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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?

Thirty and five years respectively after the two major nuclear accidents that occurred at the Chernobyl and Fukushima power plants, the ecological studies carried out on the fauna and flora exposed to chronic ionising radiation deliver conclusions that are often contradictory, notably due to the complexity of the multidisciplinary approaches that need to be deployed for an unbiased interpretation of the effects observed.

A very wide variety of biological effects have been reported in literature following observations of plant and animal species living in contaminated territories in the Chernobyl exclusion zone (and on a broader level, in the contaminated territories of Belarus) as well as in the evacuated areas of Fukushima. Publications concerning invertebrate, vertebrate and plant species report either the absence of effects or effects of varying intensity *e.g.* on development, growth, behaviour and reproduction. One of the finalised objectives of these studies carried out *in situ* mainly from the 2000s onwards for the Chernobyl exclusion zone and only a few months after the Fukushima accident was - and remains - to produce a diagnosis and a forecast of the consequences of these effects on the demographics of the populations of native species exposed to chronic ionising radiation and *in fine* of the existence of damage to the structure and functioning of the ecosystems. In order to establish a definite link between exposure to ionising radiation and the effects observed, these studies must clearly be multidisciplinary in order to prevent multiple interpretation biases (Figure 1).

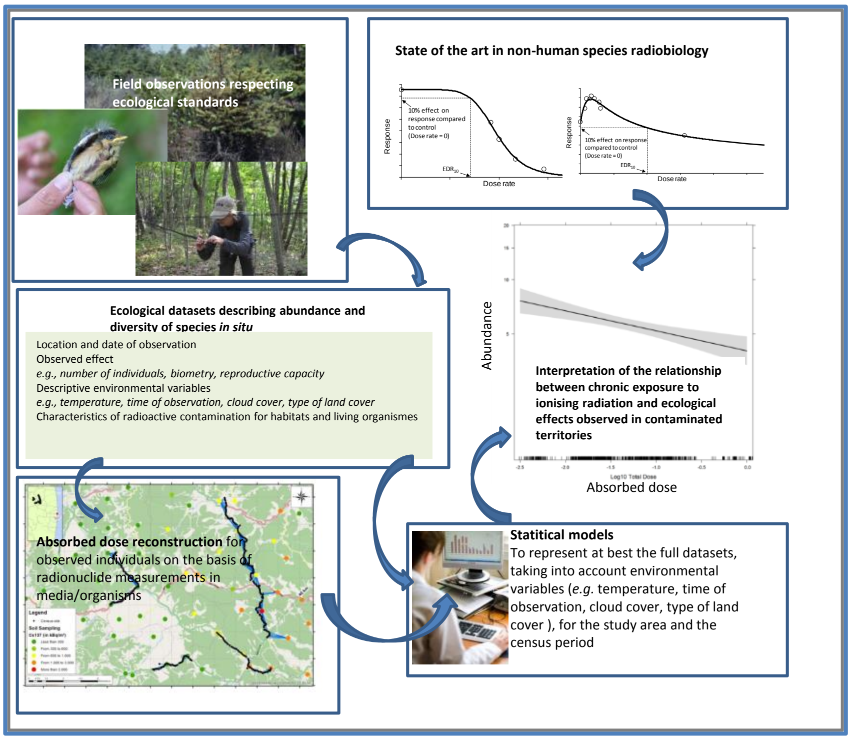

Figure 1 - Integrated multidisciplinary approach requested for the correct interpretation of ecological observations (e.g. abundance and diversity of the species present) conducted on radio-contaminated territories.

Morphological anomalies in pine trees are observed at Chernobyl as well as Fukushima. The frequency of occurrence of these anomalies would appear to be correlated with the dose absorbed by the trees, but the dosimetric estimations proposed by the authors are incomplete and do not enable solid dose-effects relations to be established.

