PLANT DOSIMETRY

TERRESTRIAL ECOSYSTEMS: CURRENT APPROACHES AND NEEDS FOR THE FURTHER DEVELOPMENT

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Outline

- Problem in general
- Needs for the dose assessments to plants
- Current approaches in plant dosimetry
- Sources of uncertainties of the dose estimates
- Example of the dose rate assessment

Problem in general

- Diversity of plants: various size, shape, life span, environment… how to deal with this?
- Various sources and scenarios of irradiation: external and internal, acute and chronic, root uptake or foliar contamination…
- Fixed location, in differ to animals. However, various processes in the ecosystems may lead to variations of exposures in time
- Heterogeneity of RN distribution in plants: is it an important factor in dosimetric calculations?
- Are there any “critical” organs in plants? Should we determine dose to the whole organism or to such organs?
- Main cases when we estimate doses to plants:
  - assessment of the potential exposures and effects
  - existing contamination of the environment

Plant dosimetry for potential exposures

Unknown:

- magnitudes of the released RN activit
- atmospheric/aquatic transportation p erns
- deposition conditions
- species / age composition of the ecos em
- phase of vegetation
- concentration ratios

Conservative assessment of the doses and effects. Typical species considered. Simple dosimetric models can be applied

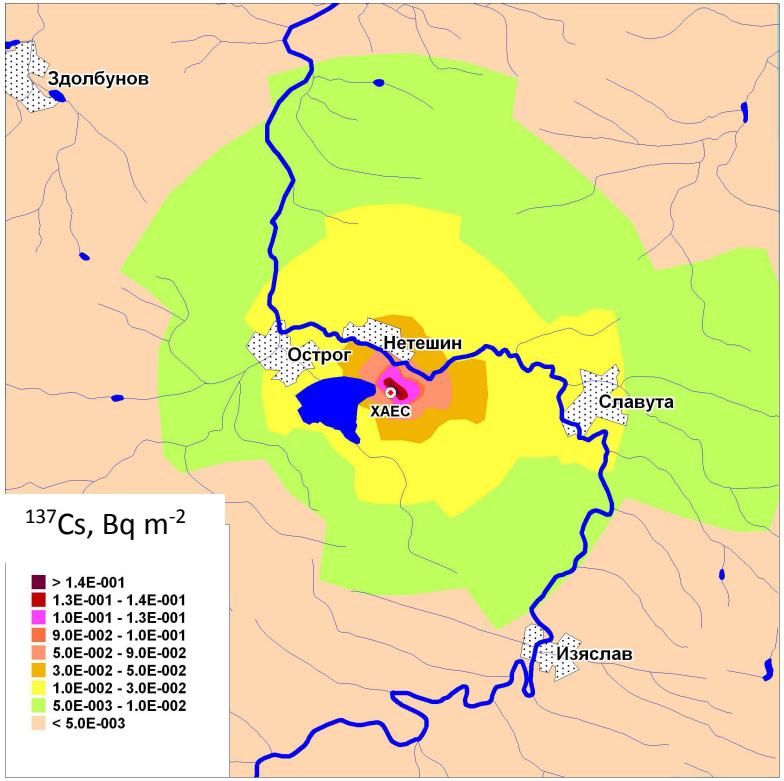
Uncertainty of estimates of environmental concentrations

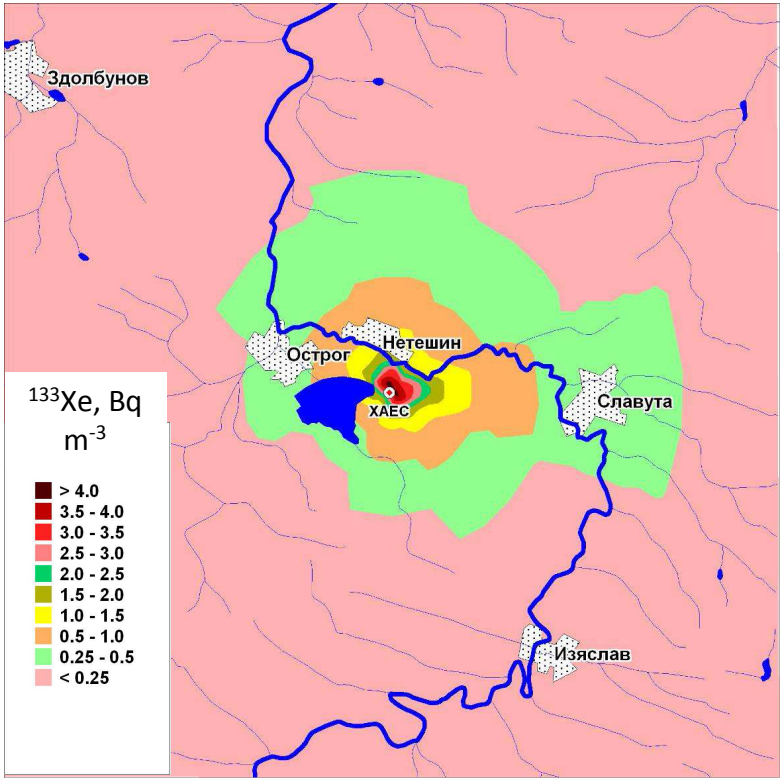
Uncertainty of estimates of incorporated RN concentrations

Example: assessment of potential impacts of the new reactors or nuclear installations to man and biota

