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The nuclear accidents in the Chernobyl NPP and the Fukushima Daiichi Nuclear Power Station

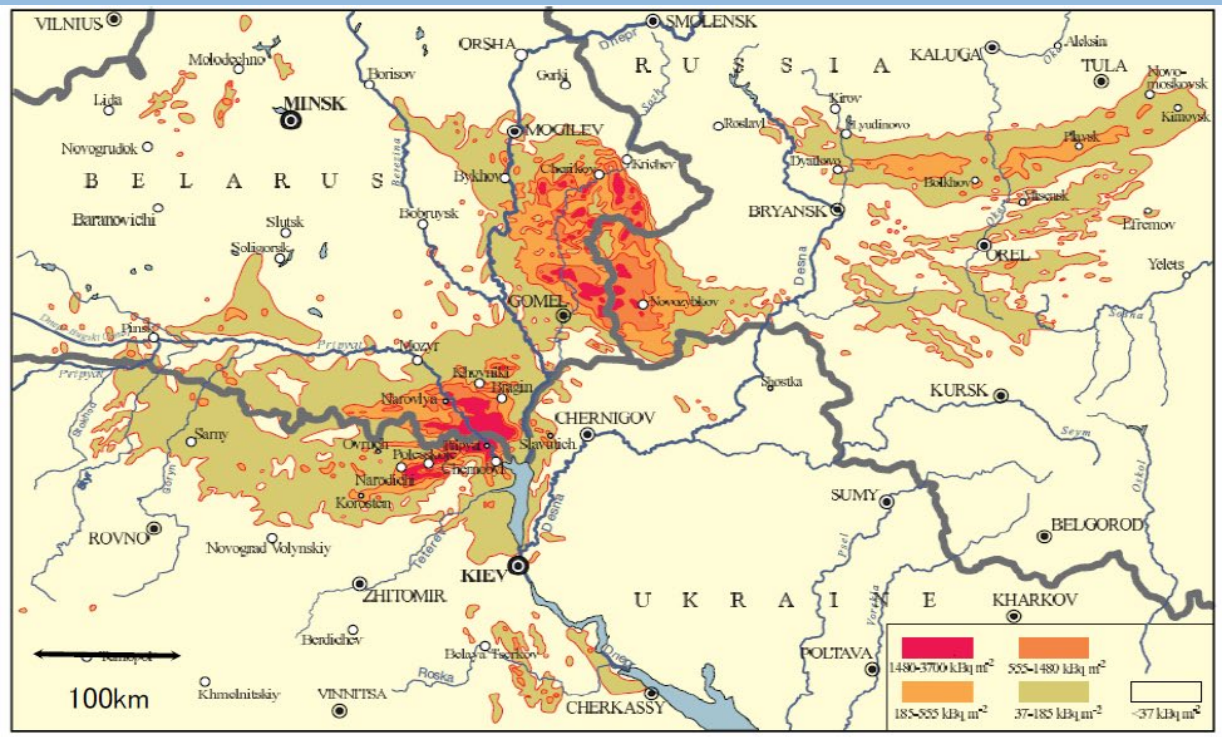
Gerhard Proehl

Releases to the terrestrial environment (IAEA 2006, IAEA 2015)

Radionuclide	Release (PBq)	
	Chernobyl (IAEA 2006)	Fukushima (IAEA 2015)
I-131	1760	100-400
Cs-134	47	8.3-50
Cs-137	85	7-20
Sr-90	10	0.003-0.14
Xe-133	6500	6000-12000

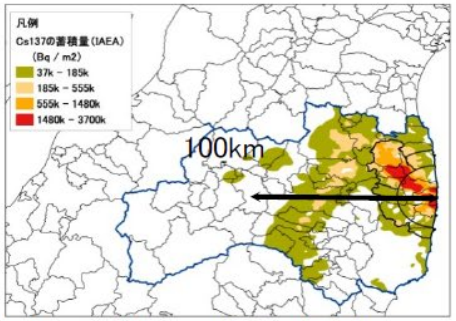
1 PBq = 10^{15} Bq

Deposition of Cs-137 in Ukraine, Belarus and the Russian Federation and in Japan



Surface ground deposition of Cs-137 near Chernobyl. (IAEA "STI/PUB/1239" , 2006)

Same scale



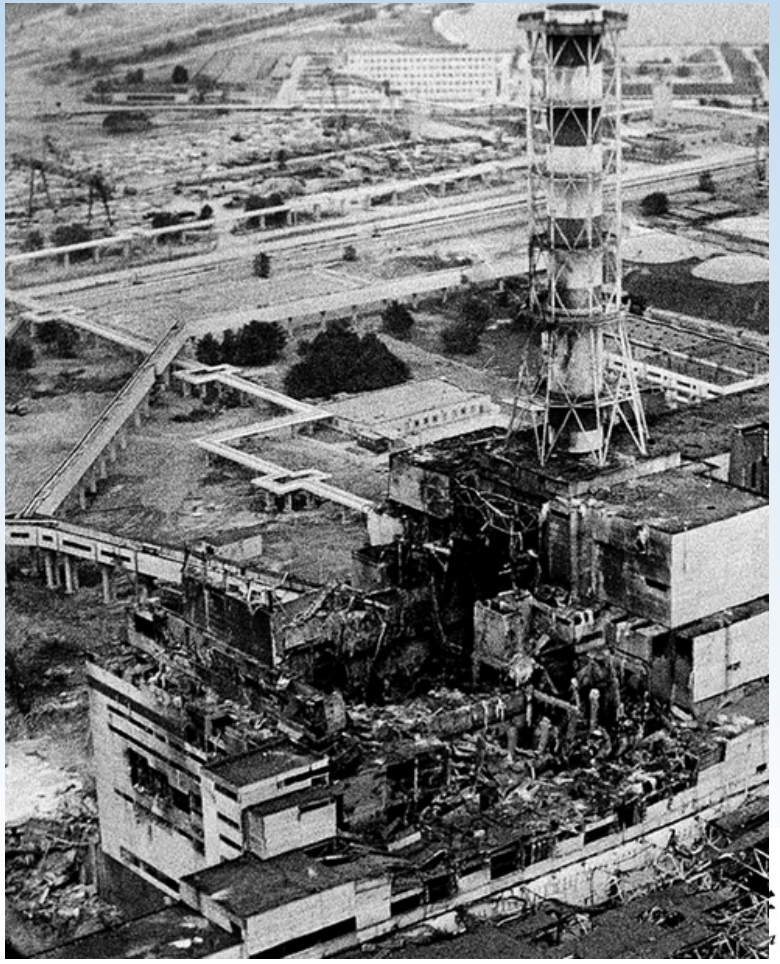
Surface ground deposition of Cs-137 near Fukushima-1. (Based on MEXT Data)

Chernobyl: What happened?

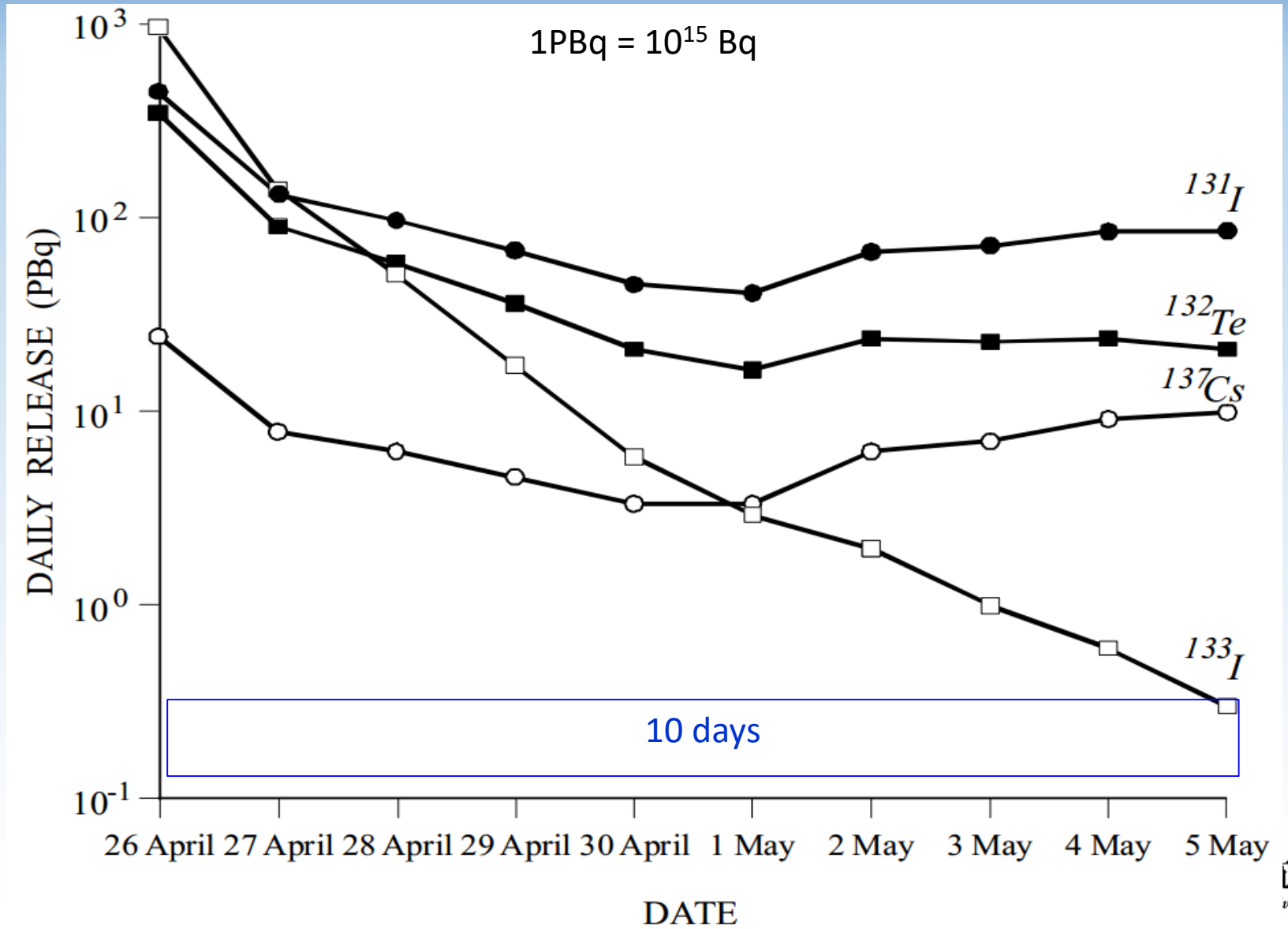
1983: Start of operation of Unit 4 of the Chernobyl reactors

26 April 1986

- 1:23:**00** am:
  - A test of the cooling system begins in unit 4
- 1:23:**40** am:
  - Emergency shut-down fails
- 1:23:**44** am:
  - The **reactor** runs out of control and **explodes**



Daily release of ^{131}I, ^{133}I, ^{132}Te, and ^{137}Cs (UNSCEAR, 2000)



Emergency measures

- Evacuation
- Application of stable iodine
- Food restrictions
- Decontamination of Surfaces
- Relocation

Early measures

26 April

- Morning, town of Pripyat (population 45000, @ 3 km)
  - Instruction to **remain indoors** and to **close doors and windows**
- γ-dose rates start rising

27 April

- γ-dose rates reach **10 mSv/h**
- Evacuation of 45000 people starts in Pripyat

Till 7 May

- ca 100 000 evacuees from 76 settlements in a radius of 30 km
- Establishment of the **Chernobyl Exclusion Zone** with a radius of 30 km

In 1986:

- 116000 evacuees in total

Beyond 1986

- Relocation of additional 220 000 people from outside the Exclusion Zone

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Measures to reduce internal exposures

- **Application of stable iodine**
  - Starting on 26 April
  - 5.4 million people in the USSR
  - No systematic distribution
- **Food restrictions**
  - Restrictions on grazing and fresh fodder to reduce thyroid doses
    => Very effective, if applied immediately
  - Delayed implementation of early countermeasures in the former Soviet Union
- **Information**
  - Delayed information of the population
    - Private farmers continue to consume fresh milk and green vegetables
      => high doses to thyroid, which could have been avoided

