IAEA’s assessment of the Fukushima Dai-ichi accident :
CONSEQUENCES FOR NON-HUMAN BIOTA

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Introduction

- Report published in September 2015
- http://www-pub.iaea.org/books/IAEABooks/10962/The-Fukushima-Daiichi-Accident

- Comprised of Report from Director General + 5 Technical volumes
- Non-human assessment sub chapter of **Technical Volume 4/5** Radiological Consequences
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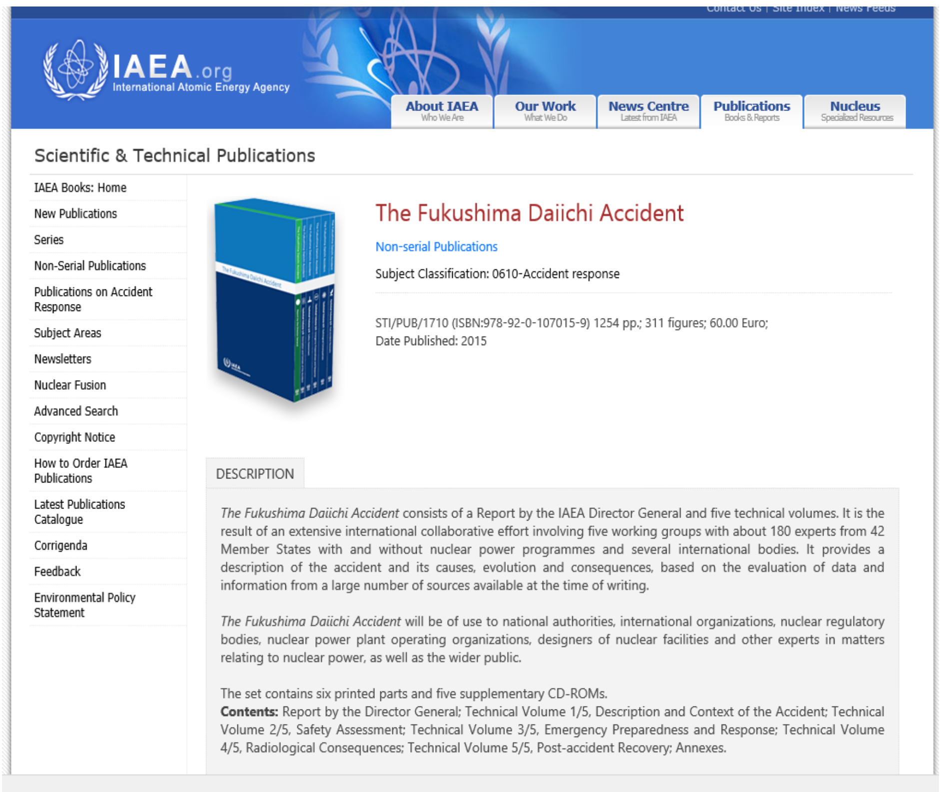

Preamble

- Protection of the environment goals vary
  - includes “the protection and conservation of: non-human species, both animal and plant, and their biodiversity; environmental goods and services”.
  - Normally environmental radiation protection objectives focus on populations.
  - The ICRP protection objectives are: ‘to prevent or reduce the frequency of deleterious radiation effects on biota to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities and ecosystems’
- Although residents within a 20 km radius of Fukushima Daiichi NPP were evacuated the exposure of non-human biota inhabiting these areas was unavoidable.
- The release of radionuclides, (and thus corresponding doses to nonhuman biota) in Japan, was much lower than in areas around Chernobyl.
  - The types of severe detriment such as the red forest observed after Chernobyl are not expected to have occurred. However, more subtle effects need to be assessed

Background to the assessment

- The natural environment around the Fukushima Daiichi NPP
- The earthquake and the tsunami
  - The severe earthquake and tsunami caused significant environmental stress to the terrestrial and marine environments along the north-eastern coast of Honshu, far in excess of that caused by radiation exposure. The earthquake induced topographic changes to the sea floor, and inundation following the tsunami resulted in the transfer of large volumes of marine sediments onshore. Elevated deposition of sediment affected the abundance of several benthic biota and may have a major impact on the biological functioning within the sediments for years to come
- Environments affected
  - Notes the MEXT soil survey as particularly useful. Samples for the first survey were collected between 6 June and 8 July 2011 from an area covering Fukushima, northern Ibaraki and southern Miyagi prefectures.