Example of the plant dosimetry for potential exposures: new reactors

Khmel'nytsky NPP, Ukraine: routine release, situation after 50 yr of operation





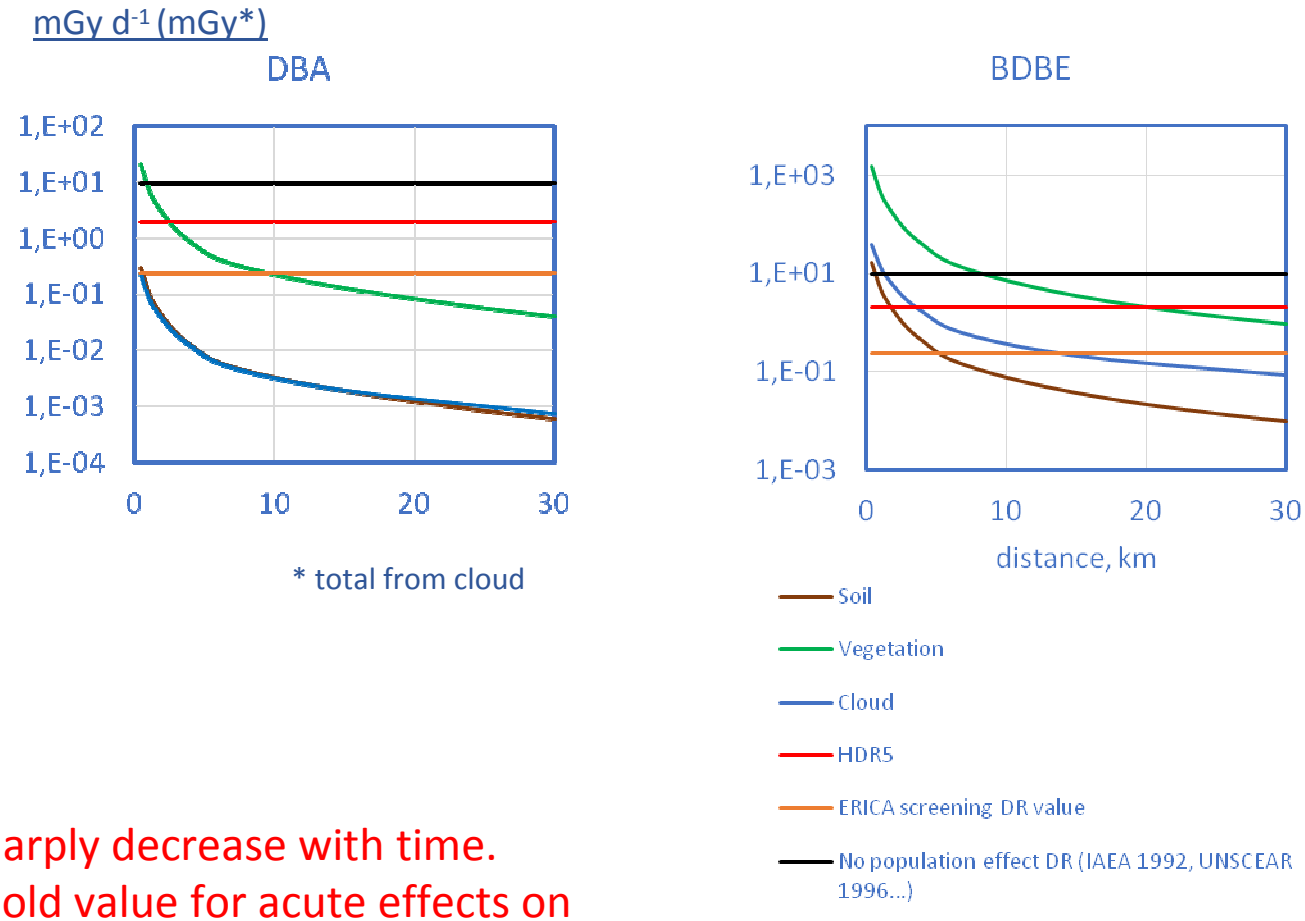
Released RN amounts are very small and do not lead to formation of any important dose rates. There is no need for detail dosimetric calculations

Example of the plant dosimetry for potential exposures: new reactors

Khel'nytsky NPP, Ukraine: design basis accident (DBA) and beyond design basis event (BDBE), first day after the release

Basic assumptions:
-worst weather conditions
-AF=1 for α- and low-energy β-radiation of the intercepted RN (foliar contamination)
-no deepening of RN in the soil profile …

+ if longer period is considered:
-AF=1 for incorporated RN
-conservative values of CR



* total from cloud

Dose rates sharply decrease with time.
The ERICA threshold value for acute effects on ecosystems is 1.8 Gy

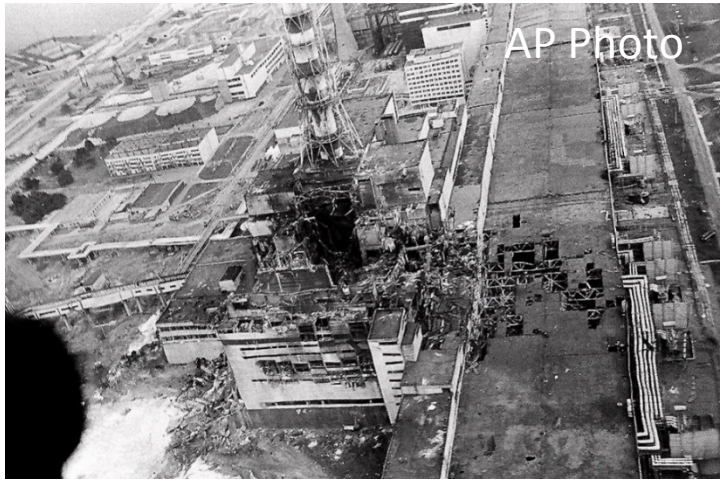
Example of the plant dosimetry for potential exposures: new reactors

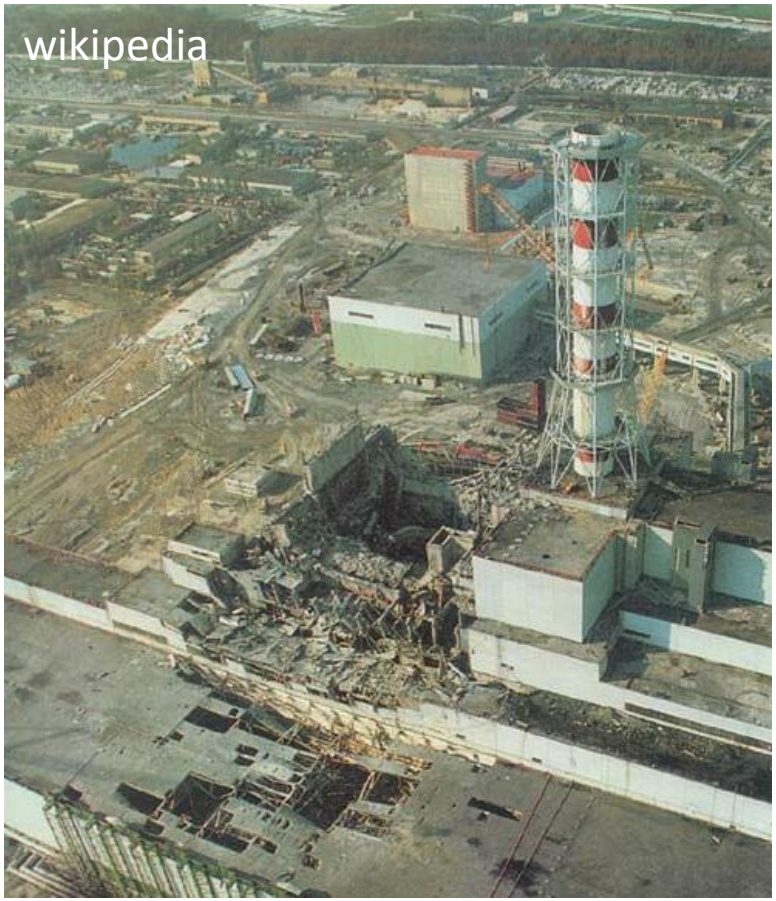
Releases: DBA, BDBE (KhNPP), Chernobyl, Fukushima