Chernobyl: Affected areas

Deposition category	Area affected (km^2)
Cs-137 per unit area (kBq/m^2)	Chernobyl (UNSCEAR 2000)
> 1480	3100
555-1480	7200
185-555	19100
37-185	116000

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Criteria for remediation

Chernobyl: In 1986, the USSR Ministry of Health introduced

- ***100 mSv*** as a temporary limit for the average equivalent whole body dose for the period 26 April 1986 until 26 April 1987,
- ***30 mSv*** for the 2nd year
- ***25 mSv*** for the 3rd and the 4th year (1988 and 1989)

From 1991: Belarus, Russian Federation, Ukraine:

- **Intervention level of *1 mSv/a*** for post-emergency situations
- Exceeding this level triggered the implementation of remediation measures

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Affected population groups and doses received

Population group	Number of people	Average thyroid dose (mGy)	Average effective dose [1] mid 1986 to 2005 (mSv)
Recovery operation workers (liquidators, 1986-1990)	530 000	NA	117 (only external dose)
Evacuees (1986)	115 000	490	31
People in areas of strict control (^{137}Cs > 555 kBq/m^2)	216 000	NA	61
People in contaminated areas (^{137}Cs > 37 kBq/m^2)	6 400 000	102	9

[1] external+internal dose, excluding thyroid doses

Long-term countermeasures to reduce exposure from radiocaesium

Residential areas (emphasis on schools, kindergartens, public buildings)

- Washing of buildings with water or special solutions
- Cleaning of residential areas and roads
- Removal of contaminated soil

Agricultural land

- Ploughing
- Food restriction: especially in milk and meat
- Treatment of pasture: ploughing, re-seeding, K-fertilizer, lime
- Clean fodder and caesium binders (Prussian Blue)

Measures to reduce Cs-137 in crops and animal products are still on-going in some areas

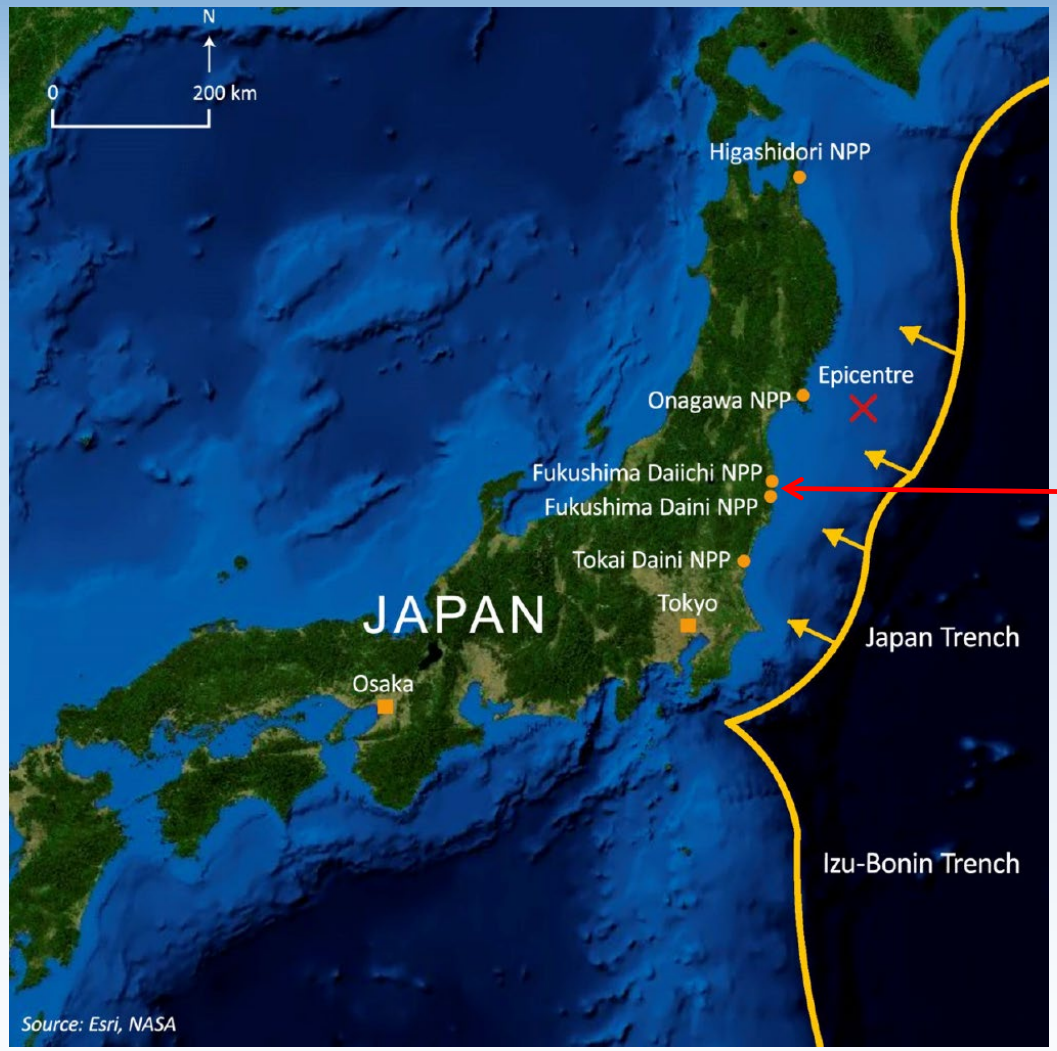
Freshwater bodies

- Early restrictions on drinking water and consumption of freshwater fish
- Other countermeasures are generally ineffective and not sustainable

Decontamination of settlements

Fukushima (Japan)
11 March 2011

The earthquake



Fukushima Daiichi Nuclear Power Station

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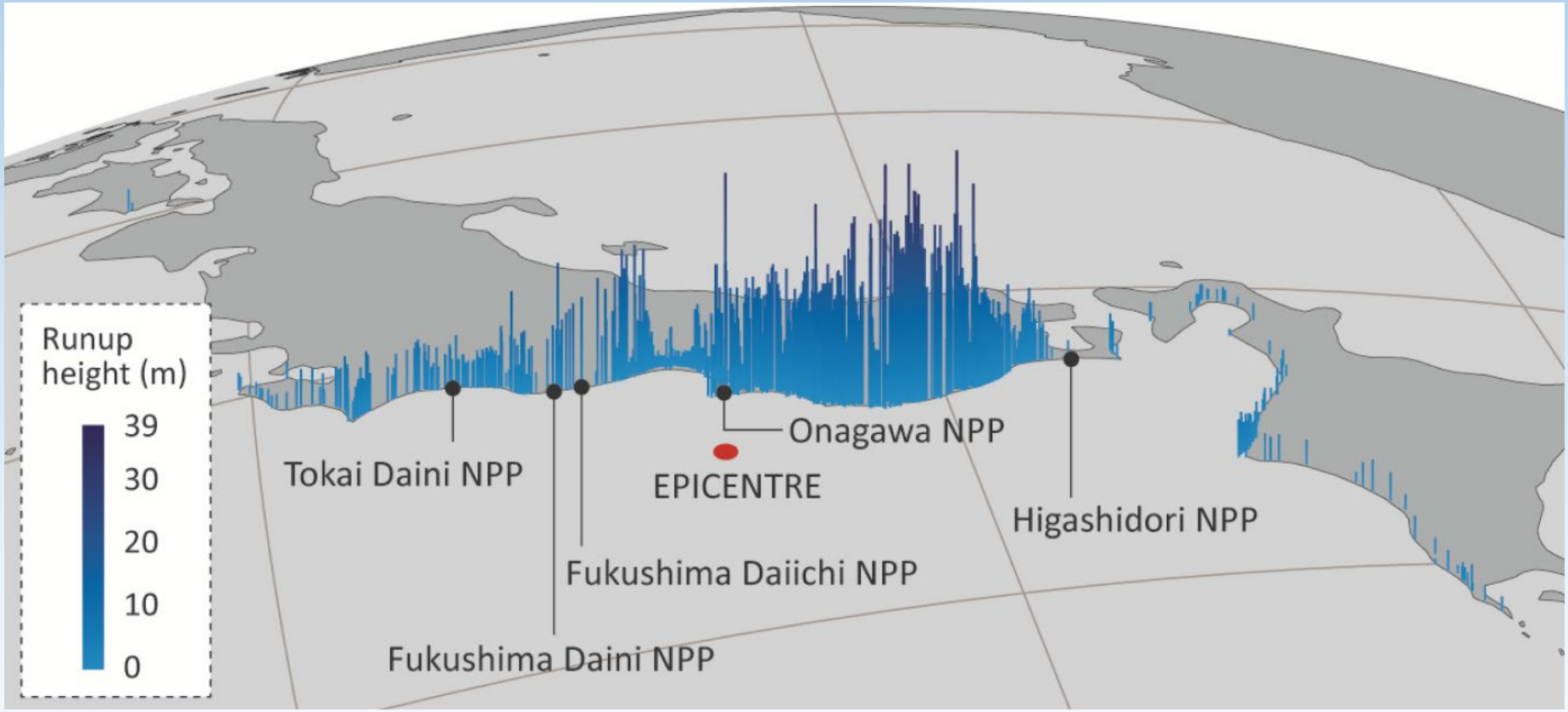
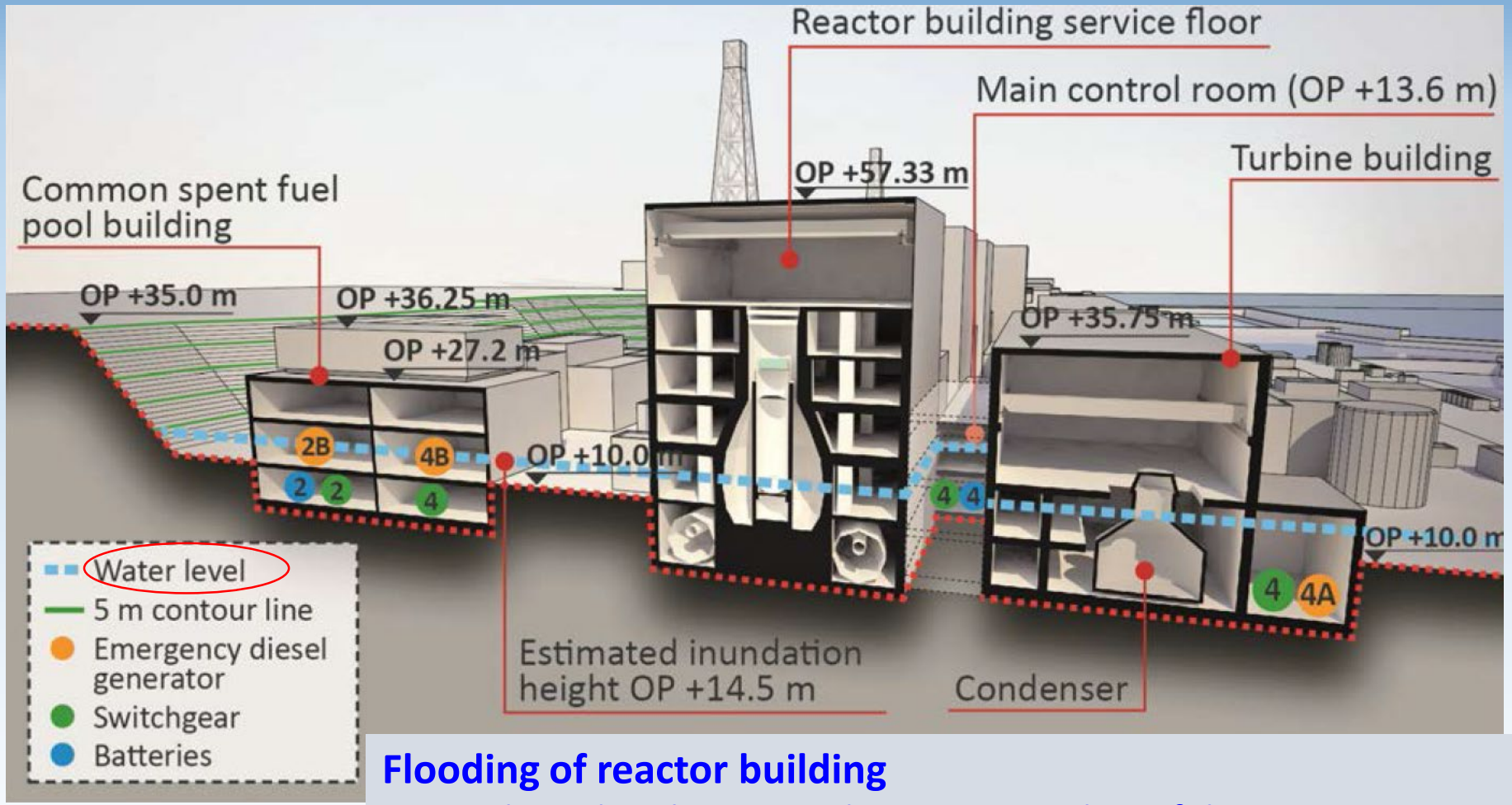
The tsunami: Run-up height of the wave