Dose assessment approaches, end points and benchmarks

- The generally accepted approach has been to focus on the viability of biota populations (and the integrity of ecosystems). It is widely recognized that the most relevant biological end points in terms of potential environmental impact are those that could lead to changes in population size or structure and affect the ability of an organism to reproduce
- The ICRP assessment approach has been adopted in this volume. This approach is based on a framework of an underlying set of twelve reference animals and plants (RAPs) that relate exposure to dose, and dose to effect, for a limited number of biota that are typical of the major environments.

Benchmarks

TABLE 4.5–1. DERIVED CONSIDERATION REFERENCE LEVELS (DCRLs) FROM ICRP 108 (2008) [260]

DCRLs (mGy/d)	Reference animals and plants
0.1–1	Deer, rat, wild duck, pine tree
1–10	Frog, trout, flat fish, wild grass, brown seaweed
10–100	Bee, crab, earthworm

- *Other benchmarks considered :* “chronic dose rates of less than 100 µGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial communities” and that “maximum dose rates of 400 µGy/h to a small proportion of the individuals in aquatic populations of biota would not have any detrimental effects at the population level”
- Benchmark of 10 µGy/h noting this is more applicable to continuous discharge regimes and Screening purposes.

Two-part assessment

1. application of activity concentration of radionuclides in environmental media, i.e. water, sediment and soil (or deposition) to calculate doses to adult RAPs following the releases from the Fukushima Daiichi NPP. The use of such data reflects the absence, or sporadic coverage, of direct radionuclide activity concentrations measurements in plants and animals in many instances and requires the application of transfer models in deriving the levels of radionuclides associated with wildlife.

2. The second part of the assessment is based on data pertaining to directly measured activity concentrations in biota (and their habitats) from review .These data provide the most precise estimates of doses, because the approach avoids the use of transfer models with their concomitant uncertainties.

Assessment based on activity concentrations of radionuclides in environmental media

- Three phases:
  - An early, acute period, during which exposures from short lived radionuclides, notably ^{131}I occurred (30 days, mid-March–mid-April 2011);
  - An intermediate period after 31–90 days (mid-May–mid-September 2011), when data on activity concentrations in the environment are available;
  - Late period after 90 days (up to one year), when equilibrium is assumed, especially for radiocaesium (chronic exposures).
- Radionuclides considered :
  - In the early and intermediate periods: ^{134}Cs, ^{137}Cs, ^{131}I
  - In the late period: ^{134}Cs, ^{137}Cs,
- Other short lived radionuclides, particularly ^{132}I and ^{132}Te, may also have been important in the early acute period. However, measurements available are too limited to allow a reliable estimate of dose rates.

Methodology – transfer I

- For terrestrial biota the whole-body concentration ratio, CR_{wo}, is defined as

$$CR_{wo} = \frac{A_{b,r}^{biota}}{A_{r}^{soil}}$$

Where:

$A_{b,r}^{biota}$ = Activity concentration of radionuclide ‘r’ in the whole organism of biota ‘b’ (Bq kg^{-1} fresh weight (fw));

A_{r}^{soil} = Activity concentration of radionuclide ‘r’ in soil (Bq kg^{-1} dry weight (dw))

- For aquatic organisms activity concentrations in soil are replaced by those in water.

Methodology – transfer II

- In case of an acute deposition the radionuclide content on vegetation at time ‘t’, accumulated via direct deposition from the air, can be calculated as:

$$C_{veg,r} = \alpha \cdot D_{tot,r} \cdot [e^{(-(\lambda_{veg,r}+\lambda_r)\cdot t)}]$$

Where:

$C_{veg,r}$ = radionuclide activity concentration in vegetation from air deposition (Bq kg-1 f.w.)