In the Chernobyl exclusion zone, modifications to plant communities are undeniable with, in the acute phase of the accident, the death of pines[1] around the damaged reactor, followed by the progressive establishment of new herbaceous species and deciduous trees. In the highly-contaminated areas where conifers have been able to persist, since 1993, 50-60% of young trees aged between two and nine years present abnormal morphogenesis (Zelena *et al.,* 2005), in particular a loss of apical dominance (*i.e.* loss of the apical bud) in conjunction with the death of the buds' meristems (tissue responsible for growth). On the other hand, anomalies concerning reproductive capacities have not been significant since 1995. The most recent analyses conducted on pines planted in the exclusion zone after the accident and subject to chronic exposure have shown that 10% and 50% of the trees exposed to a total dose rate (external and internal irradiation) of 1 and 40 µGy/h respectively, present morphological anomalies (Yoschenko *et al.,* 2011). Mousseau *et al.* (2013) reported an effect on the growth of pines at Chernobyl depending on the absorbed dose; however their study shows limitations with regard to the estimation of the level of exposure that was only evaluated through the ambient dose rate, ignoring the contribution of the internal contamination of the trees at the absorbed dose. To date, only one study addressing the consequences to trees of fallout from the Fukushima accident has been published (Watanabe *et al.*, 2015)[2]. For sites in the contaminated territories where the 2015 ambient dose rate lies between 5 and 40 µGy/h, a significant frequency of increased loss in the apical dominance of the Japanese fir (*Abies firma*) is highlighted (Figure 2). Although this study contains weaknesses in its statistical analysis and does not present an estimation of the cumulative dose by the trees, the frequencies of occurrence of the damage are consistent with the observations highlighted in the Chernobyl pines. Moreover in these studies, where the dose absorbed by trees is somewhat underestimated in relation to the real dose - due to the contribution of internal contamination not being taken into account - dose rates are generally of the same order of magnitude than the variation range of dose rates corresponding to a very low probability of the occurrence of deleterious effects on individuals published by CIPR 108 (CIPR, 2008), i.e. 4 to 40 µGy/h, and consistent with those implying morphological damage (from 40 to 400 µGy/h).

[1]During the first weeks following the accident, 90% of pines (*Pinus sylvestris* L.) died in a 6 km^2 zone around the power plant due to the lethal dose absorbed of 60-100 Gy (Geras'kin *et al.,* 2008).
[2]This study was the subject of an IRSN information note published on the institute's website in 2015 (in French : http://www.irsn.fr/FR/Actualites_presse/Actualites/Documents/IRSN-Note-Lecture-Fukushima-Pin-Contamination_20151110.pdf)