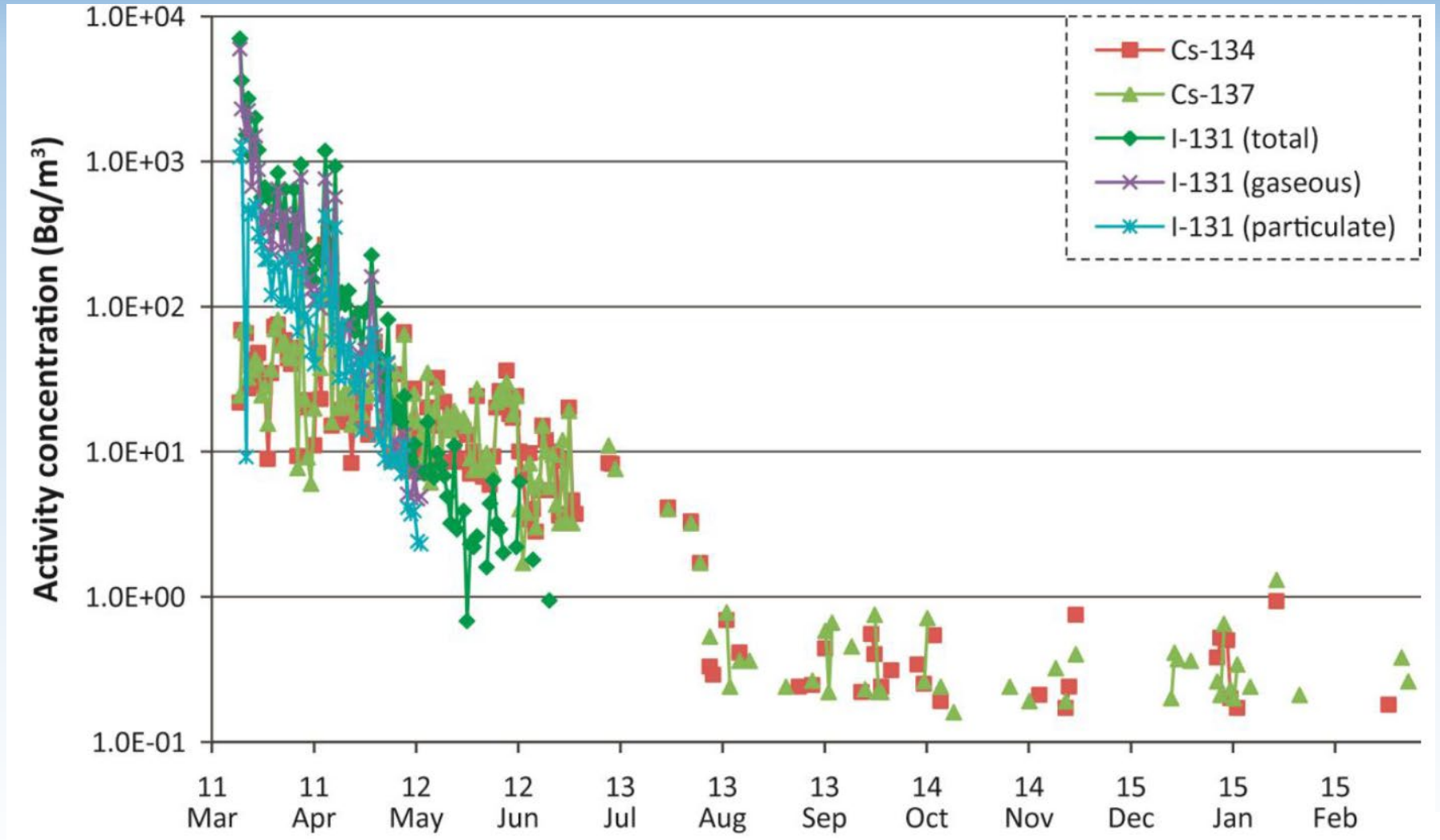
Flooding of the reactor building



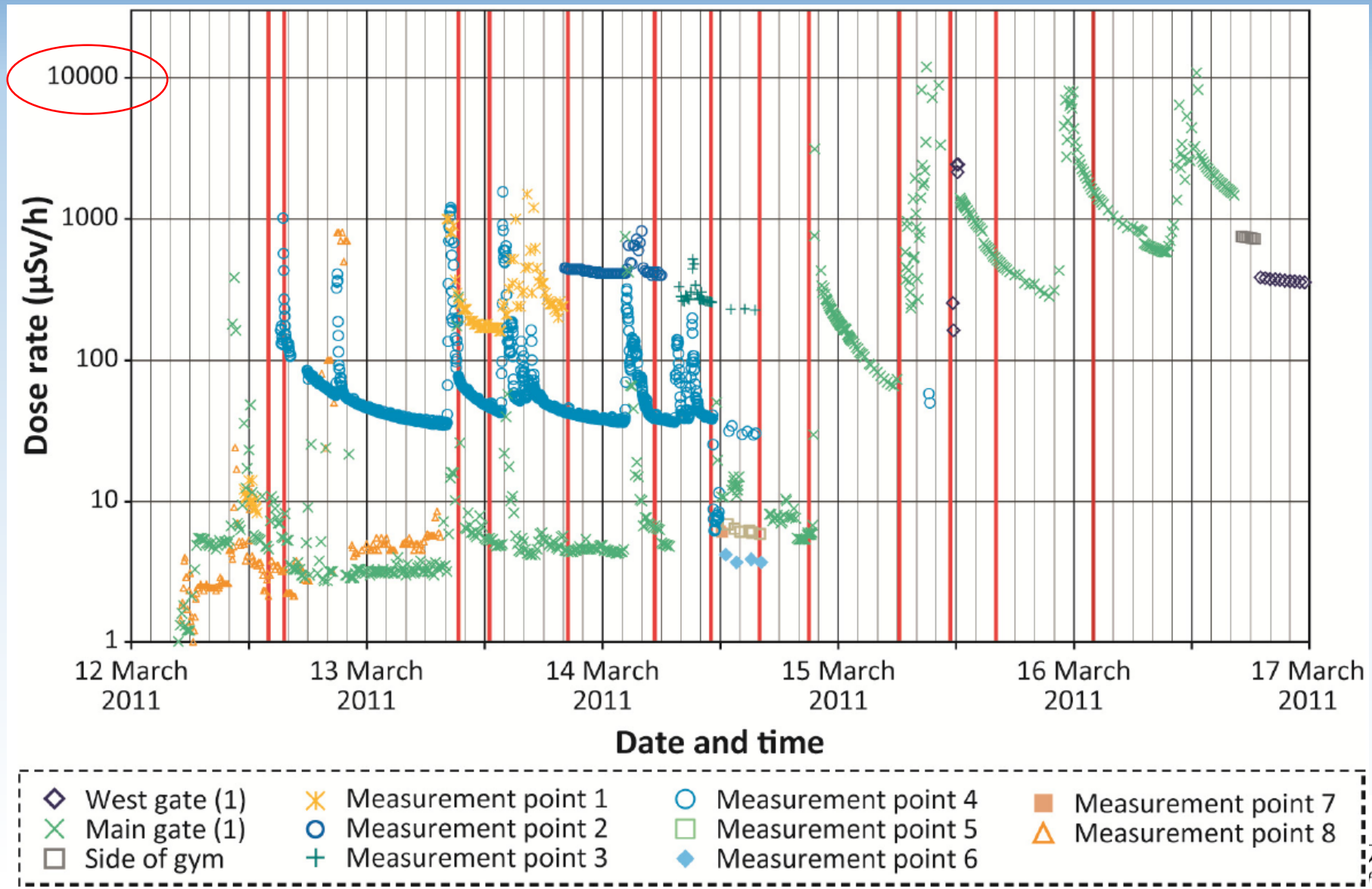
Flooding of reactor building

- Back-up diesels stop working => No cooling of the reactors
- No external power due to damage of infrastructure
- Heating up of the reactor core
- Release of radionuclides

Air concentration close to the Fukushima NPP

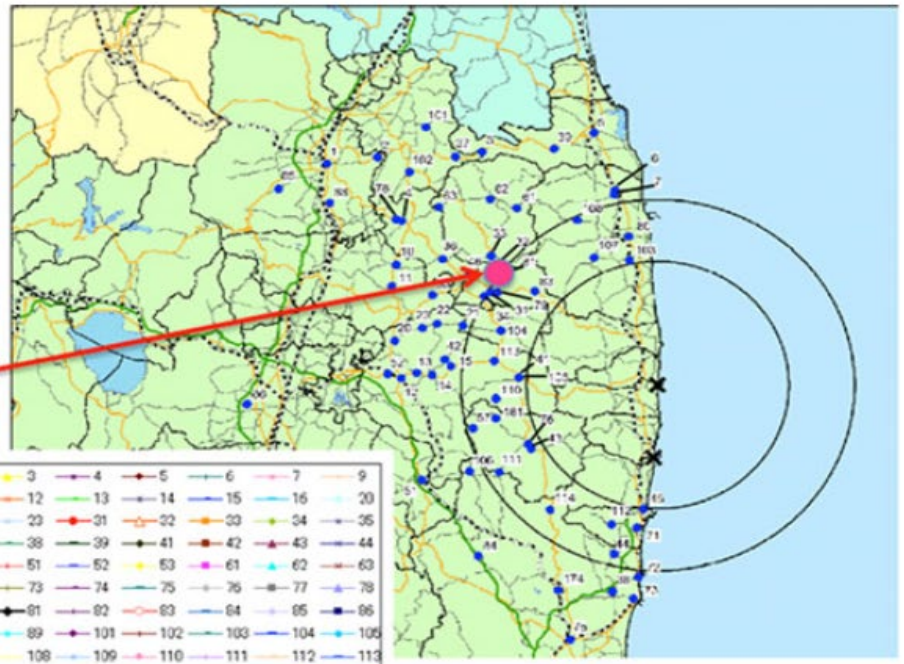


γ-dose rates at the Fukushima NPP (IAEA 2015)