α = fraction of deposited activity intercepted by vegetation per unit mass (mass interception factor, Bq kg^{-1} per Bq m^{-2}, or m^2 kg^{-1}; considered in fresh weight for vegetation)

$D_{tot,r}$ = total deposition of radionuclide ‘r’ (Bq m^{-2})

$\lambda_{veg,r}$ = weathering constant for a given vegetation for radionuclide r(d^{-1})

λ_r = decay constant for radionuclide r(d^{-1})

t = time (d)

Methodology Dose calculations

- The basic underlying equations used to derive internal (D_{int}) and external (D_{ext}) absorbed dose-rates (in units of µGy h^{-1}) from activity concentration data are given in the equations below. The total absorbed dose-rate is the sum of these components, through the application of dose conversion coefficients (DCCs).

$$\dot{D}^{b}_{int} = \sum_{i} C^{b}_{i} * DCC^{b}_{int,i} \qquad \dot{D}^{b}_{ext} = \sum_{z} v_{z} \sum_{i} C^{ref}_{zi} * DCC^{b}_{ext,zi}$$

where:

C^{b}_{i} is the average concentration of radionuclide *i* in the reference organism *b* (Bq kg^{-1} fresh weight),

$DCC^{b}_{int,i}$ is the radionuclide-specific dose conversion coefficient (DCC) for internal exposure defined as the ratio between the average activity concentration of radionuclide *i* in the organism *j* and the dose rate to the organism b (µGy h^{-1} per Bq kg^{-1} fresh weight).

v_z is the occupancy factor, i.e. fraction of the time that the organism *b* spends at a specified position *z* in its habitat.

C_{zi}^{ref} is the average concentration of radionuclide *i* in the reference media of a given location *z* (Bq kg^{-1} fresh weight or dry weight (soil or sediment) or Bq l^{-1} (water)),

$DCC^{j}_{ext,zi}$ is the dose conversion coefficient for external exposure defined as the ratio between the average activity concentration of radionuclide *i* in the reference media corresponding to the location *z* and the dose rate to organism *b* (µGy h^{-1} per Bq kg^{-1} fresh weight or Bq l^{-1}).

Terrestrial

- Concentration ratios (CRs) can be used to derive activity concentrations in biota from activity concentrations in media. These values are generally intended for application in assessing routine releases of radionuclides to the environment. However, the use of time integrated activity concentrations in media extends the applicability of this approach to situations where radionuclide concentrations are changing rapidly with time. This approach has been used to calculate whole body concentrations of radionuclides in animals during the early and intermediate periods and in all biota types, including vegetation, during the late phase.
- The highest activity of ^{137}Cs at a location in Okuma Town was used to provide an indication of exposures to the most highly exposed individuals in animal and plant populations [a]. Corresponding ^{131}I levels were based on ^{131}I:^{134}Cs ratios [b].

[a] UNSCEAR 2013 Fukushima Report
[b] TORII, T., SUGITA, T., OKADA, C.E., REED, M.S. BLUMENTHAL, D.J., Enhanced analysis methods to derive the spatial distribution of ^{131}I deposition on the ground by airborne surveys at an early stage after the Fukushima Daiichi nuclear power plant accident, Health Phys 105 2 (2013) 192–200.