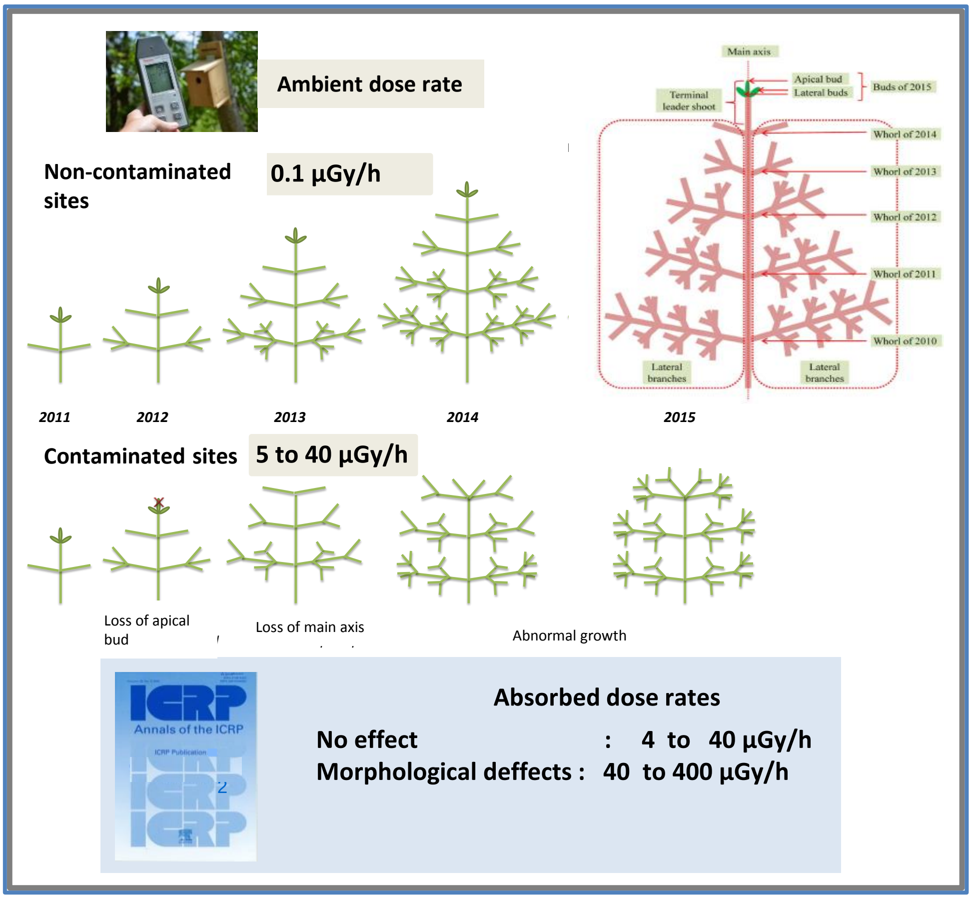

Figure 2 - Schema summarising the study of Japanese pines revealing a significant increase in morphological anomalies in pines depending on the ambient dose rate at the observation site. Comparison with knowledge about the effects of ionising radiation in pines published by the CIPR (2008).

The effects observed on the abundance of terrestrial invertebrates depend on the groups of species studied. For some of these groups only, the evolution of abundance with the ambient level of exposure is different at the Chernobyl and Fukushima sites. According to the authors, the differences in radiosensitivity between species and the effects linked to chronic exposure over several generations are the main explanations behind these differences.

In invertebrates, Jackson *et al.* (2005) observed a decrease in the diversity (but not abundance) of soil invertebrates in the Chernobyl exclusion zone for external dose rates ranging between 0.1 and 140 µGy/h. Møller et Mousseau (2009), for their part, showed a reduction in the abundance of insects (bees, grasshoppers, butterflies, dragonflies) and spiders for external doses of an order of magnitude below those published by Jackson *et al.* (2005). The decline in the abundance of pollinators in the contaminated zones seems to be accompanied by a decrease in fruit production in these same areas (Møller *et al.*, 2012a). Lecomte-Pradines *et al.* (2014) demonstrated a moderate effect of exposure to ionising radiation on the assembly of nematodes[3] collected from forest sites 25 years after the accident, putting forward the hypothesis of the rapid disappearance of the most sensitive species following the accident due to a much higher level of exposure. More recently, a study conducted on invertebrates collected from contaminated sites in the exclusion zone shows a positive correlation between the abundance of certain taxons and the ambient dose rate, whilst other taxons show a negative correlation (Bezrukov *et al.*, 2015). The authors attribute this heterogeneity to a difference in sensitivity regarding exposure to ionising radiation. Finally, a study shows that the descendants of grasshoppers from contaminated sites in the exclusion zone present anomalies with regard to development, survival and reproductive success (Beasley *et al.*, 2012). To

[3] Nematodes are small millimetric worms, found in very diverse environments (fresh/brackish water, soils).

