INSTITUT
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How can forest environments be managed after a nuclear accident?

Lessons learned following the Chernobyl and Fukushima accidents

In both Chernobyl and Fukushima, a large proportion of the highly-contaminated territories is covered by forest. Knowledge about the evolution of the radionuclides deposited within these ecosystems following the accidents, as well as differing management practices regarding these environments between the two countries, enable valuable lessons for the post-accident management of this type of environmental resource to be learned.

The main characteristics of the forest ecosystems impacted by radioactive fallout differ between the two accidents. In particular, the appearance of the "red forest" is specific to the Chernobyl accident and has not been observed at Fukushima. Despite the fact that the surface areas of the terrestrial environments affected by the disaster are very different (e.g. soils with contamination levels exceeding 600,000 Bq/m^2 represent around 600 km^2 for the Fukushima accident compared to 13,000 km^2 for the Chernobyl accident), when these two accidents occurred a large proportion of the highly-contaminated territories were forest ecosystems. In Japan, 75% of the territories contaminated following the Fukushima accident are forest land, compared to 39% in the most contaminated areas following the Chernobyl accident in Belarus (Steinhauser *et al*., 2014). In Chernobyl, the forest occupying 53% of the exclusion zone - covering a surface area of 2,600 km^2 - that was established after the accident, suffered irreversible damage. During the first weeks following the accident, 90% of pines (*Pinus sylvestris* L.) died, thereby creating the "red forest" within a 6 km^2 zone (lethal absorbed dose of 60-100 Gy) and, in a 38 km^2 "sub-lethal" area (absorbed dose between 30-40 Gy), 40-75 % of the trees turned brown and the growth of 95% of them was affected (Geras'kin *et al.*, 2008). As part of the cleaning operations, dead trees were felled and buried over an area of 4 km^2. Following the progressive planting of new herbaceous species and deciduous trees (such as birch), today the surface area of the exclusion zone covered by forest is close to 90% (Yoshenko *et al.*, 2011). In Fukushima, no mass acute effect of the "red forest" type has been reported in literature, and the forest ecosystems in place have not undergone drastic changes in terms of the structure of their component stands. Watanabe *et al*. (2015)[1] recently highlighted - for sites in the contaminated territories where the ambient dose rate in 2015 lies between 5 and 40 µGy/h - a significant frequency of an increased loss in the apical dominance of the Japanese fir (*Abies firma*)[2].

The processes governing the evolution of radionuclides in forest ecosystems imply a high remanence of the radioactive contamination of these environments. The longevity of forest ecosystems combined with periods of high radioactive decay for some of the radionuclides deposited following the accidents (e.g. 30.2 years for caesium-137) implies a high remanence of the contamination of all of the components of these environments. However, the redistribution of the radionuclides in the different compartments of the forest ecosystem is very dynamic. It is the result

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[1] 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)

[2] For more information, the reader can consult the fact sheet on the ecological consequences of nuclear accidents.

of different processes that are part of the radionuclides' cycle (foliar and root absorption, falling of leaves/needles/branches towards the leaf litter, leaching of the canopy by rain and runoff on the trunks with a return of the rain-leached water towards the soil, internal transfers within the trees, immobilisation in trunks...) as illustrated in figure 1. Moreover, there is a strong correlation between the biogeochemical cycle of radionuclides in the forest and that of organic matter within this ecosystem, and the flow dynamics between compartments depends on the types of trees considered, the soil type, climatic and anthropogenic factors (i.e. practices for the management of the forest and its resources). This management also depends on the characteristics of the radionuclides deposited and their capacity to be immobilised or internalised within the foliage (penetration in gas or particulate form in the case of iodine, dissolved for caesiums and plutoniums...) and on their mobility within the vegetation (high for caesium and strontium, very low for plutonium).