	DBA	BDBE	Chernobyl	Fukushima
Activity released (excl. noble gases), Bq	5.8×10^{12}	5.74×10^{14}	5.3×10^{18} (UNSCEAR, 2000)	$3.4\text{-}8.0\times10^{17}$ (Steinhauser et al., 2014)
^{137}Cs, Bq	2.29×10^{10}	4.48×10^{11}	85×10^{15} (UNSCEAR, 2008)	12×10^{15} (Chino et al., 2011) $(6\text{-}20)\times10^{15}$, 8.8×10^{15} (UNSCEAR, 2013)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible] (UNSCEAR, 2013)
^{90}Sr, Bq	1.85×10^{10}	4.09×10^{10}	10×10^{15} (UNSCEAR, 2008)	2×10^{13} (Steinhauser et al., 2014)
$^{238\text{-}240}$Pu, Bq	-	-	4.6×10^{13} (UNSCEAR, 2008)	?
Noble gases, Bq	2.54×10^{13}	3.62×10^{15}	^{85}Kr: 3.3×10^{16} ^{133}Xe: 6.5×10^{18} (Dreicer et al., 1996)	^{85}Kr: 4.4×10^{16} (Ahlswede et al., 2013) ^{133}Xe: 1.4×10^{19} (Stohl et al., 2012) 7.3×10^{18} (UNSCEAR, 2013)

Chernobyl and Fukushima: far beyond "the beyond design basis event"

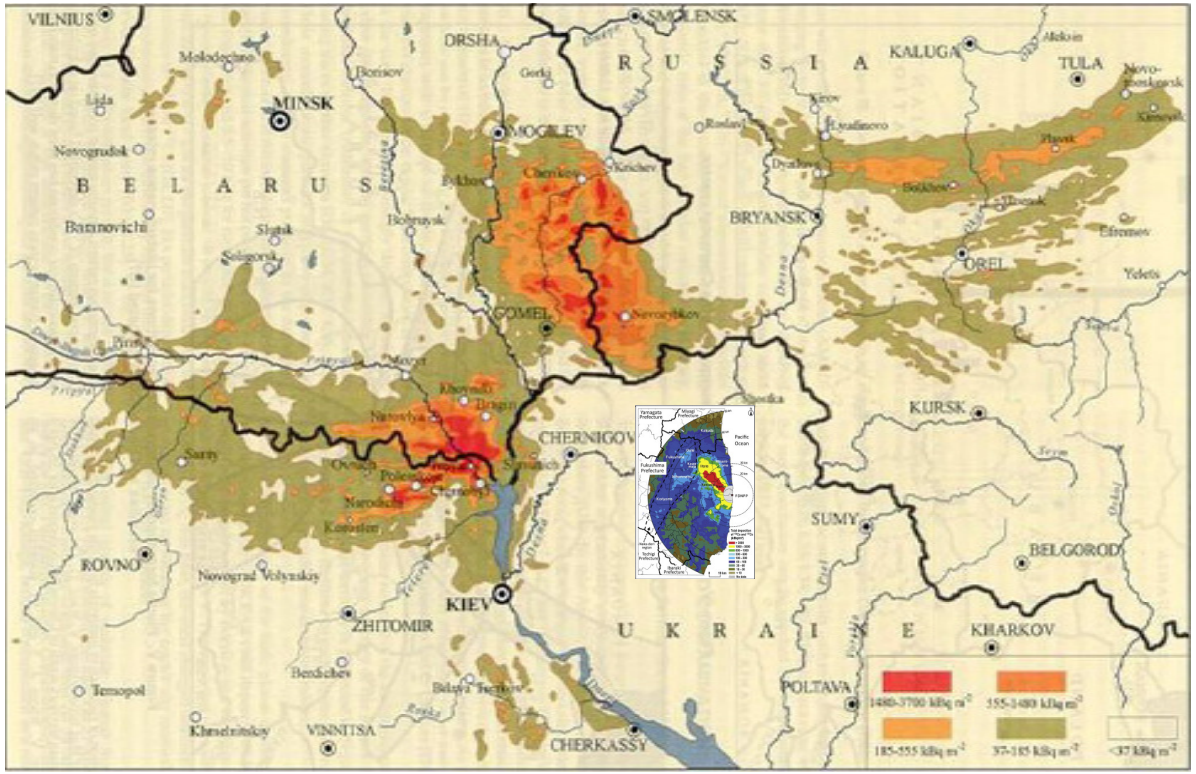
Chernobyl and Fukushima: far beyond BDBE



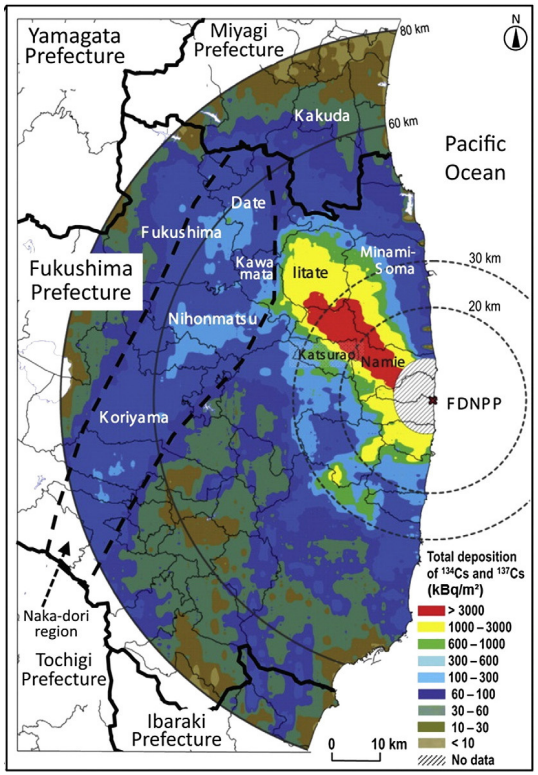


Chernobyl and Fukushima: far beyond BDBE

Chernobyl and Fukushima: far beyond BDBE



International Advisory Committee, 1991



Yoshida and Takahashi, 2012

Chernobyl resulted in contamination of the bigger area. However, in the near zone of the Fukushima accident the levels of contamination with ^{137}Cs are close to those in the Chernobyl exclusion zone

In the Chernobyl zone the numerous effects of radiation to plants have been observed at various levels of organism