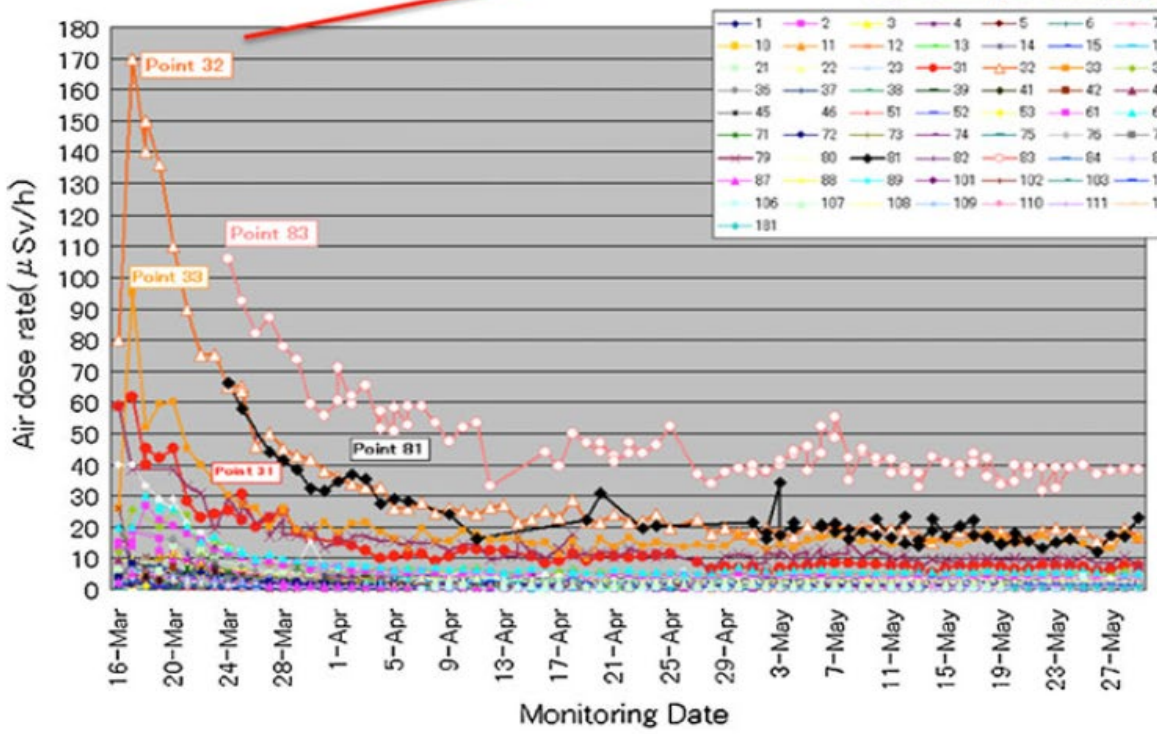


Gamma dose rates outside 20 km

Highest dose rate outside 20 km, ~ 170 µSv/h @ 17 March



Rate out of Fukushima Dai-ichi NPP



Time Dependence of Air Dose rate at Reading point out of 20 Km Zone of Fukushima Dai-ichi NPP

K. Akahane et al. (2012): The Fukushima Nuclear Power Plant accident and exposures in the environment, The Environmentalist DOI 10.1007/s10669-011-9381-2

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Protective actions for the public to reduce external exposure

- ***Evacuation***
  - The **rapid, temporary removal** of people from an area to avoid or reduce short term radiation exposure in a nuclear or radiological emergency
- ***Sheltering***
  - The **short-term use of a building for protection** from external exposure of radionuclides in air or on the ground
- ***Relocation***
  - The **non-urgent removal** of people from an area to avoid long term exposure

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Evacuation

11 March

- 14:46 Earthquake
- 19:03 Nuclear emergency declared
- 20:50 Instruction for evacuation within 0-2 km
- 21:23 Evacuation within 2-3 km, Stay indoors within 3-10 km

12 March

- 05:44 Evacuation within 10 km
- 18:25 Evacuation within 20 km

15 March

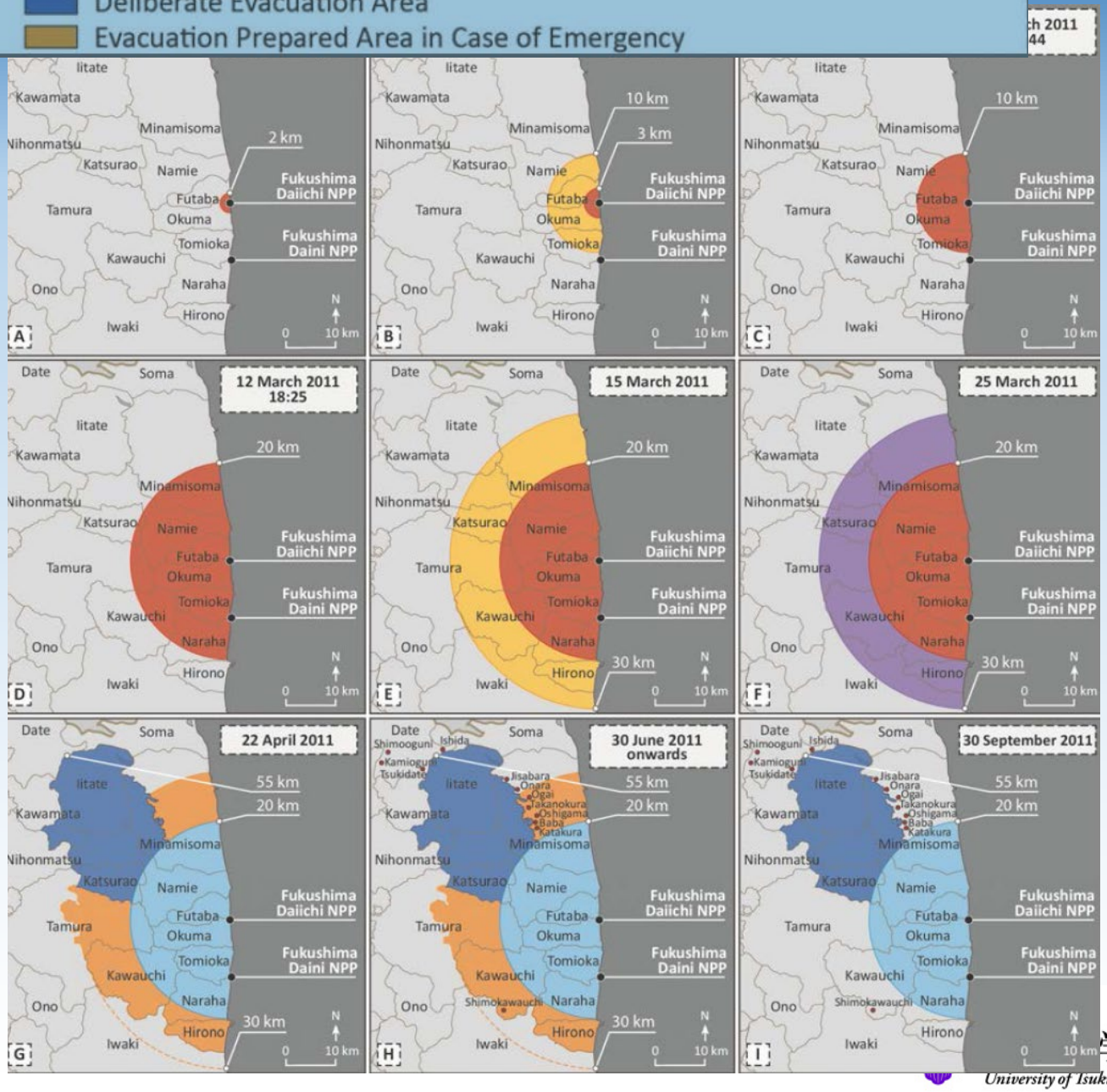
- 11:00 Stay indoors within 20-30 km

22 April

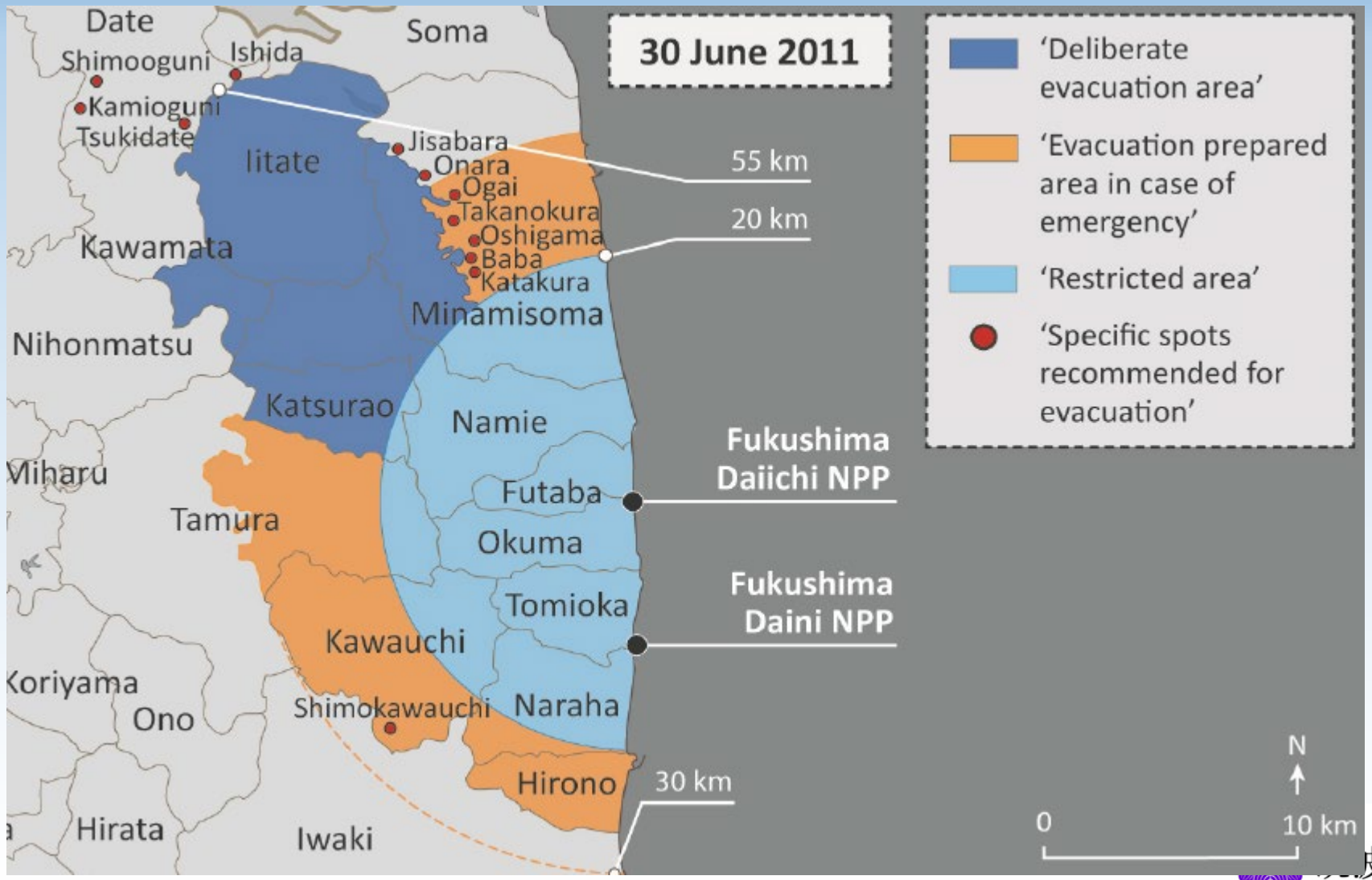
- Recommendation to leave the area NW outside 20 km