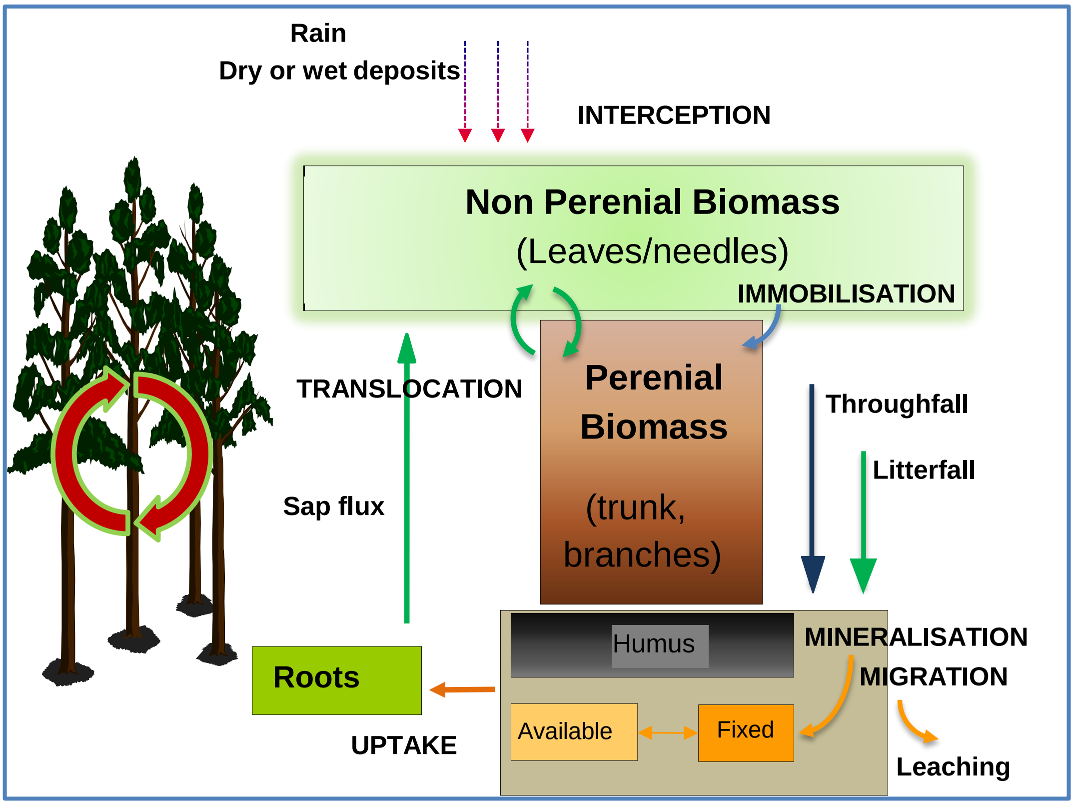

Figure 1- Representation of the biogeochemical cycle of elements in forest ecosystems (adapted from IAEA, 2002).

The interception of radioactive deposits by the canopy and transfers of radionuclides towards the leaf litter and soil are the most important processes in the early phase and first months following the accident. Little knowledge exists about this period with regard to the Chernobyl exclusion zone, but the data collected at Fukushima since 2011 enables a better understanding of the processes at stake. In the highly-contaminated zone (radiocaesium levels[3] above 1,000 kBq/m^2), two sampling campaigns carried out in August and September 2011 have shown that the radiocaesium concentration in leaf litter varied between 24 and 319 kBq/kg, a contribution of between 22 and 66% towards the total quantity of radioactive caesiums present in the forest ecosystems, for a biomass representing barely a 3% mass of forest components (i.e. leaves/needles, trunks/branches, leaf matter) of the plots studied (Hashimoto *et al.*, 2012). These initial results led the Japanese to consider the removal of leaf litter as an effective decontamination method, mainly for forests with deciduous trees. Moreover, as the Fukushima accident occurred in March (end of the winter period), a distinction must be made between, on the one hand, deciduous forest (*e.g.*, oak, *Quercus serrata*) where the majority of the contamination was deposited directly on the leaf litter

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[3] These radiocaesiums are caesium-134 and caesium-137.

on the ground (Yoshihara *et al.,* 2013; Hashimoto *et al.,* 2012) and, on the other hand, the particularly dense conifer forests in Japan (with the Hinoki cypresses, *Chamaecyparis obtusa*, the Japanese cedar, or Sugi, *Cryptomeria japonica*) whose canopy was able to intercept up to 90% of the deposits (Kato *et al.,* 2012). Hashimoto *et al.* (2012) have shown that, following the radioactive deposits, the contaminated branches, leaves and leaf litter in the highly-contaminated zone represented a total volume of 33 million m^3 for a mass estimated at 21 million tonnes (dry matter).