Needs for the dose assessments to plants

EUROPEAN COMMISSION

Community research

STRATEGIC RESEARCH AGENDA FOR RADIOECOLOGY

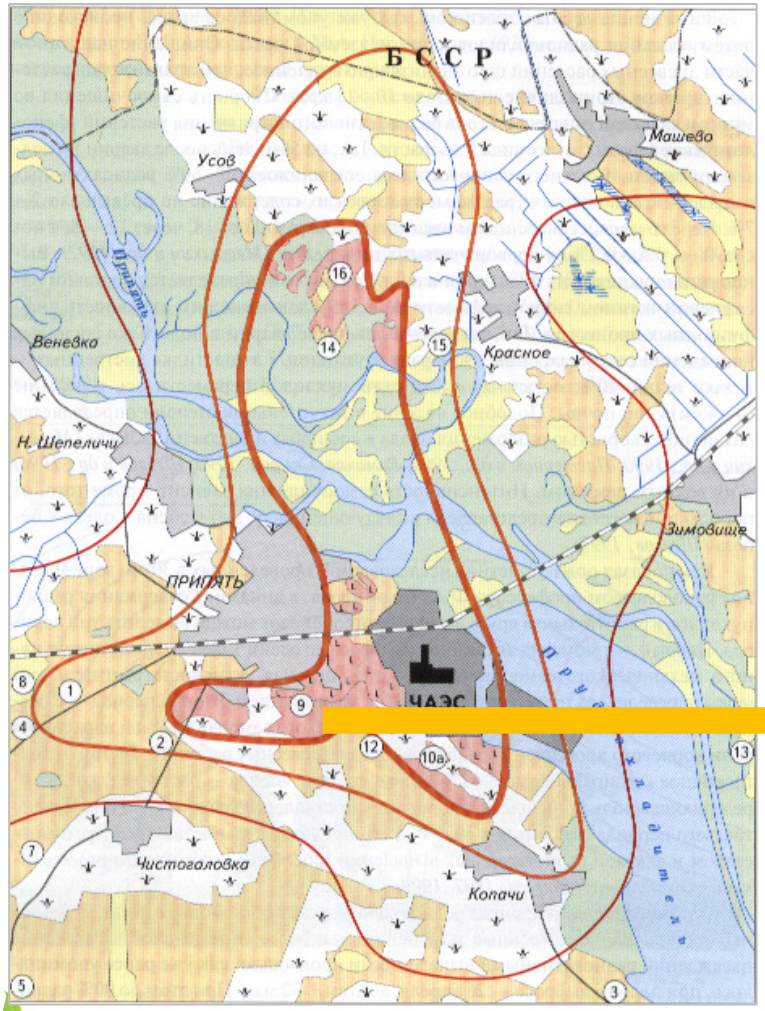
CHALLENGE TWO: **To Determine Ecological Consequences under Realistic Exposure Conditions**

Our strategic vision is that over the next 20 years radioecology will have gained a thorough mechanistic understanding of the processes inducing radiation effects at different levels of biological organisation, including the consequences on ecosystem integrity, and be able to accurately predict effects under the realistic conditions in which organisms are actually exposed.

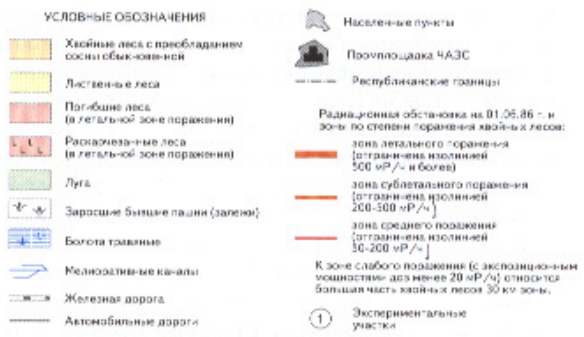
Do we have to calculate doses (dose rates) not to “plants” but to certain plant species which show the response to radiation?

Needs for the dose assessments to plants

Do we have to calculate doses (dose rates) not to “tree”, “shrub” or “grass” but to the plant species which show the response to radiation?



EFFECTS OF ACUTE RADIATION, CHERNOBYL



Zones of damages to the coniferous species (by Kozubov and Taskaev, 2002)

Needs for the dose assessments to plants

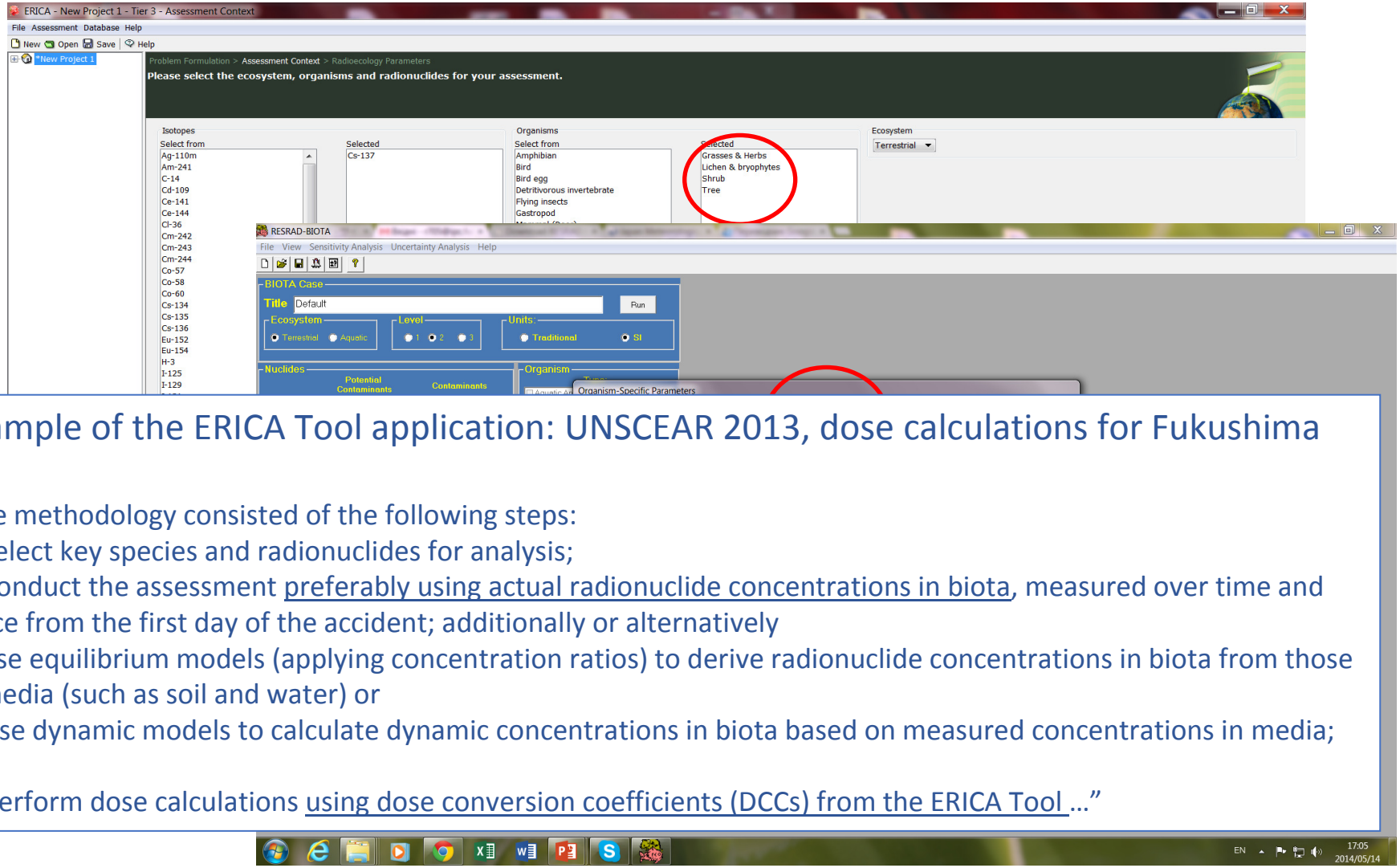
Do we have to calculate doses (dose rates) not to “tree”, “shrub” or “grass” but to the plant species which show the response to radiation?