Evacuated areas

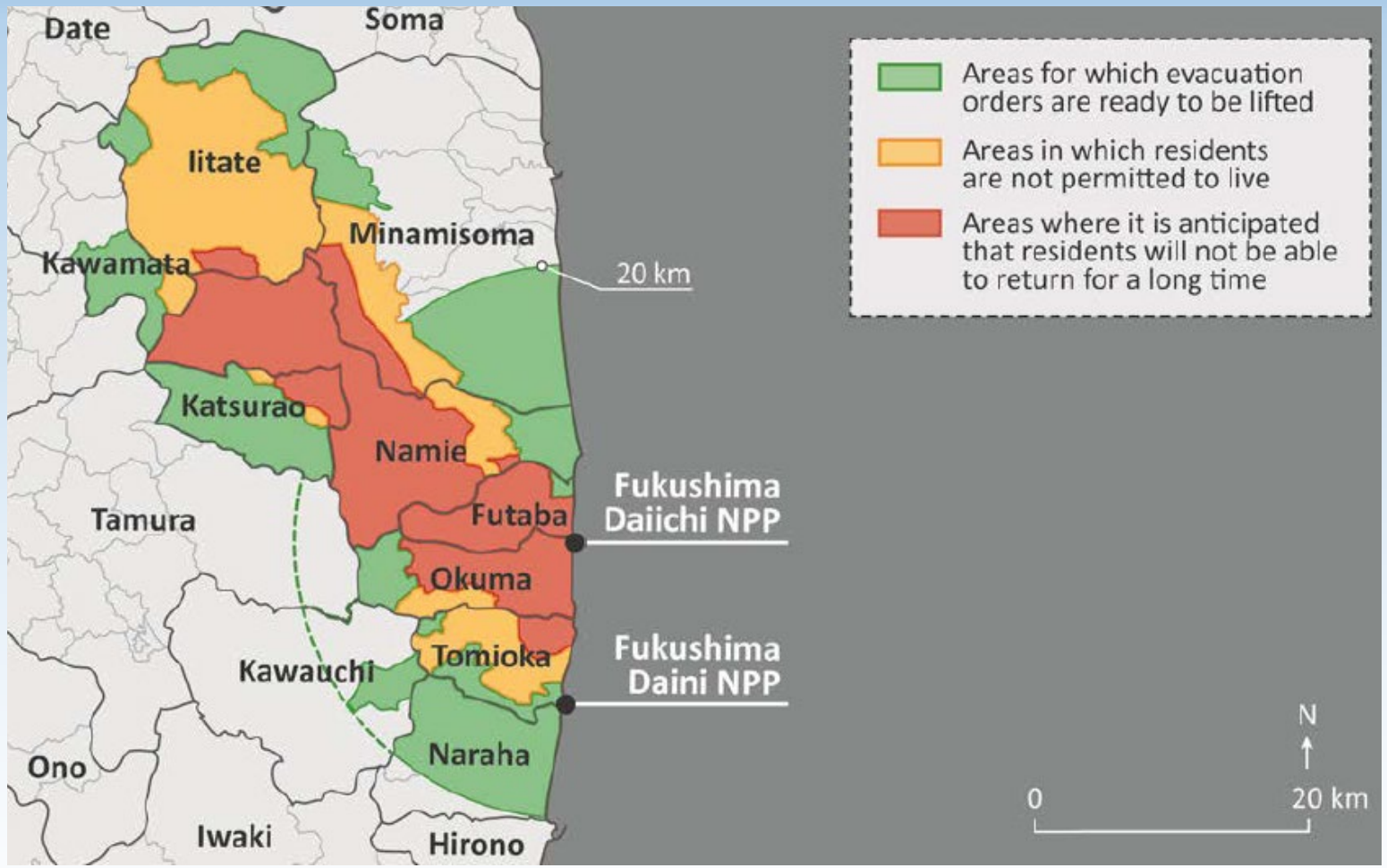
Evacuees in June 2011:
164 000



Areas with instructions or recommendations for evacuation or staying indoors



Evacuation areas as of October 2014



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Early actions for the public to reduce internal exposure

Measures taken

- Intake of stable iodine to block uptake of radioiodine by the thyroid
- Setting a limit for total caesium (Cs-134/ Cs-137) in food
  - March 2011 to March 2012: 500 Bq/kg
  - From April 2012: 100 Bq/kg
- Monitoring on the field and on the market
- Providing information on the activity levels in food
- Use of clean feed

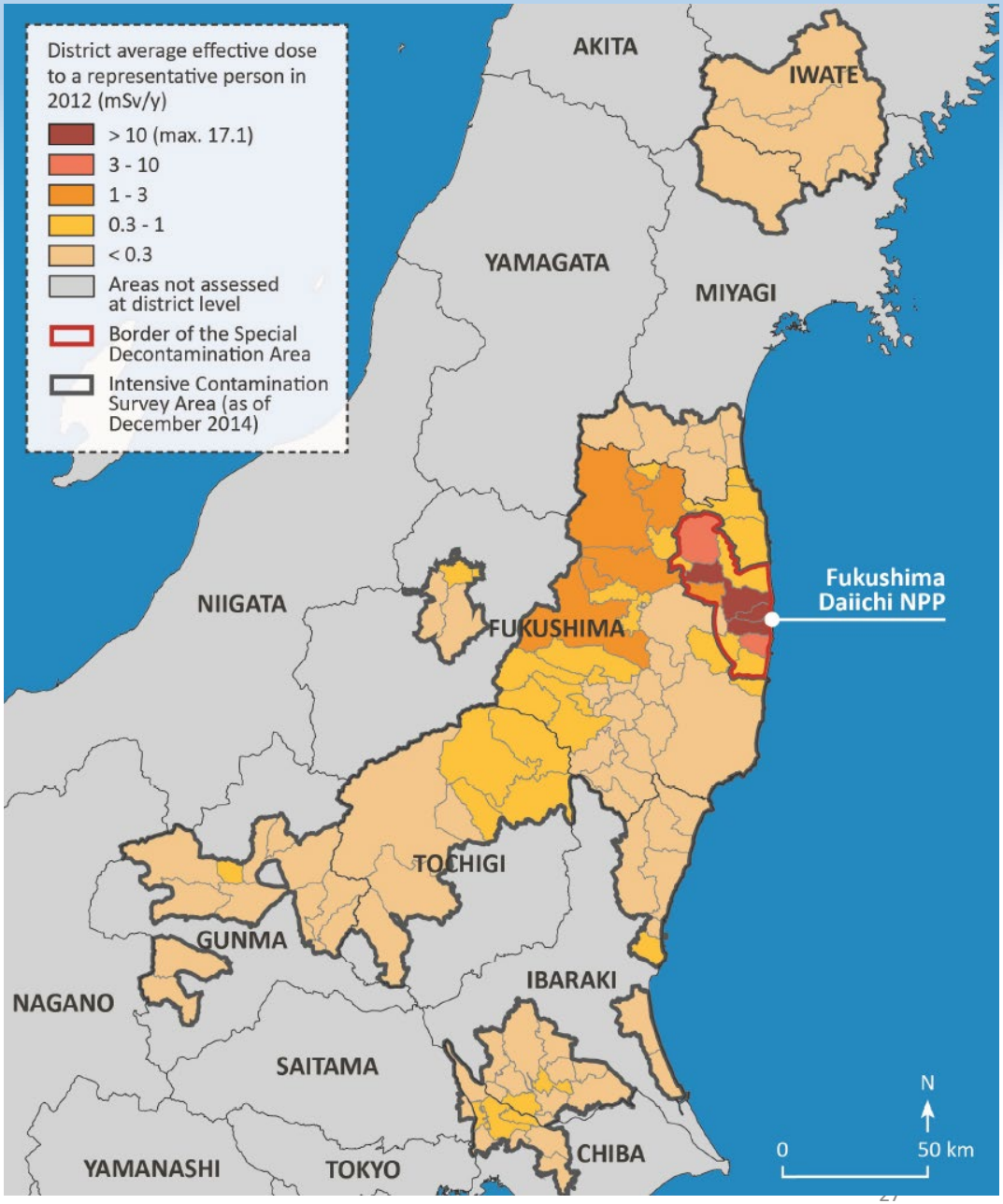
Effect of the measures

- The rapid application of such measures kept the internal exposure due to intake of food low

Fukushima:
District average dose to a representative person in 2012
(IAEA, 2015)

- **External exposure by far dominating**

- **Internal exposure is very low**
  - Strict monitoring of food
  - Low limits in foods
  - Nation-wide food supply



Decontamination and remediation activities

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Radiological criteria set by the Government of Japan

Reference level* for remediation of land

- 1 mSv/a as a long-term goal
- Areas with a gamma dose rate > 0.23 µSv/h were decontaminated
  - According to the algorithm applied to determine the dose to people from the gamma dose rate, 0.23 µSv/h is equivalent to a dose of 1 mSv/a

Activity in food

- Total radiocaesium (Cs-134 + Cs-137) in food
- March 2011 to March 2012: 500 Bq/kg
- From April 2012: 100 Bq/kg

*A reference level is a target, not a strict limit

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Fukushima: Typical remediation measures (IAEA, 2015)

Target	Remediation measures
Houses, buildings	Removal of deposits from the roof, gutters and any decking Wiping roofs and walls Vacuum sanding High pressure washing
Schoolyards, gardens and parks	Topsoil removal Weed/grass/pasture removal
Roads	Removal of deposits in ditches High pressure washing
Gardens and trees	Mowing Removal of fallen leaves Removal of topsoil High pressure washing Paring of fruit trees
Farmlands	Tillage reversal Topsoil removal Soil treatment (e.g. enhanced application of fertilizer) Soil hardening and removal Weed/grass/pasture removal
Animal production	Control of radiocaesium levels in animal feed
Forests and woodland	Removal of fallen leaves and lower twigs Pruning

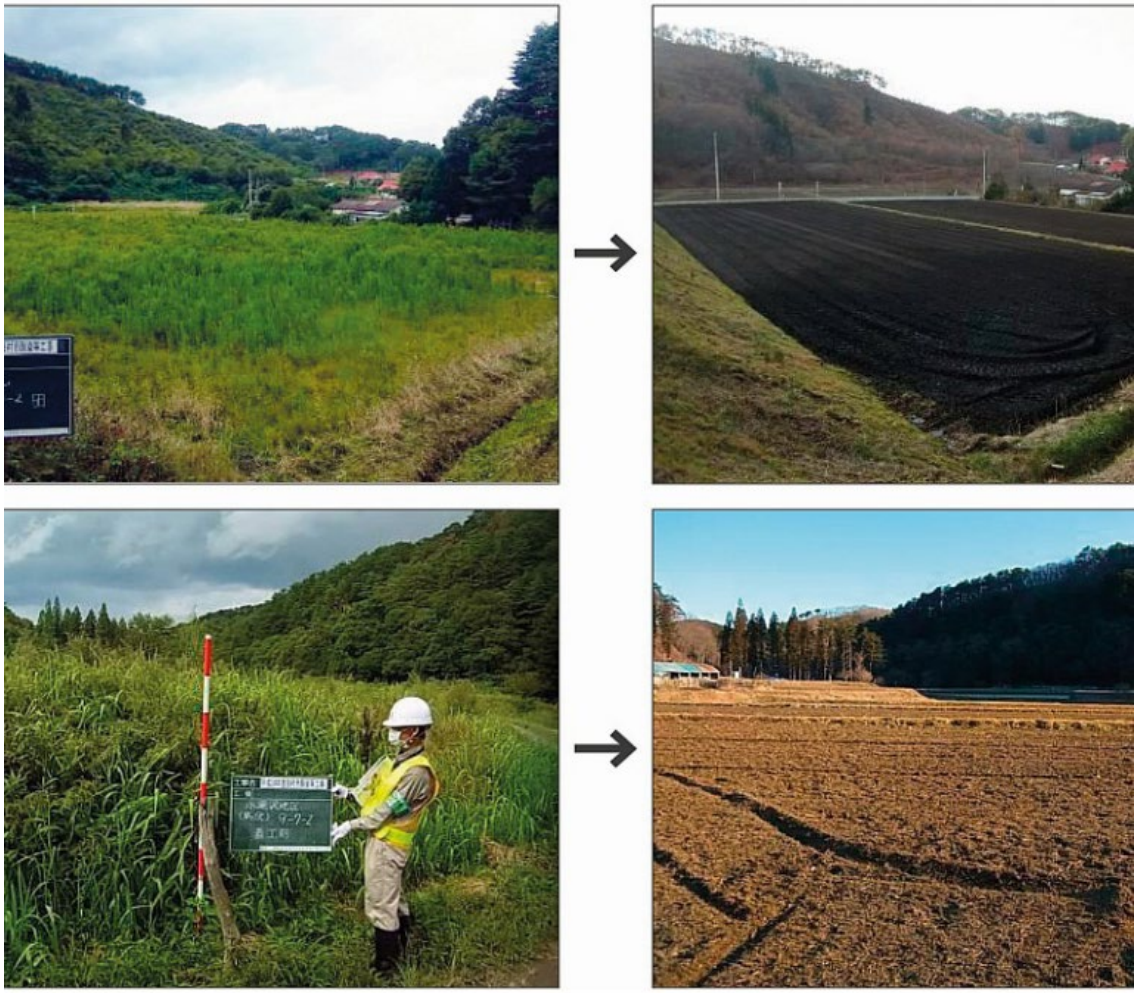
Techniques for decontamination and remediation