Terrestrial dose rates

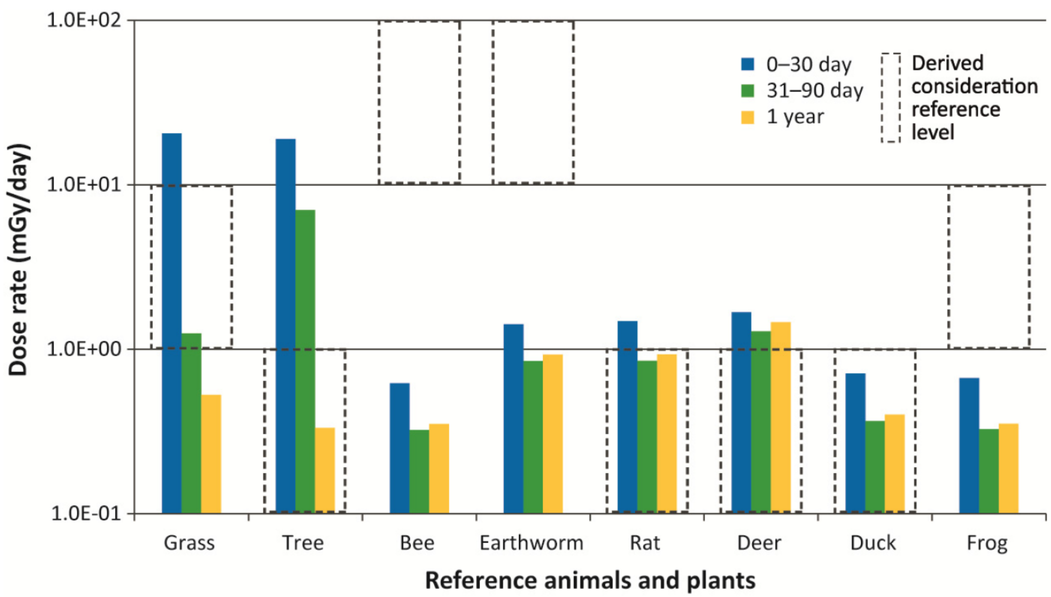

FIG. 4.5–1. Dose rates (mGy/d) for terrestrial RAPs versus time at Okuma Town.

Maximum dose rates were calculated for the (wild) grass and (pine) tree in the initial 0–30 day period post-accident. These dose rates decreased rapidly within the first year of the assessment. Substantially lower dose rates were calculated for animals. Maximum dose rates were estimated in the initial 0-30 day period reflecting the contribution of ^{131}I to total exposures.

Marine

- The datasets for a point 30 m north of the discharge channel of Units 5 and 6 of Fukushima Daiichi NPP and the south channel, approximately 1.3 km south of the discharge channel from Units 3 and 4, were selected from UNSCEAR (2014). These constitute the sampling locations where activity concentrations were at a peak.