EFFECTS OF CHRONIC RADIATION, CHERNOBYL

ANY EFFECTS IN

In certain plant species we can observe effects under existing exposures.
In order to formulate the dose-effect dependencies we need the accurate estimates of the doses (dose rates) for these species

Needs for the dose assessments to plants

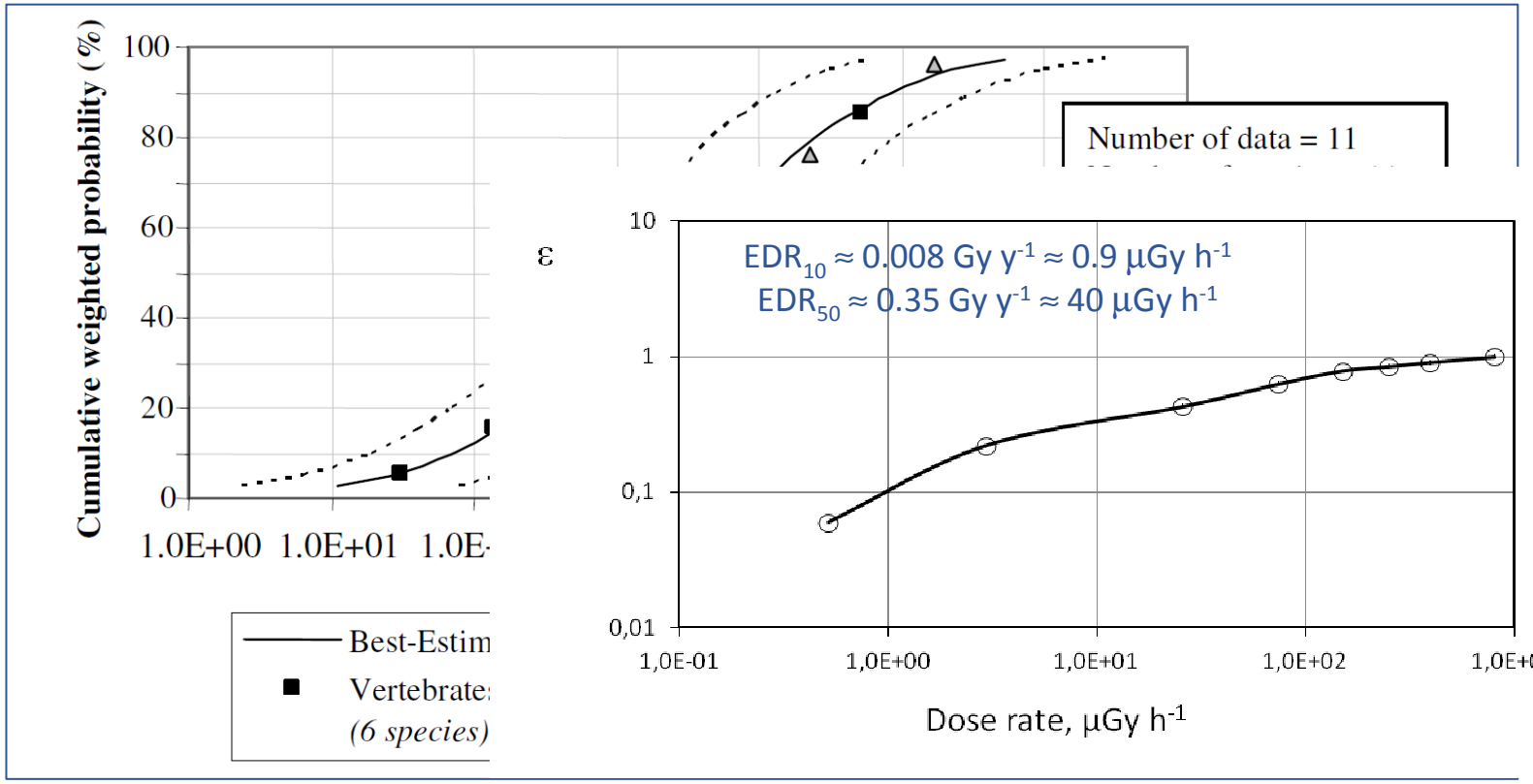


Example of the ERICA Tool application: UNSCEAR 2013, dose calculations for Fukushima

"The methodology consisted of the following steps:
(a)select key species and radionuclides for analysis;
(b)conduct the assessment preferably using actual radionuclide concentrations in biota, measured over time and space from the first day of the accident; additionally or alternatively
(c)use equilibrium models (applying concentration ratios) to derive radionuclide concentrations in biota from those in media (such as soil and water) or
(d)use dynamic models to calculate dynamic concentrations in biota based on measured concentrations in media; and
(e)perform dose calculations using dose conversion coefficients (DCCs) from the ERICA Tool …"

Needs for the dose assessments to plants

What should be an accuracy of the dose estimate?