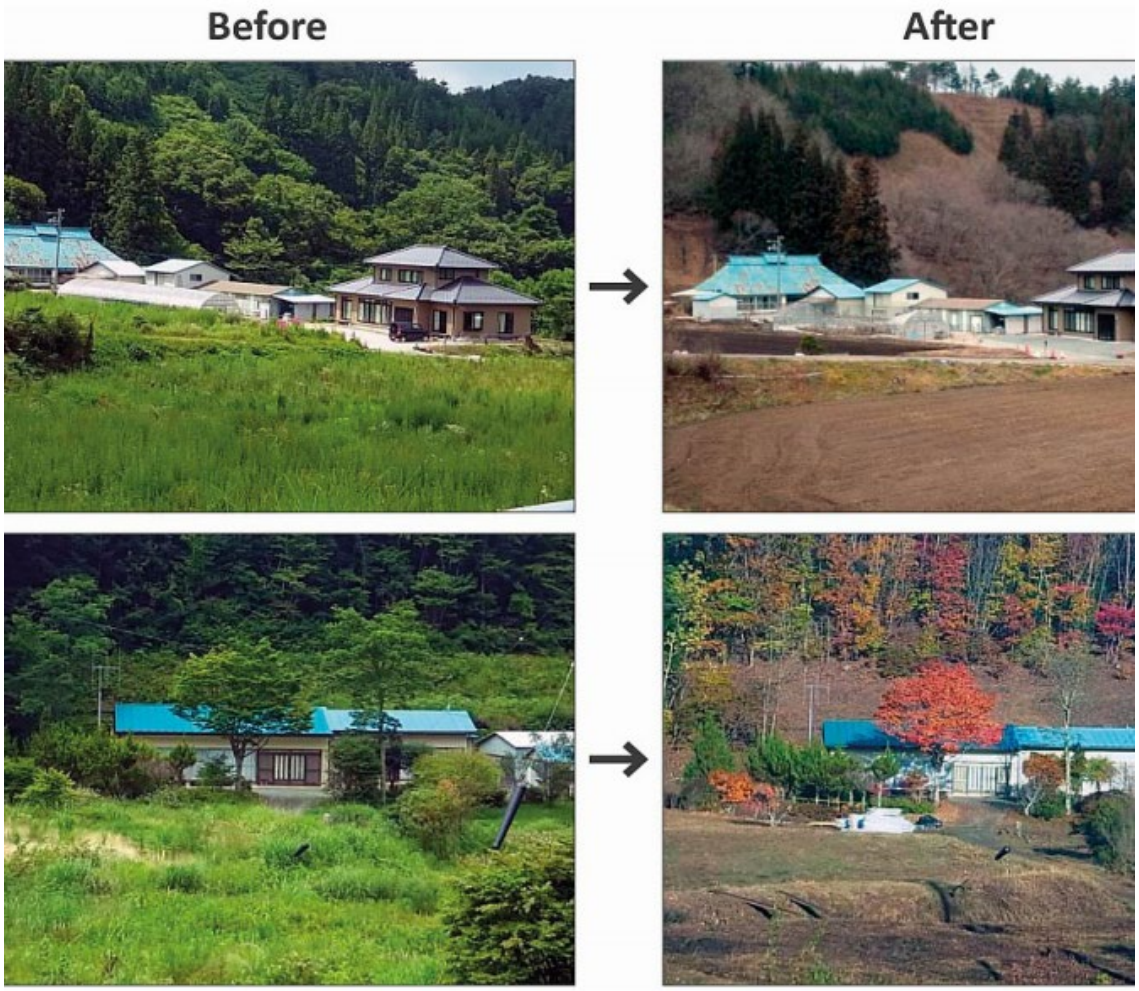




Source: HPA - EURANOS Handbook



Before and after contamination work in Tamura City (IAEA, 2015)



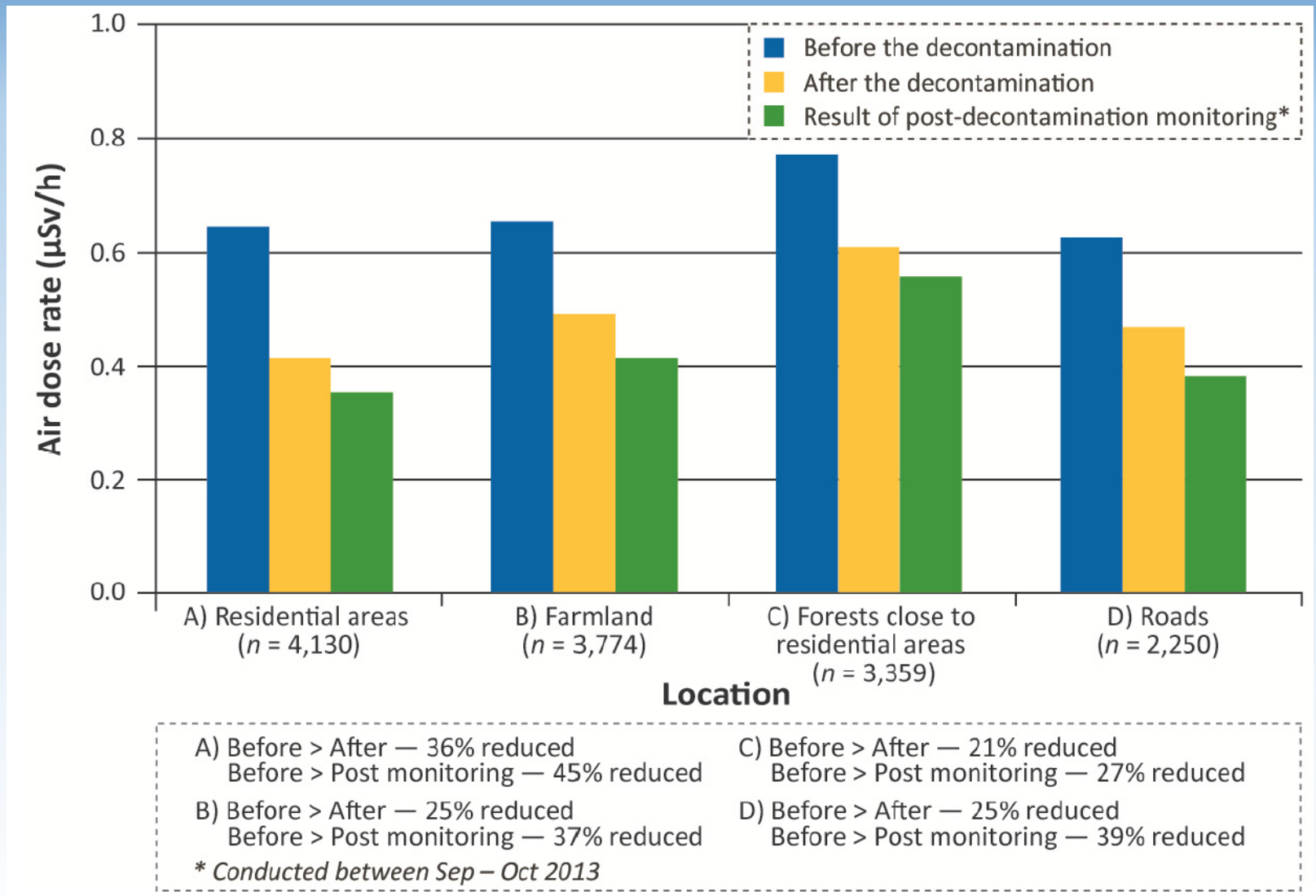
Before and after contamination work in Tamura City (IAEA, 2015)

Temporary Storage Sites for clean-up waste

ca. 20 million m³ waste
ca. 1000 storage sites

Soil, debris, vegetation

Reduction of dose rate in a city of the Fukushima Prefecture



Reduction of γ-dose rates by ca. a factor of 1.5

Systematic monitoring of locally grown rice
(IAEA, 2015)

Effectiveness of countermeasures

- **Effective measures available**
  - Reduction of surface contaminations
  - Reduction intake of activity
    - Restriction of food intake and grazing of animals
    - Modification of agricultural practice
    - Information for people on foods to avoid

- **Dose reduction achieved**
  - External dose
    - 10-50 % (Chernobyl, Fukushima)
  - Internal dose
    - Chernobyl:
      30 % of the collective ingestion dose (Fesenko, 2009)
    - Fukushima:
      Ingestion doses largely avoided due to strict monitoring and food restrictions

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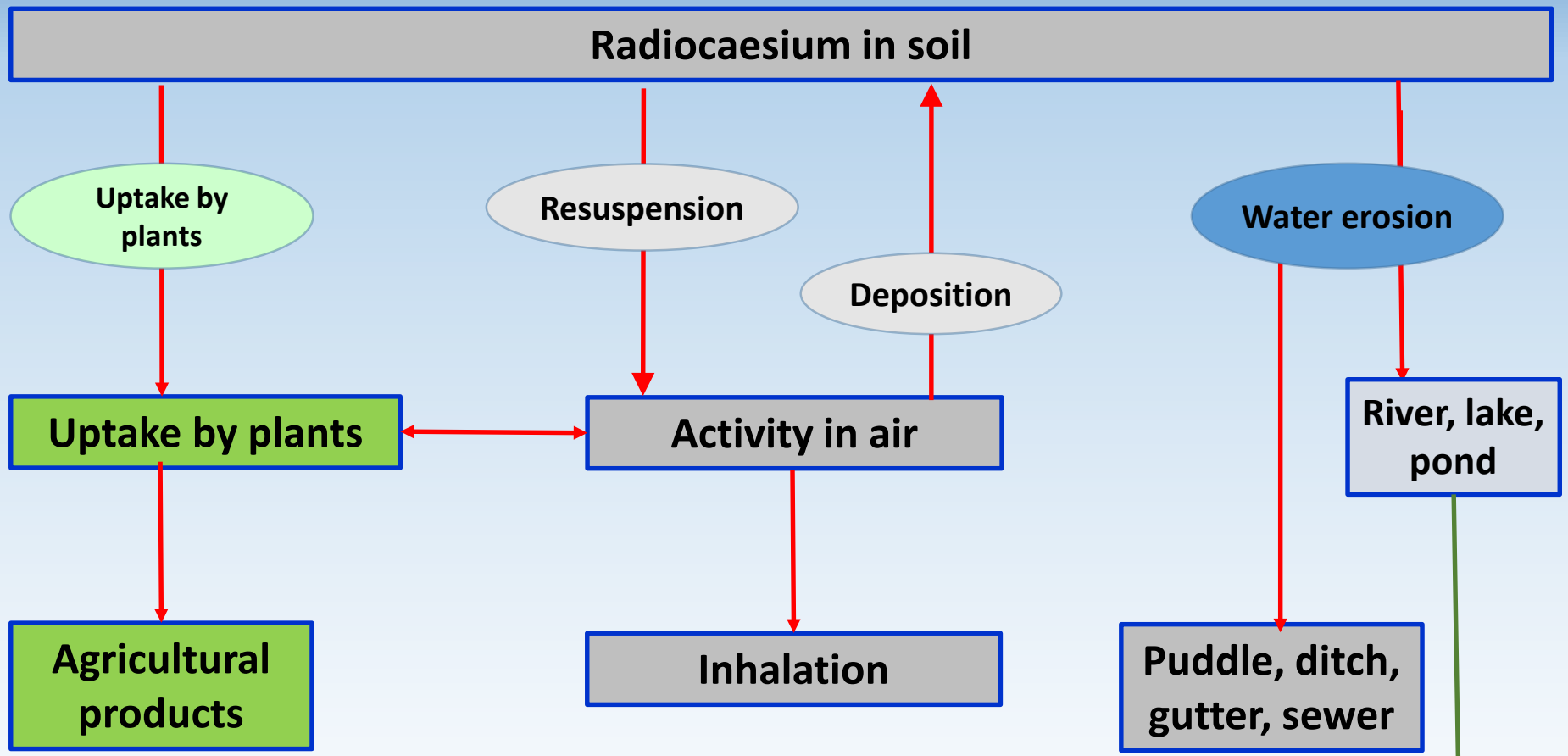
Interaction of thyroid doses due to I-131 with living habits, monitoring and information of the public