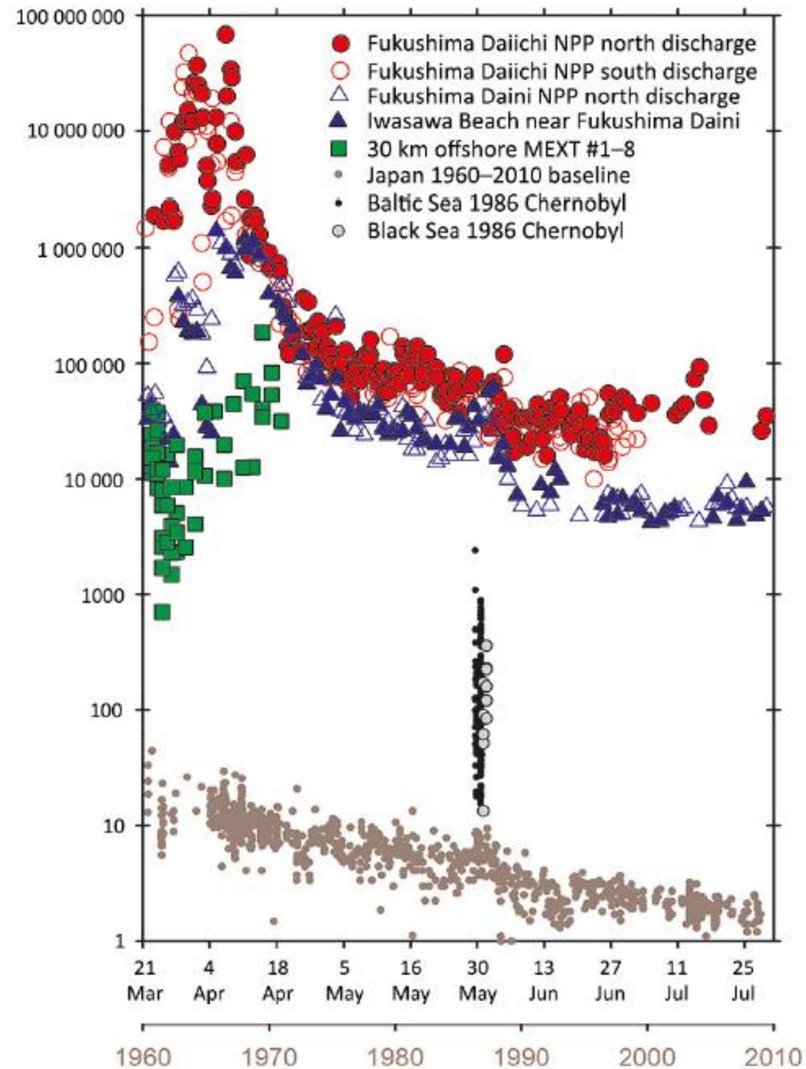

FIG. 4.1–21. Surface ocean concentrations of ^{137}Cs (in Bq/m^3) from 21 March to 31 July 2011 for two sites near the Fukushima Daiichi NPP, Fukushima Daini NPP, Iwasawa Beach near the Fukushima Daini NPP and 30 km offshore. These are compared on the lower x axis (1960–2010) to the historical record of ^{137}Cs off the east coast of Japan and to waters influenced by the Chernobyl accident in 1986 in the Baltic and Black Seas [118].

Marine dose rates

- Maximum exposures were derived for Brown seaweed for which dose rates exceeded 3 mGy/h (>70 mGy/d) in the initial 0-30 day period. This elevated dose rate reflected the relatively high bioaccumulation of radioiodine by macroalgae from seawater.

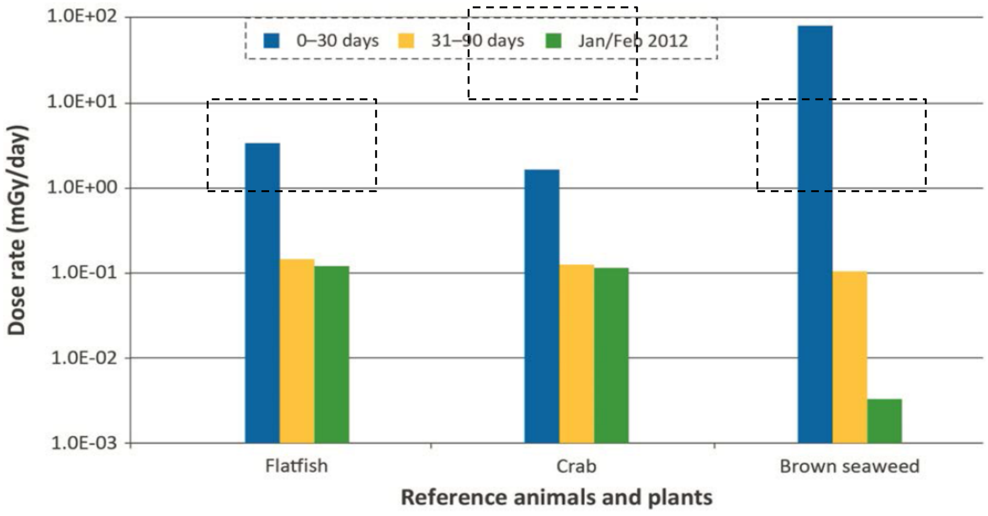

FIG. 4.5–2. Dose rate (mGy/d) for marine RAPs versus time at location 30 m north of discharge channel of Units 5 and 6 of the Fukushima Daiichi NPP.

- However, dose rates decreased rapidly for this RAP group with dose rates approaching 0.1 µGy/h (2.4E-03 mGy/d) after 1 year of elapsed time.
- Accumulated doses for the first 30 days were up to 2.4 Gy for seaweed.

