019. Exposure to environmental radionuclides is associated with altered metabolic and immunity pathways in a wild rodent. Mol. Ecol. (20):4620-4635. https://doi.org/10.1111/mec.15241

Lerebours, A., Gudkov, D., Nagorskaya, L., et al. 2018. Impact of Environmental Radiation on the Health and Reproductive Status of Fish from Chernobyl. Environ Sci Technol. 52(16):9442-9450. https://doi.org/10.1021/acs.est.8b02378

Lerebours, A., Robson, S., Sharpe, C., et al. 2020. Transcriptional Changes in the Ovaries of Perch from Chernobyl. Environ Sci Technol. 54(16):10078-10087. https://doi.org/10.1021/acs.est.0c02575

Lyons, P., Okuda, K., Hamilton, M., et al. 2020. Rewilding of Fukushima's human evacuation zone. Front Ecol Environ. 18(3) : 127-134. https://doi.org/10.1002/fee.2149

Mappes, T., Boratyński, Z., Kivisaari, K., Lavrinienko, A., Milinevsky, G., Mousseau, T. A., Møller, A. P., Tukalenko, E., and Watts, P.C. 2019. Ecological mechanisms can modify radiation effects in a key forest mammal of Chernobyl. Ecosphere 10(4):e02667. https://doi.org/10.1002/ecs2.2667

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC. http://www.millenniumassessment.org/en/Synthesis.html

Møller, A. and Mousseau T. et al. 2013. Assessing effects of radiation on abundance of mammals and predator–prey interactions in Chernobyl using tracks in the snow. Ecological Indicators. 26 : 112-116. https://doi.org/10.1016/j.ecolind.2012.10.025

Møller, A., Hobson, K., Mousseau, T., et al. 2006. Chernobyl as a population sink for barn swallows : tracking dispersal using stable-isotope profiles. Ecological Applications. 16 : 1696-1705. https://doi.org/10.1890/1051-0761(2006)016[1696:CAAPSF]2.0.CO;2

Møller, A., Mousseau, T. 2006. Biological consequences of Chernobyl: 20 years on. Trends Ecol Evol. 21(4):200-7. https://doi.org/ 10.1016/j.tree.2006.01.008

Møller, A., Mousseau, T. 2015. Strong effects of ionizing radiation from Chernobyl on mutation rates. *Sci Rep* **5,** 8363.,https://doi.org/10.1038/srep08363

Møller, A.P., Barnier, F. Mousseau, T.A. 2012. Ecosystems effects 25 years after Chernobyl: pollinators, fruit set and recruitment. *Oecologia* 170, 1155–1165. https://doi.org/10.1007/s00442-012-2374-0

Møller,A. and Mousseau,T. 2016. Are Organisms Adapting to Ionizing Radiation at Chernobyl? Trends in Ecology & Evolution 31 (4): 281-289 https://doi.org/10.1016/j.tree.2016.01.005

Mousseau, T.A., Milinevsky, G., Kenney-Hunt, J. et al. 2014. Highly reduced mass loss rates and increased litter layer in radioactively contaminated areas. Oecologia 175, 429–437. https://doi.org/10.1007/s00442-014-2908-8

Newbold., L., Robinson,A., Rasnaca, I., et al. 2019. Genetic, epigenetic and microbiome characterisation of an earthworm species (*Octolasion lacteum*) along a radiation exposure gradient at Chernobyl. Environmental Pollution. 255, Part 1. https://doi.org/10.1016/j.envpol.2019.113238

Ochiai, K., Hayama, S., Nakiri, S. et al. 2014. Low blood cell counts in wild Japanese monkeys after the Fukushima Daiichi nuclear disaster. Sci. Rep. 4:5793. https://doi.org/10.1038/srep05793

Ruiz-González, M., Czirják, G., Genevaux, P. *et al.* 2016. Resistance of Feather-Associated Bacteria to Intermediate Levels of Ionizing Radiation near Chernobyl. *Sci Rep.* **6 :** 22969 https://doi.org/10.1038/srep22969

Sakauchi, K., Taira, W., Toki, M., et al. 2021. Nutrient Imbalance of the Host Plant for Larvae of the Pale Grass Blue Butterfly May Mediate the Field Effect of Low-Dose Radiation Exposure in Fukushima: Dose-Dependent Changes in the Sodium Content. Insects 2021*,* 12*,* 149. https://doi.org/10.3390/insects12020149

Shuryak, I. 2020. Review of resistance to chronic ionizing radiation exposure under environmental conditions in multicellular organisms. J. Environ. Radioact. 212:106128. https://doi.org/10.1016/j.jenvrad.2019.106128

Taira, W., Hiyama, A., Nohara, C., et al. 2015. Ingestional and transgenerational effects of the Fukushima nuclear accident on the pale grass blue butterfly. J Radiat Res. 56 Suppl:i2-18. https://doi.org/10.1093/jrr/rrv068

Taira, W., Nohara, C., Hiyama, et al. 2014. Fukushima's biological impacts: the case of the pale grass blue butterfly. J Hered. 105(5):710-22. https://doi.org/10.1093/jhered/esu013

Urushihara, Y., Suzuki, T., Shimizu, Y. et al. 2018. Haematological analysis of Japanese macaques (*Macaca fuscata*) in the area affected by the Fukushima Daiichi Nuclear Power Plant accident. Sci Rep. 8(1):16748. https://doi.org/10.1038/s41598-018-35104-0