After initial interception by the canopy, the transfer of contamination towards the soil results from two processes: leaching by the rain of the canopy and trunks, and the fall of biomass (leaves, needles, branches...) to form leaf litter. Various authors have shown that, in Chernobyl as well as Fukushima, the natural decontamination of the canopy, via rain leaching and the fall of biomass to form leaf litter, took place following two kinetics: one quick and the other slower (Bunzl *et al.,* 1989; Kato *et al.,* 2015). Although aerial biomass litterfall for conifers was more significant in Fukushima than in Chernobyl, certain observations have shown that the median remanence time of radiocaesiums in the conifer canopy during the first months following the accident was longer in Fukushima (6 to 10 months) than that observed at Chernobyl (3 months) (Kato *et al.,* 2015). This behavioural difference can be attributed to the nature of the tree species (different canopy renewal rates), and the type of deposits (dry or wet) that collectively influence the interception of radionuclides by the canopy, but also their residence time (Gonze *et al.,* 2015). Figure 2 shows the temporal evolution since the accident of the relative contribution of the processes of leaching by the rain, runoff on the trunks, and the fall of biomass towards the leaf litter for a plot of mature (31 years) or young (15 years) Japanese firs, and for a mixed plot comprising three deciduous species (oak - *Quercus serrata,* viburnum - *Viburnum furcatum* and pine- *Pinus densiflora*). Regardless of the plot type, Kato *et al.* (2015) quantify a major contribution during the first months of the rain leaching process of caesium flows towards the soil, and a very low contribution of runoff along the tree trunks. According to Bird et Little (2013), a campaign by the Japanese Forestry Agency, published in December 2011, showed that around half of the radiocaesium deposits were present at the soil surface and in the leaf litter, with the other half in the leaves, trunks and branches (with a greater balance in forest soils in deciduous forests). Other trials, also commented on by Bird and Little (2013), have made it possible to quantify that by cutting one tree out of three the ambient dose rate was reduced by up to 23%, and that this remediation measure, combined with the removal of leaf litter, enabled a 50% reduction in the ambient dose rate. However, given the importance of leaching by the rain and the formation of contaminated leaf litter over time, the felling of trees becomes less effective because the soil's contribution to the ambient dose rate becomes preponderant.

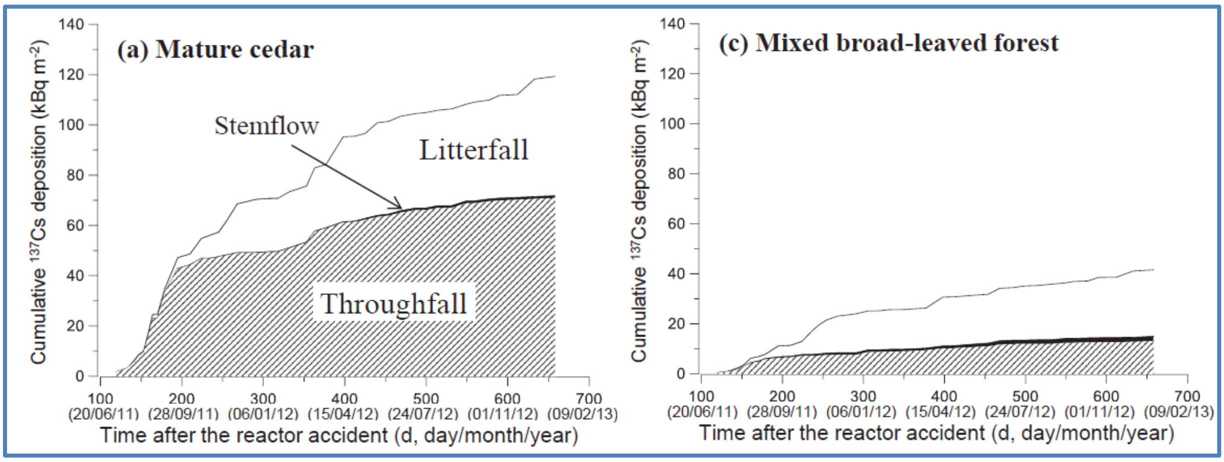

Figure 2 - Temporal evolution since the accident of the relative contribution of the processes of leaching by the rain of aerial biomass, runoff on trunks and the fall of biomass towards the leaf litter for a plot of mature Japanese cedars (31 years) and a mixed plot comprising three species of deciduous trees - *Quercus serrata, Viburnum furcatum* and *Pinus densifolora* (from Kato *et al.*, 2015).