date, only very few studies address the consequences of the Fukushima accident on invertebrate populations. A study carried out on different taxons suggests that the abundance of butterflies and cicada is negatively impacted by exposure to radioactive contamination. However, unlike Chernobyl, no association between the absorbed dose and the abundance of dragonflies, grasshoppers and bees was observed after the first summer following the disaster. An increase in the number of spiders was even observed at the most contaminated sites (Møller *et al.,* 2013). The butterfly *Zizeeria maha* has been used in order to monitor and understand the impact of the contamination from the Fukushima accident[4]. Adults sampled from the contaminated sites in 2011 show morphological anomalies that are not observed at control sites, nor impacted by radioactive fallout. These morphological anomalies are even more acute in the next two generations obtained under control conditions (Hiyama *et al.,* 2012). The monitoring of the populations of this butterfly in contaminated zones between 2011 and 2013 shows a progressive return to normal after two years (Hiyama *et al.,* 2015). Nohara *et al. (*2014) reproduced, in the laboratory, the increase in the mortality and morphological anomaly rates by feeding larvae of butterflies from a control zone with leaves collected in a contaminated area. This result underlines the importance of taking the internal dose into account when evaluating effects (Nohara *et al.,* 2014) but does not inform about the absorbed doses having led to the occurrence of the effects or the molecular mechanisms at the origin of these phenomena. Similarly, acute morphological anomalies as well as increased mortality have been observed in aphid samples taken in spring 2012 from the contaminated zone close to the Fukushima Dai-ichi power plant. Nevertheless, these malformations have not been transmitted to the next generation and, in 2013, the authors observed an improvement compared to 2012 (Akimoto, 2014).

Bird communities have been the subject of long-term observations in the Chernobyl exclusion zone and in the contaminated territories of Fukushima. According to the authors of the publications, the decline in abundance observed in both cases has been correlated with the increase in the ambient dose rate. A recent IRSN study based on a dosimetric reconstruction in Fukushima birds,showed that the effects observed were consistent with knowledge about the reduction in reproductive capacity linked to the increase in absorbed doses.

Various publications by Møller et Mousseau (Møller *et al.,* 2006; Møller et Mousseau, 2009) address, through eco-epidemiological style approaches, the consequences of chronic exposure to ionising radiation in bird populations in the Chernobyl exclusion zone. These studies demonstrate that, more than 30 years after the accident, the specific richness, abundance and density of bird populations in the forest environment decrease with the increase in the level of exposure to ionising radiation. The authors conclude as to the cause of this drastic decrease via a statistical relationship between estimated exposure levels and the intensity of the effects observed at said levels of exposure: the abundance of birds would appear to fall by 60% between "high-level irradiation" sites with 0.1 to 1 mGy/h in external irradiation (without however providing information on the level of internal contamination) and the so-called "control" sites, with around 0.1 µGy/h in external irradiation. The authors put forward the hypothesis of a direct effect of exposure levels to ionising radiation on survival and fertility rates (25% in contaminated zones), reducing population size (Møller *et al.,* 2005) and/or associated indirect effects to avoidance behaviour regarding contaminated habitats (Møller et Mousseau, 2007a) or to a reduction in the abundance of food, essentially comprising soil invertebrates (Møller et Mousseau, 2007b; 2009). The susceptibility of birds differs depending on gender and life stage. Thus, age ratios observed in bird populations in the exclusion zone favour younger life stages, indicating significant mortality in adults. Also, the gender ratio strongly favours males in the most contaminated zones (Møller *et al.,* 2012b).

[4]This study was the subject of an IRSN information note published on the institute's website in 2012 (In French: http://www.irsn.fr/FR/Actualites_presse/Actualites/Documents/IRSN_NI_Effet-biologique-Fukushima-papillon_08102012.pdf).

These effects on life history traits are accompanied by physiological or morphological changes. A high rate of morphological anomalies (e.g. partial albinism, beak malformations, tumours) is also observed in swallows in the exclusion zone, associated with a lower survival rate (Møller *et al.*, 2007). In addition, bird populations from the exclusion zone, all species combined (546 individuals from 48 sampled species), present significantly smaller brains than in the control zones. The authors quantify a reduction of 5% in brain volume when the dose rate varies between 0.02 µGy/h and 100 µGy/h (Møller *et al.,* 2011). In another study carried out by this team, the incidence of cataracts increases with the level of ambient radiation (57 species sampled) (Mousseau et Møller, 2013).