Part II assessment

- Based on review
- Reasonable coverage
  - Different trophic levels, vertebrates invertebrates
- Many data within first year of accident but poorer coverage in the early/intermediate phases.

TABLE 4.5–2. INPUT DATA USED AND DOSE RATES DERIVED FOR THE ASSESSMENT BASED ON DIRECTLY MEASURED ACTIVITY CONCENTRATIONS IN TERRESTRIAL BIOTA

Species (RAP)	Activity concentration Bq/kg fresh weight biota (radionuclide)	Activity concentration Bq/kg dry weight or Bq/L (media)	Notes (date, location, methods)	Reference	Dose rate (mGy/d)
Japanese monkey, *Macaca fuscata*	2.5×10^4 (radiocaesium)	4.6×10^3 (soil)	April 2011; Fukushima City (>50 km NW of Fukushima Daiichi NPP); bespoke DCCs derived using the methodology outlined by Ulanovsky et al. (2008) [394] and bodyweight data provided in article	Hayama et al. (2013) [395]	0.2
Japanese monkey, *Macaca fuscata*	1×10^3 (radiocaesium)	4.6×10^3 (soil)	July 2011; Fukushima City (>50 km NW of Fukushima Daiichi NPP); bespoke DCCs derived as above	Hayama et al. (2013) [395]	0.03
Japanese cedar, *Cryptomeria japonica* (Pine Tree)	3.3×10^3 (Cs-137) 2.8×10^3 (Cs-134)		August 2011; Kawauchi Village (37°20′15″N, 140°48′34″E) approximately 20 km W of Fukushima Daiichi NPP; whole tree activity concentrations, weighted according to model tree	Kuroda et al. (2013) [397]	0.1
Earthworm, *Amynthas sp.* (Earthworm)	1.2×10^4 (Cs-137) 1.0×10^4 (Cs-134)	1.2×10^4 (Cs-137) 1.0×10^4 (Cs-134)	August 2011; Kawauchi Village (37°17′18 ″N, 140°47′47 ″E)	Hasegawa et al. (2013) [398]	0.4
Web spiders *Nephila clavata L. Koch* (Bee)	1.4×10^3 (Cs-137) 8.6×10^2 (Cs-134)	1.5×10^4 (Cs-137) 9.6×10^3 (Cs-134)	October 2012; streamside secondary forest dominated by broadleaved trees, about 33 km north-west of Fukushima Daiichi NPP; dry/fresh ratio = 0.36 for site. No soil data but	Ayabe et al. (2014) [399]	0.1

Terrestrial dose rates

- Dose rates generally lower than those calculated via transfer models
  - But ad hoc sampling location not all of which were in the most contaminated areas
- Highest dose rates for vegetation
- Aquatic dose rates very much lower
  - but marine = generally distant off shore locations

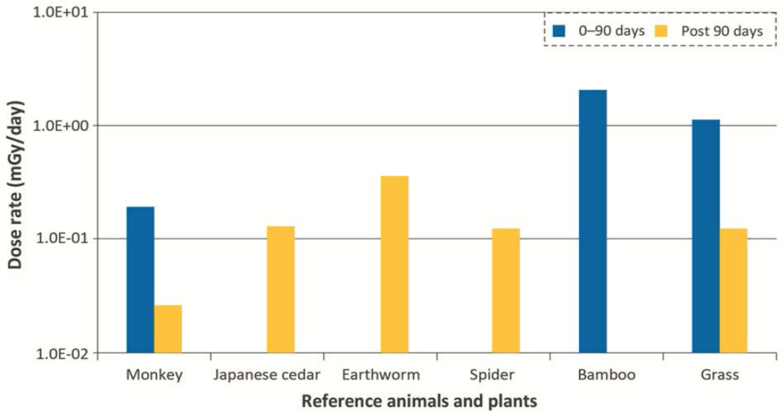

FIG. 4.5–3. Dose rates for terrestrial plants and animals for which direct activity concentration measurements in biota were available.