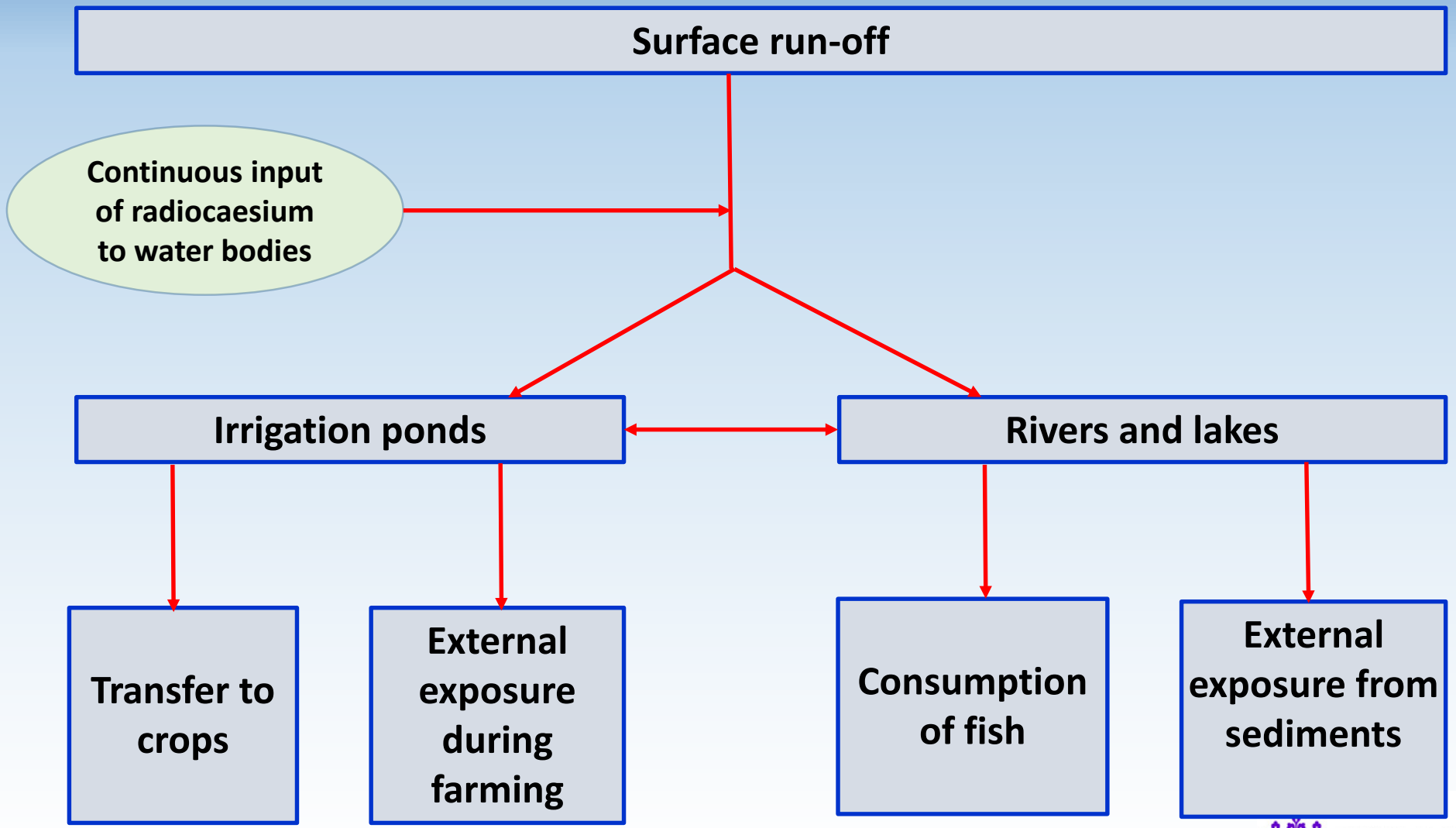
Factor	Fukushima	Chernobyl
Time of accident	before the growing period	during/after the start of the growing period
Milk consumption	low	high
Food monitoring	intensive	less intensive in the beginning
Degree of self-supply	low	high to very high
Information of the public	fast	delayed
=> Thyroid exposure due to ingestion	**relatively low**	**high**

Long-term aspects of Cs-137 in the environment

Long-term processes in the terrestrial environment



Long-term processes in the aquatic environment



Long-term behavior of Cs-137

Root uptake, resuspension and erosion

=> Lead to a continuous re-distribution of radionuclides

Related migration rates are low

- Uptake from arable soil: ca. **0.01 % per year**
- Resuspension**: < 0.1 % per year**
- Water erosion: depends on topography
  - –Insignificant on a regional scale
  - –Could have local relevance
    - Accumulation in puddles, ditches, gutters may occur

Decay rate of Cs-137 is 2.3 % per year

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Countermeasures taken in freshwater

Aim	Measure taken
Reduce transfer of radiocaesium from irrigation water **to crops**	**Rivers and lakes** • Reducing **sediment** inflow • **Sediment** deposition in dams **Irrigation ponds** • Reducing **sediment** outflow • Removing contaminated bottom **sediments** • Enhanced application of **potassium** fertilizer
Reduce radiocaesium **intake by fish**	**Rivers and lakes** • Food **restrictions** • Application of **potassium** in lakes
Reduce external exposure	**Rivers and lakes** • Removing riverbed **sediments** • Flood control to avoid distribution of **sediment** **Irrigation ponds** • Removal of **sediment** • Covering of excavated **sediments**

“The trend is your friend”

Continuous decline of activities and dose–rates

- Cs-137-activities in suspended sediments
- Air-dose rate above decontaminated river banks
- Suspended Cs-137 in river water

The decline is faster than the natural decay only

- Migration in soil
- Attenuation by less affected sediment- or soil layers
- Strong fixation of Cs-137 by clay => low uptake from soil

Global experience indicate that these trends will continue

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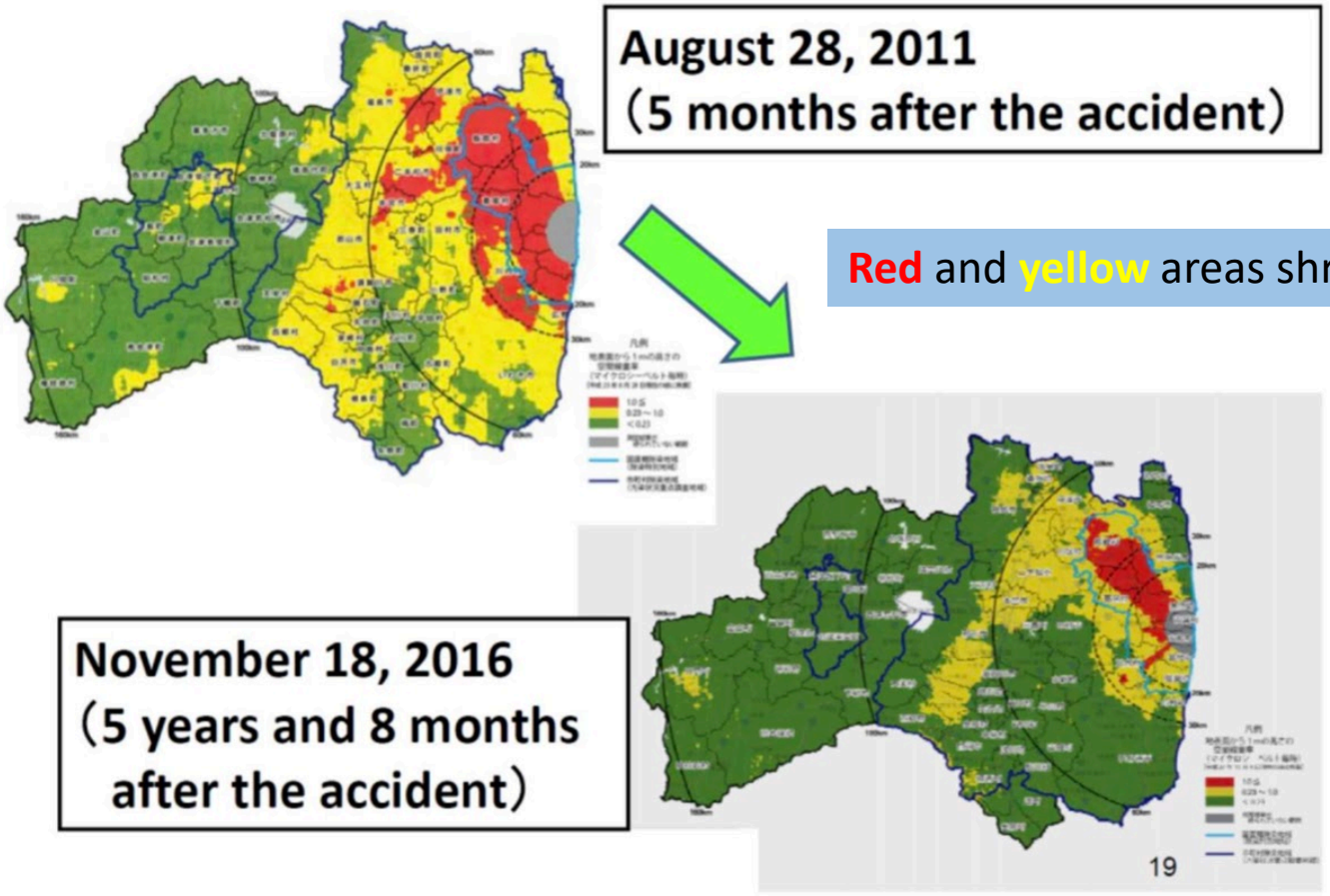
Air dose rate, 1 m above ground