In Fukushima also, a fall in the abundance of birds was observed (45 species) with increasing ambient dose rate levels between March and July 2011 (Møller *et al.,* 2012b). This decline is accentuated over time (from 2011 to 2014, 57 species) (Møller *et al.,* 2015). Based on this dataset describing the Fukushima bird community, Garnier-Laplace *et al.* (2015) carried out dosimetric reconstruction research making it possible to take into account external and internal irradiation channels in order to estimate the absorbed dose, as well as specificities regarding the exposure of birds based on their lifestyle. As a result, reconstructed dose rates can be higher, up to factor 20, compared to the ambient dose rates measured *in situ* by portable survey meters. This new analysis has provided a framework to quantify that 90% of species are chronically exposed to dose rates liable to affect their reproduction, confirming the conclusions of Møller *et al.* (2015) with regard to the link between exposure levels and deleterious effects on bird abundance. The statistical analysis based on the reconstructed dose reveals a significant negative effect from the total absorbed dose on the total number of birds within the community observed in a 50 km radius of the damaged Fukushima power plant over the period 2011-2014 (Garnier-Laplace *et al.*, 2015)[5].

The evacuation of human populations is considered to be a deciding factor concerning the return of animals to the contaminated territories by certain authors having published works on the large mammals of the Belarusian reserves. In a study that has just been submitted to *Biology letters*, IRSN demonstrates, with regard to Fukushima bird communities, that the evacuation status of the zones where observations are carried out does not modify the fall in abundance due to the increase in absorbed dose, but that the abundance is higher in these zones compared to non-evacuated areas. [6]

At the present time, the question relating to the influence of the evacuation of human populations from contaminated territories on the diversity and abundance of animal species is subject to debate. Two recent studies conducted on mammals in the Chernobyl exclusion zone are contradictory. Their abundance has been studied via the counting of tracks in the snow (Møller and Mousseau, 2013). Of the 12 species identified, abundance was correlated negatively with the ambient dose rate, with very marked effects for certain species such as foxes, and much lower for other species such as wolves. The second study paired up multi-annual campaigns to count tracks in the snow as well as counts via aerial surveillance, providing indications as to the dynamics of the mammal populations (Deryabina *et al.,* 2015). The authors conclude that the density of the mammals is not correlated with radioactive contamination. Furthermore, densities of large ungulates, such as elk, roe deer or wild boar, are comparable to those observed in uncontaminated nature reserves, with the wolf density in the exclusion zone even being seven times higher than that observed in said reserves. Finally, 10 years of aerial surveillance data between 1987 and 1996 show an increase in the densities of elk, roe deer and wild boar. Nevertheless, this data does not enable a comparison between the temporal evolution studied in Belarus and that observed in identical

[5]This publication was the subject of an IRSN information document at the time of its publication in November 2015 (http://www.irsn.fr/EN/newsroom/News/Documents/IRSN_Information-Note_Fukushima-Impact-Birds_20151124.pdf)
[6] One of these reserves (Polessye State Radioecological Reserve), corresponds to the Belarus sector of the Chernobyl exclusion zone;

climate zones in Europe, nor does it allow for a separation between the positive effect due to the abandonment of the exclusion zone by human populations (leading to a halt in hunting, farming and logging) and from a potential negative effect of ionising radiation. To date, only one recent IRSN study answers this last question in a thorough manner, based on the statistical analysis of ecological data describing the bird community observed within a 50 km radius of the damaged Fukushima power plant over the period 2011-2014 (Garnier-Laplace *et al.*, submitted). On the basis of the statistical model best representing the entire dataset including the total reconstructed absorbed dose for birds, and taking into account confusing descriptive variables of environmental conditions (*e.g.*, temperature, time of observation, snow cover, type of landscape), for the zone and study period, IRSN has estimated that the absorbed dose has more weight in the reduction in the total number of birds than the evacuation of human populations (Figure 3).