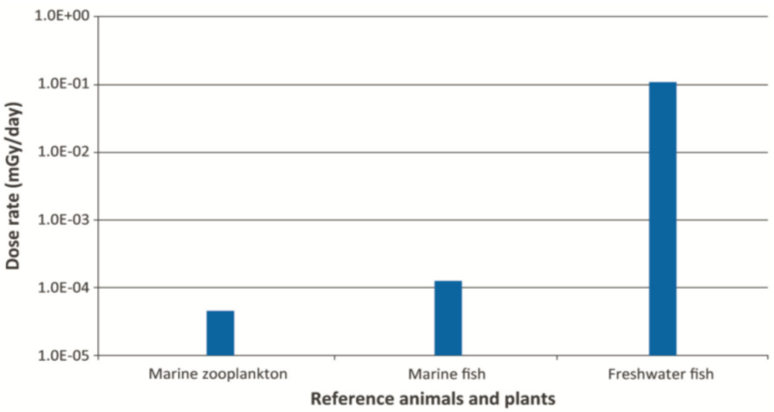

FIG. 4.5–4. Dose rates for freshwater and marine animals for which direct activity concentration measurements in biota were available (summer 2011).

A brief note on uncertainties

- Difficult to account for short lived radionuclides in the initial post-accident period.
- The dynamics of contamination transfer in the early phase of the accident was considered a weakness
  - Additional calculations made with the more detailed and well-validated model FORESTLAND*.
  - The doses to the top of crowns calculated based on this approach are in a range of 200–400 mGy for the first 30 days after the deposition and in a range of 250–500 mGy for 90 days after the deposition. These values are similar to those given for the (pine) tree RAP based on the generic model
- Heterogeneity of radionuclides within the body of plants and animals
  - Little information on meristems for plants
  - Iodine-131 (and 132) in thyroid of animals may be an issue. After Chernobyl this was a primary pathway for grazing animals : An impaired thyroid function in cattle was related to the dose received by the thyroid and the estimated thyroid doses at which no effects were observed were found to be about 20 Gy

*AVILA, R., et al., “Conceptual overview of forestland — a model to interpret and predict temporal and spatial patterns of radioactively contaminated forest landscapes”, Contaminated Forests (LINKOV, I., SCHELL, W.R., Eds), Springer, Amsterdam (1999) 173–183.

Consequences – general considerations (limitations)

- An exposure that is lethal when delivered as an acute dose may cause (only) sub-lethal effects when delivered over a protracted time periods - time allows for the recovery of tissues or organs.
- Real systems are complex and hence there is difficulty in assessing or measuring the (system) response(s) to a stressor. For this reason, toxicological investigations most often focus on simpler systems, or on tissue and individual effects. Attempts must then be made to extrapolate individual effects data to populations and the higher levels of organization. While most scientific data available on radiation dose–effect relationships concern individual animal and plant biota, these data lack information on higher system level effects.
- Direct effects on the variation of species and ecosystems that are induced by radiation are rare but could be observed in large controlled field studies where external irradiation was performed with gamma radiation sources at high and very high dose rates. As for radiation accidents like Chernobyl, ecological impact stems from the first acute period of exposure, when the releases of activity are the highest. At a later stage, indirect effects may become more pronounced.

Radiological consequences for biota in proximity to the FDNPP – IAEA conclusions

- The estimated doses to the terrestrial biota during the first weeks after the accident were highest for plants.
- The accumulated dose was approximately 0.6 Gy for the first 30 day period for both (pine) tree and (wild) grass groups.
- From data collated for forest affected by deposition after the Chernobyl accident, UNSCEAR [2008] reported that
  - minor damage characterized by disturbances in growth, reproduction and morphology of conifers could be observed at doses from 0.5 to 1.2 Gy.
  - More serious, sublethal damage, including destruction of meristems and partial death of conifers, was not observed until doses were in the range of 10–20 Gy.
- Herbaceous plants, including grasses, are considered to be more radioresistant, and after the Chernobyl accident, sterility of seeds was not observed at doses below 5 Gy [UNSCEAR, 2008].
- From the assessed doses, it is possible to infer that any direct lethal effects in even relatively sensitive plants such as conifers would (probably) not have occurred.