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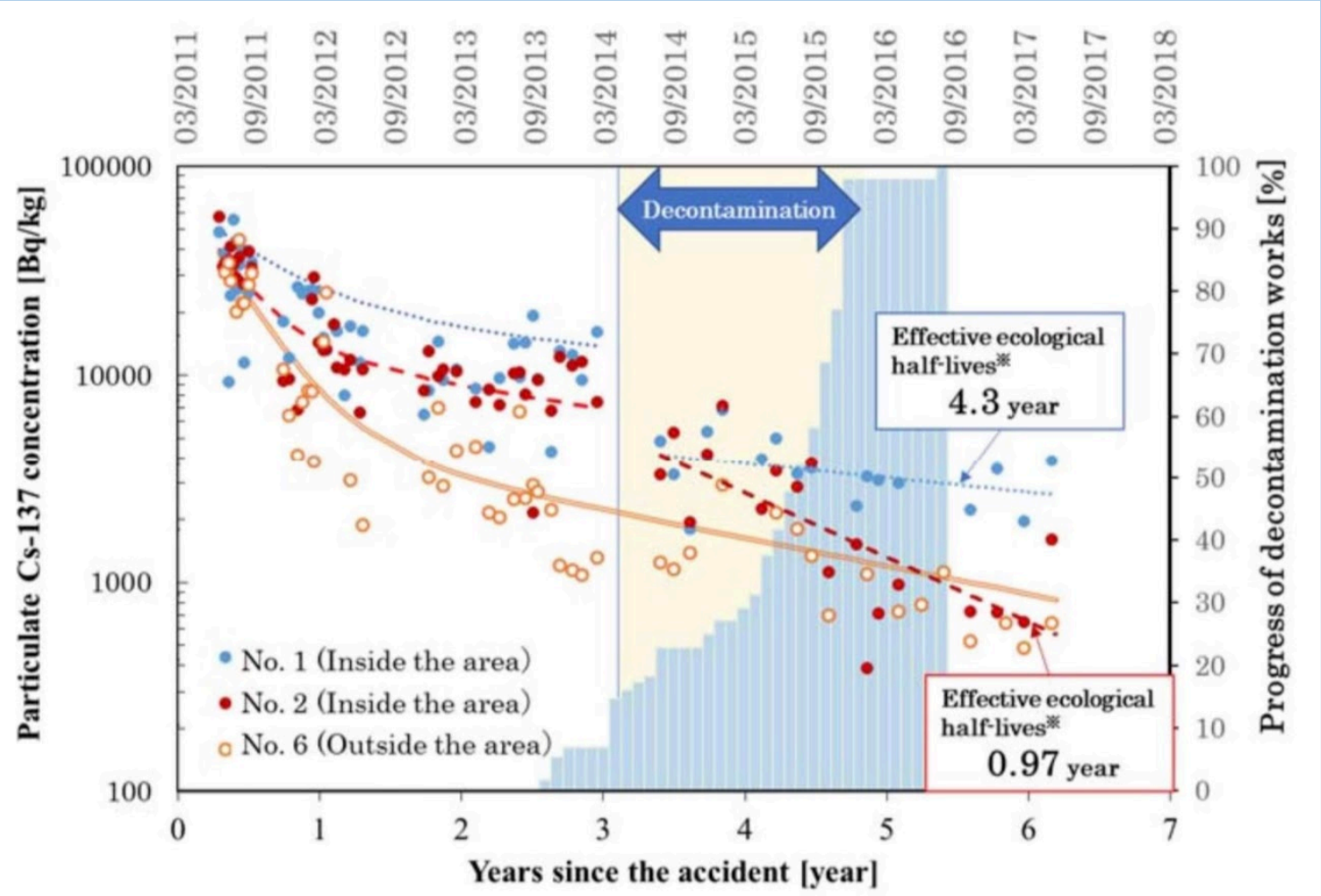
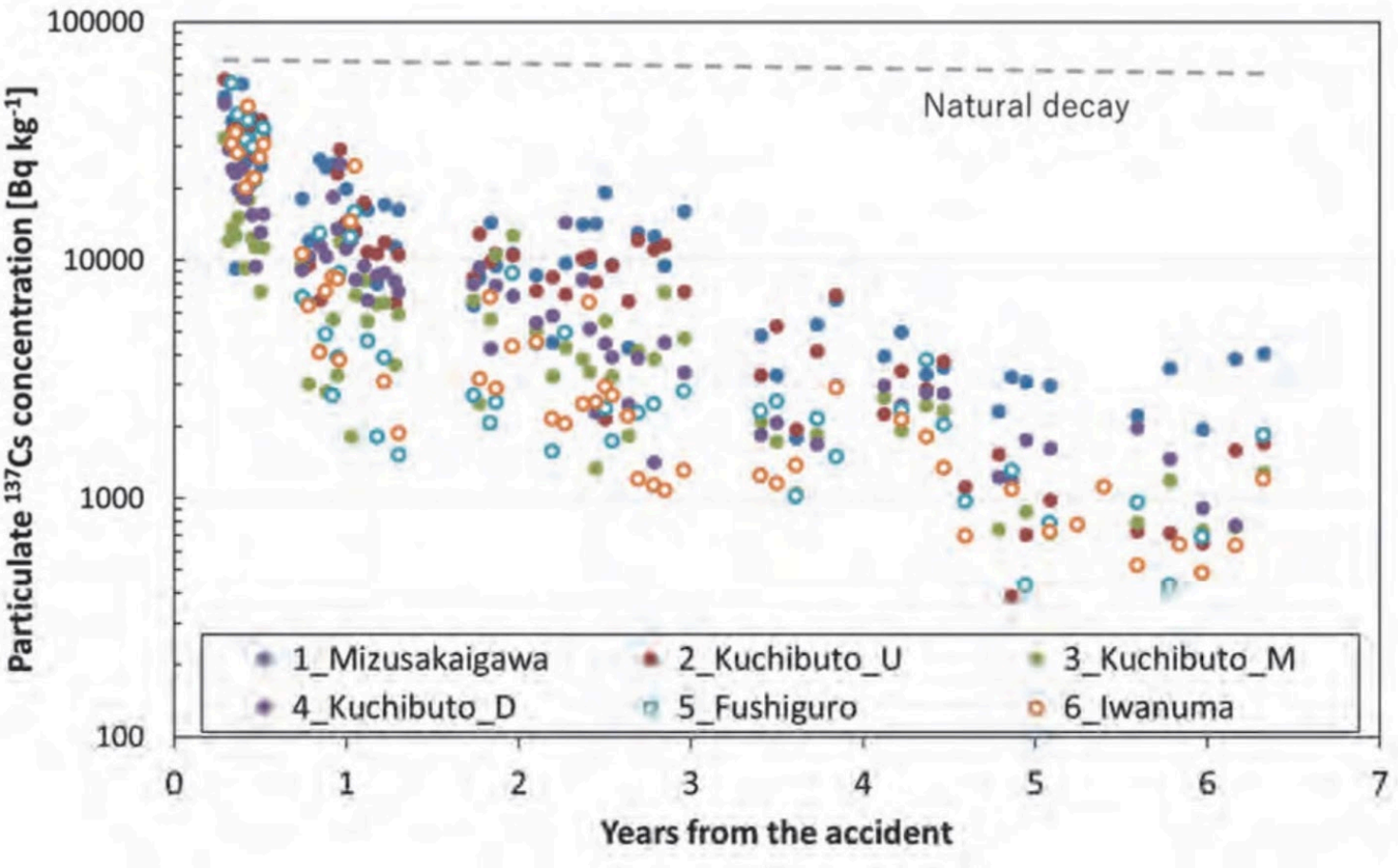
Suspended Cs-137 in water:
Inside (1,2) and outside (6) the special decontamination area



Cs-137 in suspended matter:
Rivers of the Fukushima Prefecture (2011-2017)



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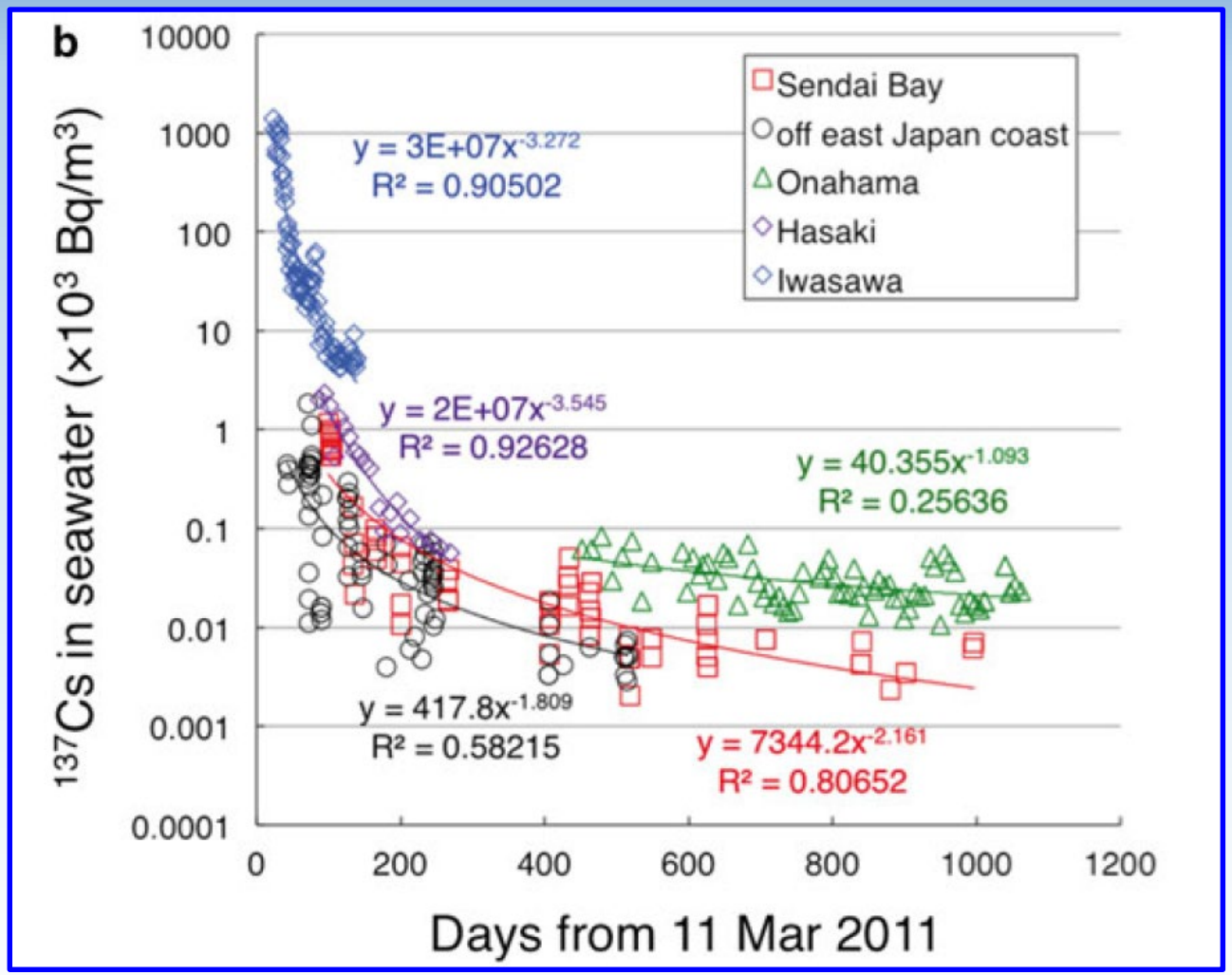
Cs-137 in seawater



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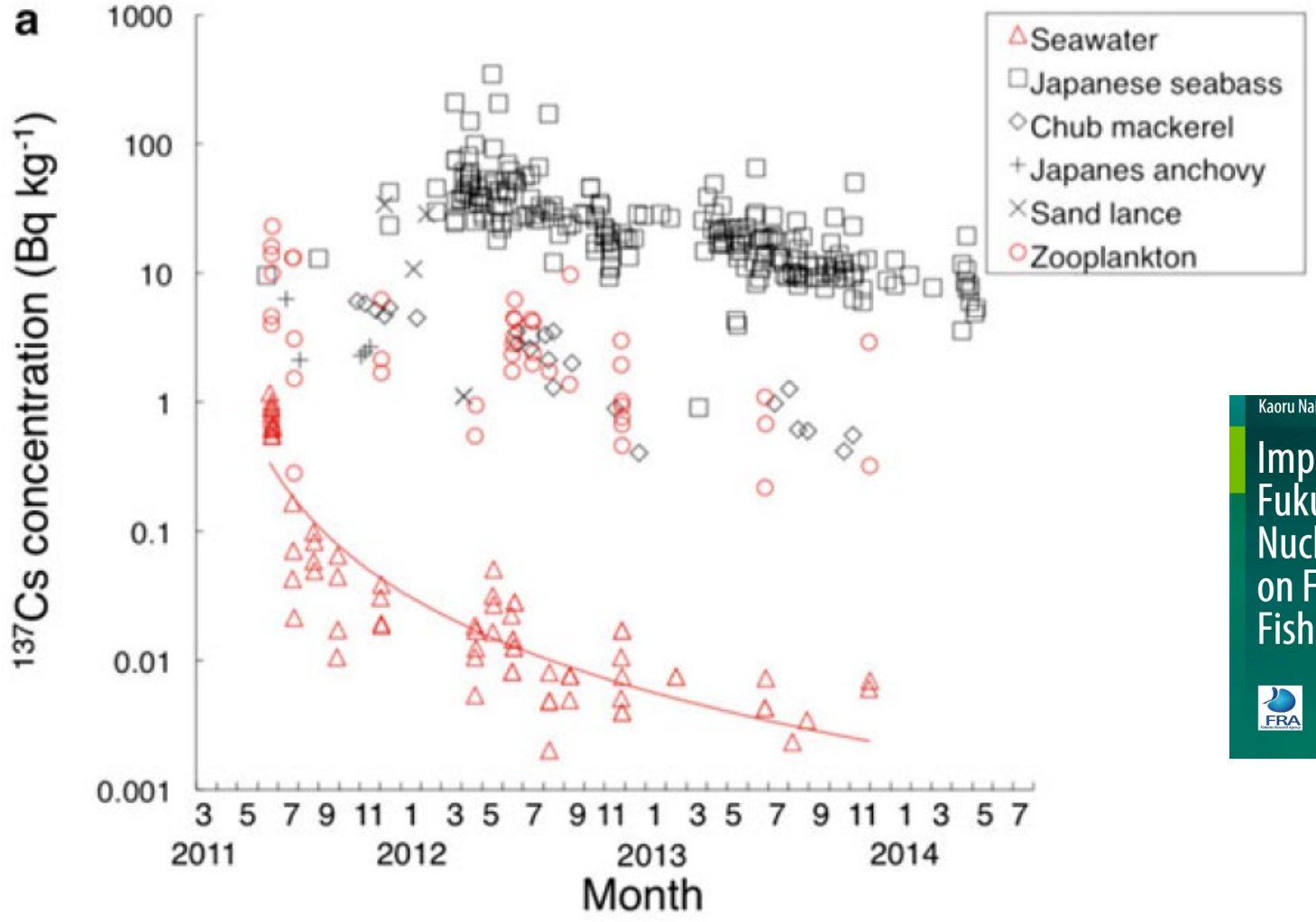
Cs-137 in seawater and fish

Sendai Bay and off the coast of the Miyagi prefecture



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Decline of air dose rate in a decontaminated and control area