SSD, terrestrial ecosystem, chronic exposure (Doses, 2007)

Mysl'ovskaia et al, 2007; Yoschenko et al, 2011)

Current approaches in plant dosimetry

ICRP (A.Ulanovsky, G.Pröhl, 2012):
RAPs: tree, shrub, grass. Species and age: not specified. RN distribution: uniform

External exposure

Source: soil, 3 scenarios

- plant on/above the uniform planar RN source at a depth of 0.5 g cm^{-2} (fresh deposit)
- plant on/above the uniformly contaminated 10-cm topsoil layer (aged contamination)
- plant in the middle of the uniformly contaminated 50-cm soil layer

Source: uniformly contaminated air layer

Plants: layers of uniform mixtures of biomass and air of different thickness and density located one above the other

- grass: 10 cm, 13.7 kg m^{-3}
- shrub: 90 cm, 3.4-6.8 kg m^{-3}
- tree: 9 m, 2.3-2.9 kg m^{-3}

DCC: α and β are non-penetrating; for γ $DCC_{ext} = \sum_{\gamma} Y_{\gamma} \cdot K_{air}\left(E_{\gamma}\right) \cdot R(E_{\gamma}, M)$

Dose in the organ *g* from radionuclide ν localized in the source *s*: $D_g = \int_{\Delta T} \sum_s \sum_{\nu} DCC_{g,s,\nu}(t) \cdot q_{s,\nu}\,(t)\,dt$

Internal exposure

Source: radionuclides which are uniformly distributed in the organ (currently in the whole body)

Plants shape: simplified (ellipsoid)

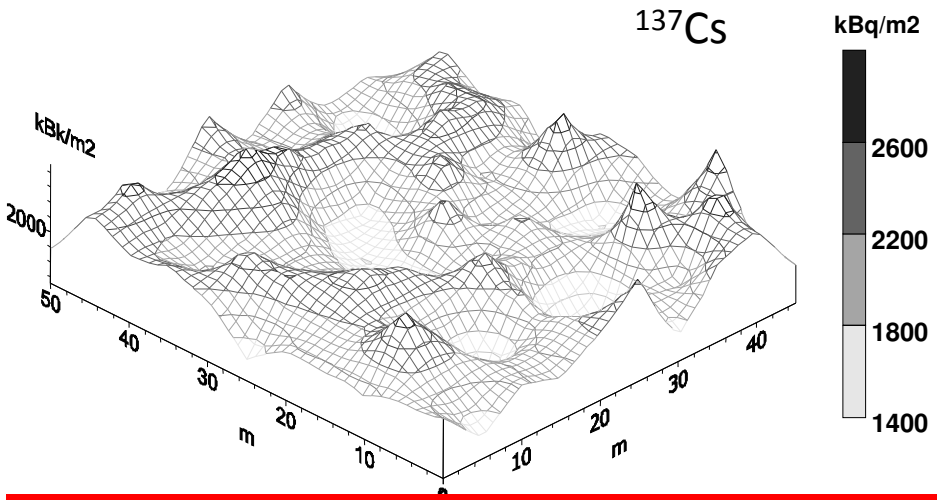
DCC: α is non-penetrating; for β and γ $DCC_{int} = C \cdot \left(\sum_i Y_i \cdot E_i \cdot \phi(E_i) + \int N(E) \cdot E \cdot \phi(E)\,dE\right)$

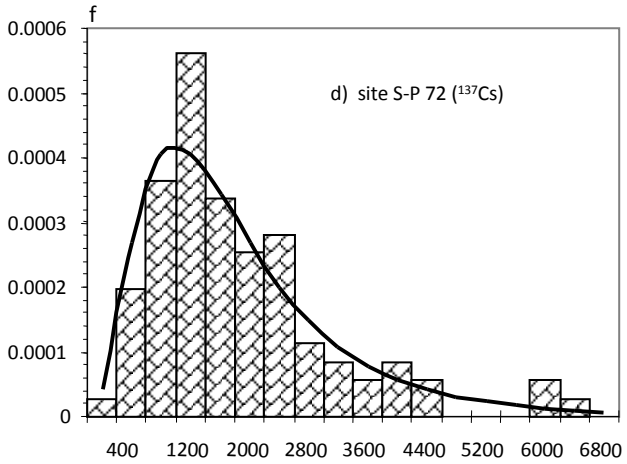
Dose in the organ *g* from radionuclide ν: $D_g = \int_{\Delta T} \sum_{\nu} DCC_{g,\nu}\boxed{t}\,\boxed{\cdot q}\,g,\nu\,\boxed{t}\,dt$

Specific activity of incorporated RN: $\boxed{q}\,g,\nu(t) = \boxed{CR}\,g,\nu\,\boxed{(t) \cdot q}\,\nu env(t)$

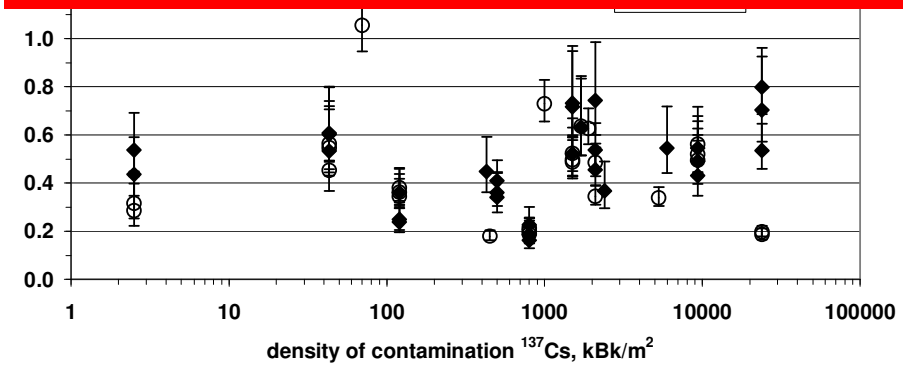
Sources of uncertainties of the dose estimates: external exposure

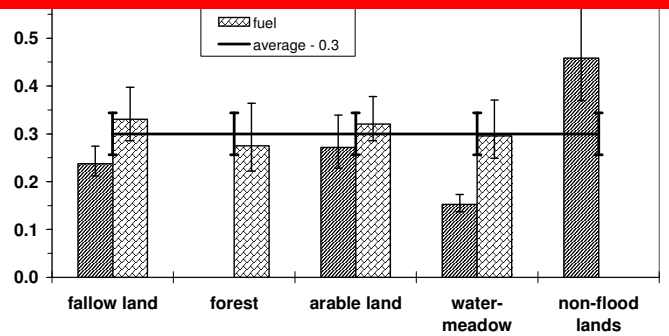
Heterogeneity of the source (contaminated soil). Chernobyl zone (data by UIAR)





standard deviation of logarithm of the soil contamination density with ^{137}Cs at the non-gradient contaminated sites in the CEZ can be estimated as 0.30±0.09