Radiological consequences for biota - II

- For large terrestrial mammals (exemplified by deer RAP), the estimated dose rate of 1.7 mGy/d for the period of 0–30 days falls just within the range (1–10 mGy/d) where there is a potential for reduced reproductive success, owing to increased male sterility [ICRP-108]
- Comparison with the $LD_{50/30}$ data for the deer RAP indicates that the calculated accumulated doses were orders of magnitude below levels at which lethal effects would be observed.
- The estimated total dose during the acute phase was such that no major acute radiation induced effects would have been expected (in large mammals) at the calculated exposure levels.

Radiological consequences for biota - III

- Brown seaweed received the highest exposures : dose rates exceeding 70 mGy/d in the initial period of 0–30 days.
  - Dose rates in the range of 10–100 mGy/d have the potential to cause effects on reproduction and growth rate in macroalgae [ICRP-108].
- The associated accumulated doses was 2.4 Gy,
  - same order of magnitude as the acute threshold value proposed at the ecosystem level for the marine environment of 4.84 Gy (UNSCEAR, 2008].
- Nonetheless, these elevated exposures were limited in space
  - the values used in the assessment relate to a position 30 m from the main release area.
- The spatially limited and transient nature of the highly elevated exposure indicates that releases from the Fukushima Daiichi NPP were unlikely to have caused any substantial harm to regional populations of brown seaweed.

Radiological consequences for biota - IV

- Limited impacts on terrestrial biota may be inferred from the second part of the assessment based on experimental data on radionuclide activity concentrations measured directly in plants and animals.
- for grass, the calculated dose rate of 2 mGy/d in the 0–30 day period fell within the ICRP's DCRL band but below a dose rate where reduced reproductive capacity in these types of plants has been recorded [ICRP-108].
- Dose rates for Japanese monkey at 0.2 mGy/d in the early phase fell in a DCRL band, considered for the related deer and rat RAPs, to constitute a very low probability of effects.
- Dose rates for earthworms (0.4 mGy/d) fell substantially below the corresponding DCRL (10–100 mGy/d) where effects are considered unlikely.

Radiological consequences for biota - V

- Dose rates for offshore marine biota in the late phase were extremely low, and the maximum dose rate for freshwater fish of 0.1 mGy/d fell substantially below the appropriately comparable DCRL band for trout (1–10 mGy/d).
- Nevertheless, short lived radionuclides, including ^{131}I, were generally not included in the assessment, based on measured activity concentrations in plants and animals; actual doses in the early phase may have been somewhat higher than those calculated.
- It is possible that dose rates (for freshwater organisms) may have exceeded corresponding DCRL bands in some cases, but they are unlikely to have been at a level that would cause detriment to populations of wild plants and animals.

Main Conclusions

- Although the methods used for the assessments are simple, they are robust and encompass the main exposure pathways relevant for assessing exposures to wild plants and animals.
- Nonetheless, the treatment of heterogeneous distributions of some radionuclides, such as radioiodine, is subject to considerable uncertainty. The possibility that some individual biota received rather high local doses, for example to the thyroid, cannot be excluded, although a response at the population level would be unlikely given the short duration of elevated radioiodine levels in time and space.
- Interactions between species and other constituents in the environment affected by radiation may have indirect implications for ecosystem function but are difficult to disentangle from effects on individuals.
- It is possible to conclude that, although dose rates exceeded some reference values included in ICRP and UNSCEAR publications in the early phases of the accident, no impact on populations and the ecosystems (both terrestrial and marine environments) is expected. Furthermore, long term effects are not expected, given that the estimated short term doses were generally well below levels at which highly detrimental acute effects might be expected, and dose rates declined relatively rapidly after the accident.