As a result of leaching of the canopies and fall of aerial biomass, the soil progressively becomes the preponderant reservoir where radiocaesiums can be found. Even if a greater remanence of radiocaesiums in the Fukushima conifer canopies was observed during the first months compared to those contaminated by the Chernobyl accident, five years after the Fukushima accident almost all of the radiocaesium deposited on the forest ecosystems (between 80 and 90%) was entrained into the top layers of the soil or humus - which is comparable to the rates observed in Chernobyl. Twenty years after the Chernobyl accident, the aerial biomass from trees and trunks contains less than 20% of the radionuclides present in the forests (Ministry of Ukraine of Emergencies and Affairs of Population Protection from the Consequences of Chernobyl Catastrophe, 2006). This progressive decontamination of the canopies and its return to the soil also explain a fall in dose rates measured by the Japanese authorities during the airborne campaigns (airborne detectors at an altitude of between approximately 100 and 300 m, between April 2011 and December 2012): digital simulations carried out by the IRSN (Gonze *et al.*, 2015) have demonstrated that in a forest environment the dose rates at considered flying altitudes have decreased by around 40% per year (consistent with the measures), with half of this decrease being induced by the progressive decontamination of the canopies that themselves increase the mitigation by plant cover of the radiation measured by airborne detectors. In contrast, simulations demonstrate that the dose rates close to the soil in a forest environment rose slightly during the first months following the accident, the soil contamination having logically increased due to the effect of leaching (Gonze *et al.*, 2015).

During this phase, organic input to the soil (fall of biomass to form the leaf litter) decomposes, and a fraction of the contaminants that were immobilised are released into the soil thus becoming available for removal by roots and deep drainage. Radiocaesiums, at a rate of 99% of the soil stock, are mainly found in the top 10 centimetres (Figure 3), where the percentage of organic matter is over 10%, suggesting that an essential part is played by the cycle of organic matter in the distribution and therefore mobility of caesium in the soil (Teramage *et al.*, 2014a et b).

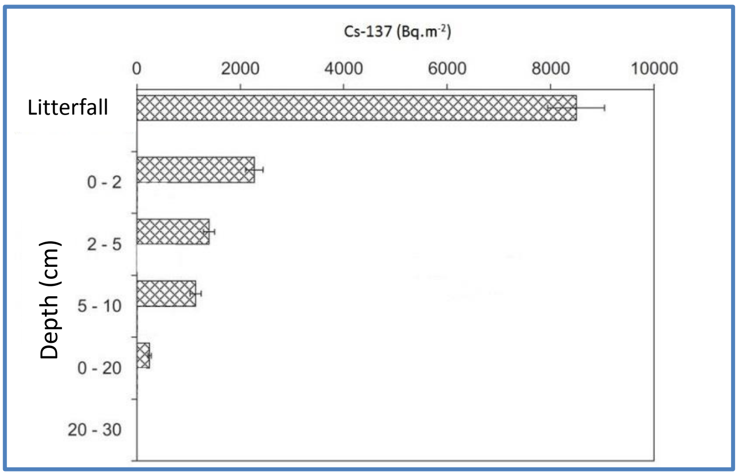

Figure 3- Distribution of the caesium-137 stock (Bq/m^2) in undisturbed soil in conifer forest in Fukushima in October 2012 (adapted from Teramage *et al.*, 2016).

The migration velocity of ^{137}Cs in forest soils appears to be quicker in Fukushima than Chernobyl (Teramage *et al.*, 2014b). This difference can be explained by differences in the prevailing environmental conditions at each site. Firstly, rainfall is higher in Fukushima (≈ 1200 mm/year) than in Chernobyl (≈ 500 mm/an), which can entrain the radiocaesiums available downwards more easily. On the other hand, over a large section of forest soils in Fukushima, humus is thicker than for the majority of the Chernobyl soils, which generates greater organic matter content in the top layers of the soil. This phenomenon, combined with a lower mica clay mineral content in the forest soils of

Fukushima (Andosols/Cambisols), is a factor that favours caesium mobility (e.g. Valcke, 1993; Vandebroek *et al.*, 2012). Over the coming years we can therefore expect a higher recycling of ^{137}Cs via root removal in the Fukushima forests than at Chernobyl. Thiry *et al.* (2009) had estimated that the Chernobyl pines could annually incorporate 0.004% of the caesium-137 present in the soil through root transfer. The AMORAD project, coordinated by IRSN[4] will make it possible to confirm or refute if this incorporation rate is also valid for Fukushima.

The long-term studies carried out at Chernobyl have shown that the migration velocity of ^{137}Cs decreased over time. For example, Rosén *et al.* (1999) demonstrated that between 1987 and 1995, the migration velocity of ^{137}Cs had been reduced by half for Swedish soils contaminated following the Chernobyl accident. With a fall in migration velocity, the majority of the ^{137}Cs deposited in the forests close to Chernobyl are still currently found in the top centimetres of soil and in the organic layer (humus), even 30 years after the accident. This stabilisation phenomenon will also certainly occur at Fukushima, as suggested by Teramage *et al.* (2014b).