Sources of uncertainties of the dose estimates: external exposure

Attenuation. RN distribution in the soil profile

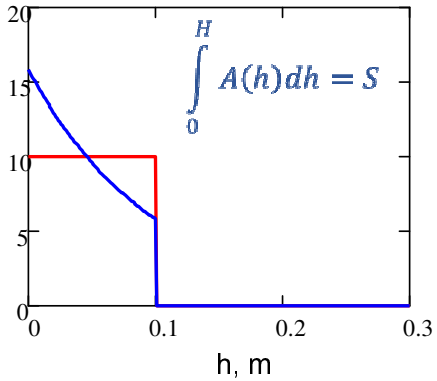
Planar RN source, S, Bq m^{-2}

Dose rate DR_{surf}, Gy h^{-1}

RN in the soil profile, A(h), Bq m^{-3}

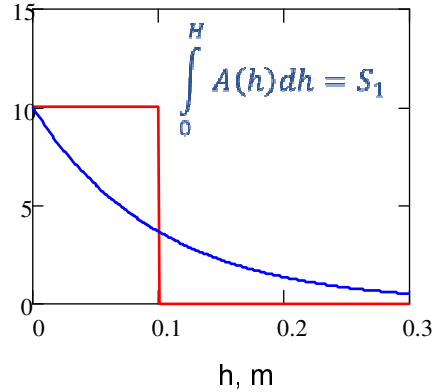
$A_{un}(h)$

$A_{exp}(h)$



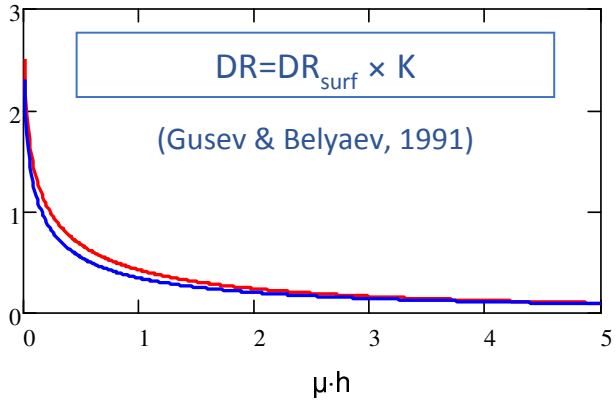
$A_{un}(h)$

$A_{exp}(h)$



$K_{un}(\mu,h)$

$K_{exp}(\mu,h)$



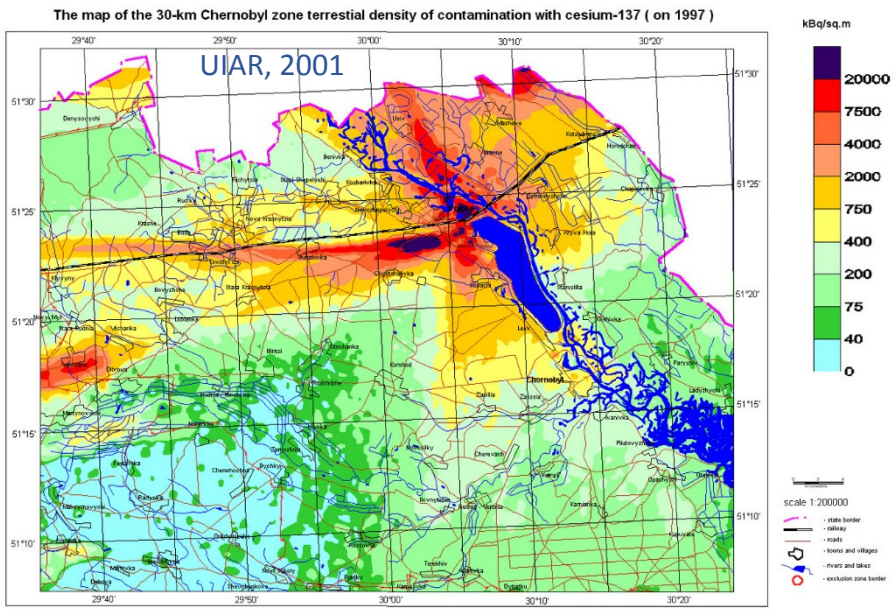
$DR=DR_{surf} \times K$

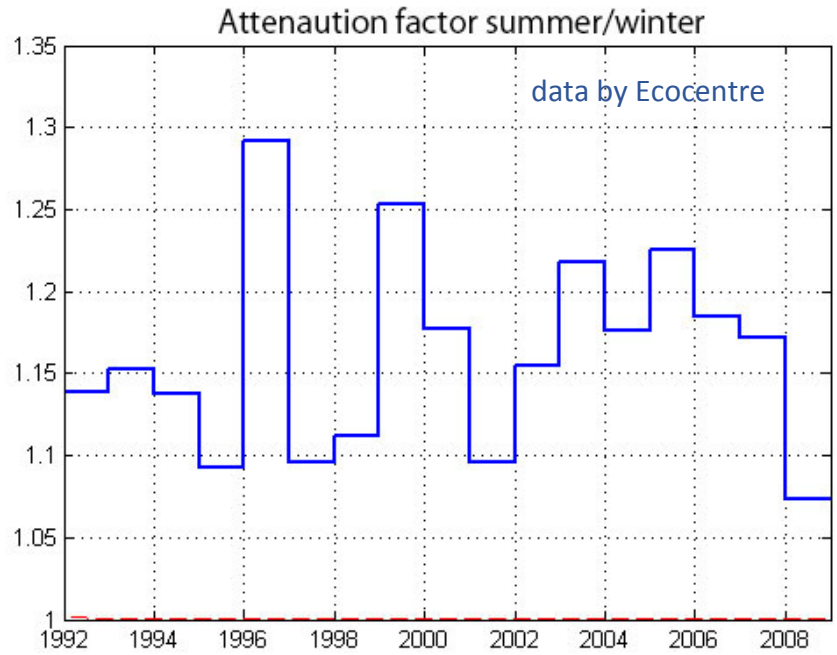
(Gusev & Belyaev, 1991)

S_1<S:
calculations of the external exposure from RN in soil should be based on measured or calculated *A(h)*

Sources of uncertainties of the dose estimates: external exposure

Attenuation. Effect of snow cover (Chernobyl zone)