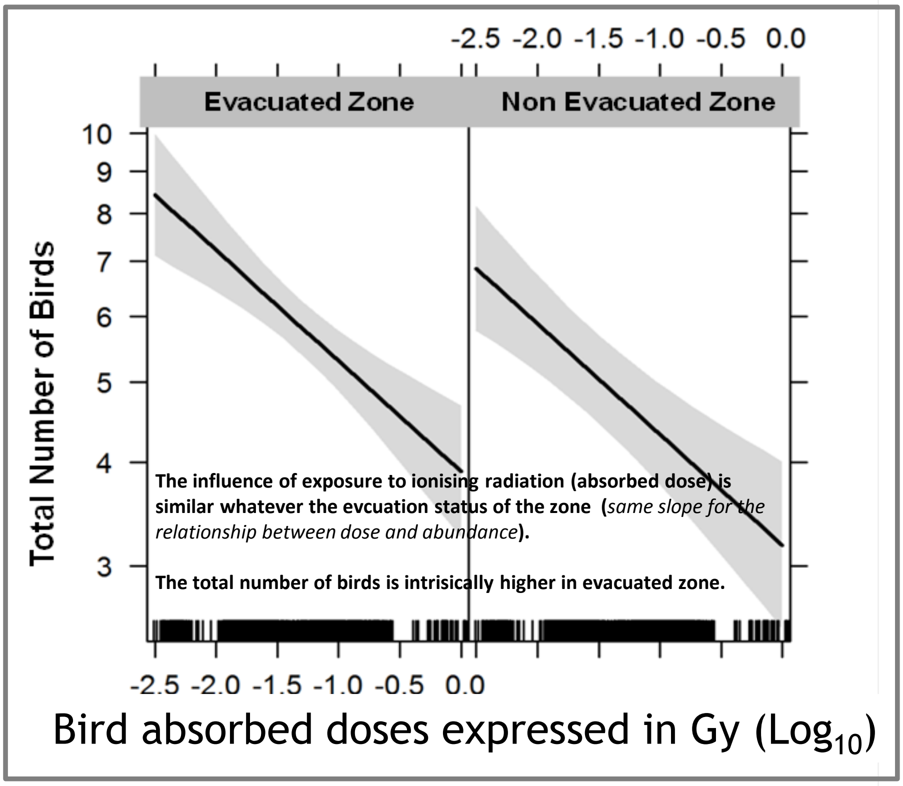

Figure 3 - Relationship between the dose absorbed by birds and the abundance of individuals by observation site according to the evacuation status of the zone where the site is located (adapted from Garnier-Laplace *et al.*, submitted).

In conclusion

There exist numerous ecological studies conducted in the contaminated territories following the two major nuclear accidents at Chernobyl and Fukushima that demonstrate the existence of effects on animal and plant species in relation to the radioactive contamination of the territories. Nonetheless, the review of publications in this field does however reveal shortcomings in cooperation between the basic scientific disciplines; a situation that can lead to biased conclusions. IRSN's latest work, bringing its expertise in dosimetry and radiobiology to the analysis of ecological data from the observation of the Fukushima bird community, illustrates the benefits brought by cooperation between these disciplines in order to draw solid conclusions about the ecological consequences of a nuclear accident. By multiplying this type of integrated analysis, answers will be found to important questions that are still pending, such as transgenerational effects, the adaptation of organisms to stress, the mechanisms governing the difference in radiosensitivity between species, etc…

To find out more - A longer version of this summary is available in the form of an IRSN report (C. Adam-Guillermin, O. Armant, J-M Bonzom, P. Henner, C. Lecomte. "Ecological consequences of the Chernobyl nuclear accident". IRSN report N°PRP-ENV/SERIS/2016-06).

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