The management of forest ecosystems contaminated following the Fukushima accident differs from that applied to the forest ecosystem in the Chernobyl exclusion zone. The Chernobyl exclusion zone is one of the realisations of the strategy adopted by the Soviet (then Ukrainian) authorities for the management of the health impact of the accident. Emptied of residents and with all practices prohibited (apart from those linked to urgent cleaning operations and work to secure the facilities), the trees and other plants making up the ecosystem in this zone stabilise contamination (*e.g.* in Sr^{90}, Cs^{137} and plutonium isotopes) that essentially remains in the forest soils for many years more. The ban on all human activity (residence, farming, logging, hunting and harvesting) contributes to preventing the dissemination of the radionuclides outside the zone and makes it possible to limit doses to surrounding populations. The forest is therefore, as a strategic choice, left to grow naturally. On the contrary, Japan has chosen a strategy based on extensive decontamination. For the forest ecosystems, which are an important resource in Japanese farming, after a year of conducting exploratory trials of a variety of exposed decontamination techniques (collection of leaf litter, felling of trees...), the authorities ultimately decided that it was unrealistic to decontaminate the forests in their entirety, due to the volumes of waste generated. Moreover, the dramatic ecological consequences that could result from mass actions to remove leaf litter or fell trees, boosting soil erosion which is naturally low thanks to the density of the forest cover, have been underlined. Modifying this stand density would inevitably lead to significant erosion and landslides, due to the steep slopes on which the forests are established.

Without such measures, a small percentage of radionuclides currently present in the forests migrate *via* water or air (Bird and Little, 2013). The IAEA (2011) recommended the implementation of restrictions on uses of the forests and consumption of forest products such as wild and cultivated mushrooms, game, etc. Some of these products still regularly exceed the marketable limits, with for example concentrations over 10,000 Bq/kg fresh weight still observed in 2015 in wild boar meat from the most affected areas in the Fukushima prefecture[5]. Japan has integrated, in an adapted and progressive way, the management of forest environments into the plan to recover territories by distinguishing three types of forest surfaces: those located around the residential areas with the removal and disposal of contaminated leaf litter and humus within a 20 m radius of the houses, or more if the ambient dose rate is too high; those visited by workers on a daily basis, particularly for mushroom (shiitake) farming, where decontamination measures are in place and, finally, those of the so-called "deep" forest where measures aim to restrict the dispersion of radionuclides mainly by preventing soil erosion, the major risk being landslides. Research and development actions in order to prevent this dispersal are under way (Ministry of the Environment, Japan, 2016). On this basis, the monitoring of contaminated Japanese forest sites as part of the AMORAD project carried out by

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[4] The AMORAD project is co-funded by the ANR RSNR ("Improvement of models of dispersal prediction and evaluation of the impact of radionuclides within the environment").

[5] For more information, the reader can consult the fact sheet on foodstuffs.

the IRSN (Figure 4) will enable an enrichment of existing databases and contribute towards the understanding of contamination recycling processes and kinetics within forest environments and dissemination flows *via* the air or water. Moreover, this will enable the obtention of expertise adapted to France and its varied forest land, in order to prepare elements of post-accident management of these environments.

Finally, there is a high risk of fire in the Chernobyl exclusion zone where the forest, left to evolve naturally, can be exposed to periods of drought - the probability of this occurring increases with climate change. This risk is comparatively lower in Japan because it is limited by the short dry season in the spring. Nonetheless, such fires would constitute catastrophic events, leading to the mass dissemination of radionuclides on a local, and even regional, scale (Zibtev *et al.*, 2015; Bird et Little, 2013). The fires of summer 1992 that affected the Chernobyl exclusion zone led to a significant increase in radionuclide concentrations in the air, from 0.017 to 1.5 Bq/m^3 in the town of Chernobyl, close to where the fires broke out. Combining this information with knowledge about the radionuclide stock of forest biomass, Zibtev *et al.* (2015) estimated that the total caesium-137 activity released into the air at this time was between 28 and 130 TBq[6]. By extrapolation, a fire affecting 1 km^2 of forest with soils contaminated to a level of 40MBq/m^2 (or a total stock of 40 TBq of caesium-137) represents potential releases into the air of around 40 to 70% of the Cs^{137} contained in combustible matter (trees and leaf litter; Amori *et al.*, 1996), i.e. around 6 TBq.

Figure 4 - Sampling campaigns in the contaminated forests of the Fukushima prefecture
(AMORAD programme. IRSN, 2013)

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[6] 1TBq=10^{12} Bq

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