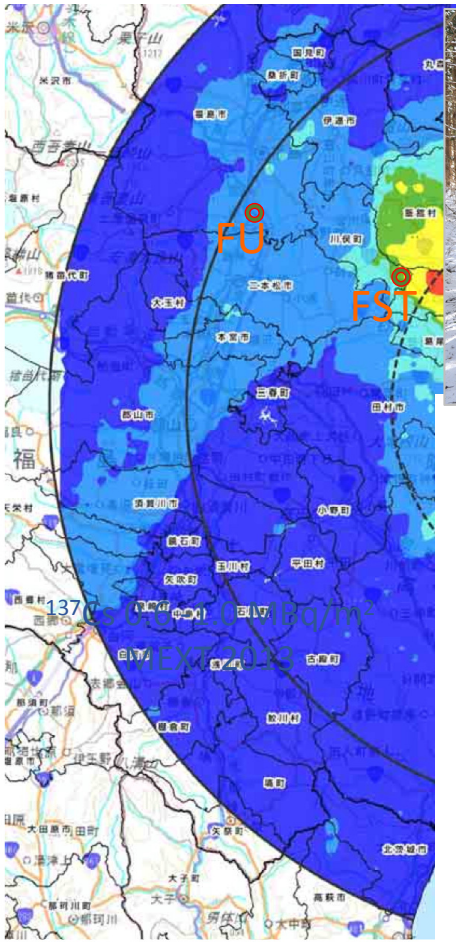




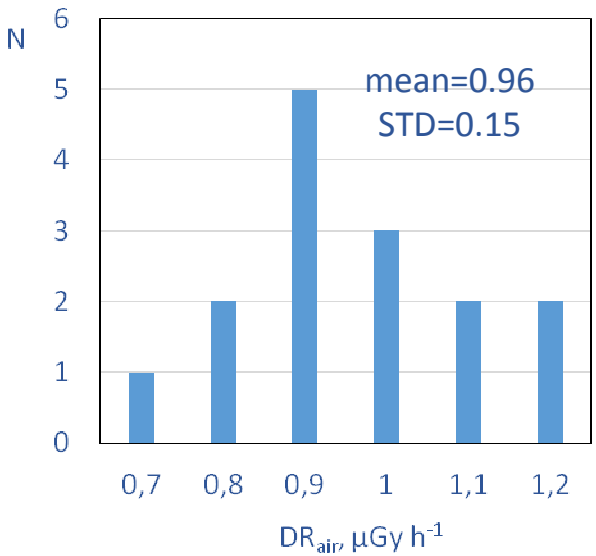
$$\text{Attenuation factor} = \frac{\langle DR_{May\text{-}Sept} \rangle}{\langle DR_{Dec\text{-}March} \rangle}$$

Sources of uncertainties of the dose estimates: external exposure

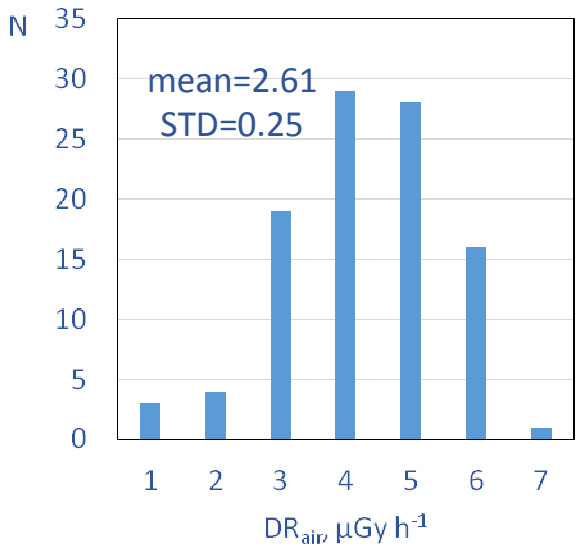
Attenuation. Effect of snow cover (Fukushima, data by IER)



Feb 2014



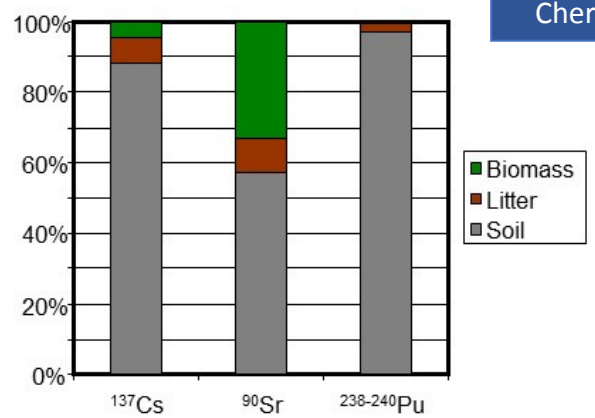
April 2014



Sources of uncertainties of the dose estimates: external exposure

Site specific sources of radiation (aboveground biomass, litter, foliar contamination…)

Chernobyl



Typical RN distribution. Scots pine
(Yoschenko et al, 2006)

Fukushima

(Matsunaga et al, 2013)

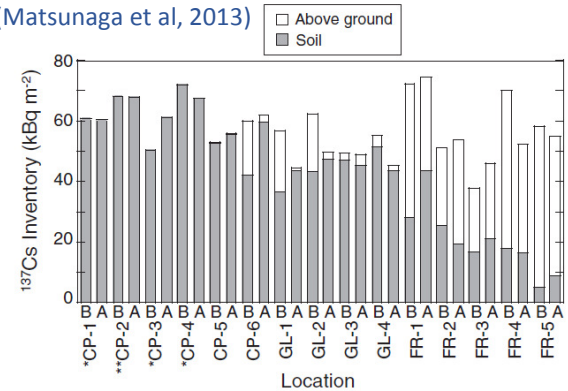
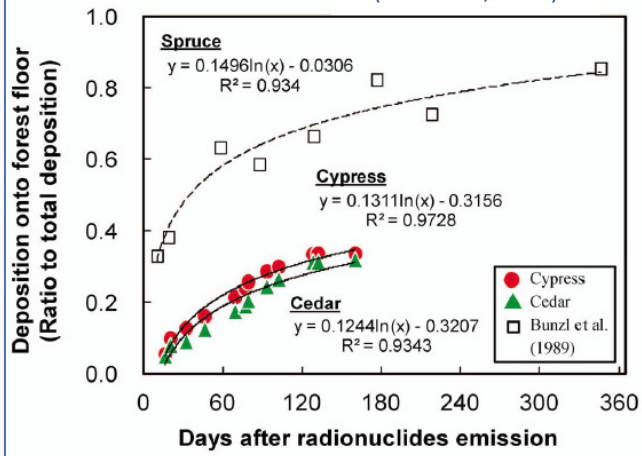


Fig. 1. Comparison of ^{137}Cs inventory in the pre- (marked with B) and post-rainy season periods (marked with A) over the 15 studied locations.

CP – cultivated plots, GL – grasslands, FR - forests

(Kato et al, 2012)

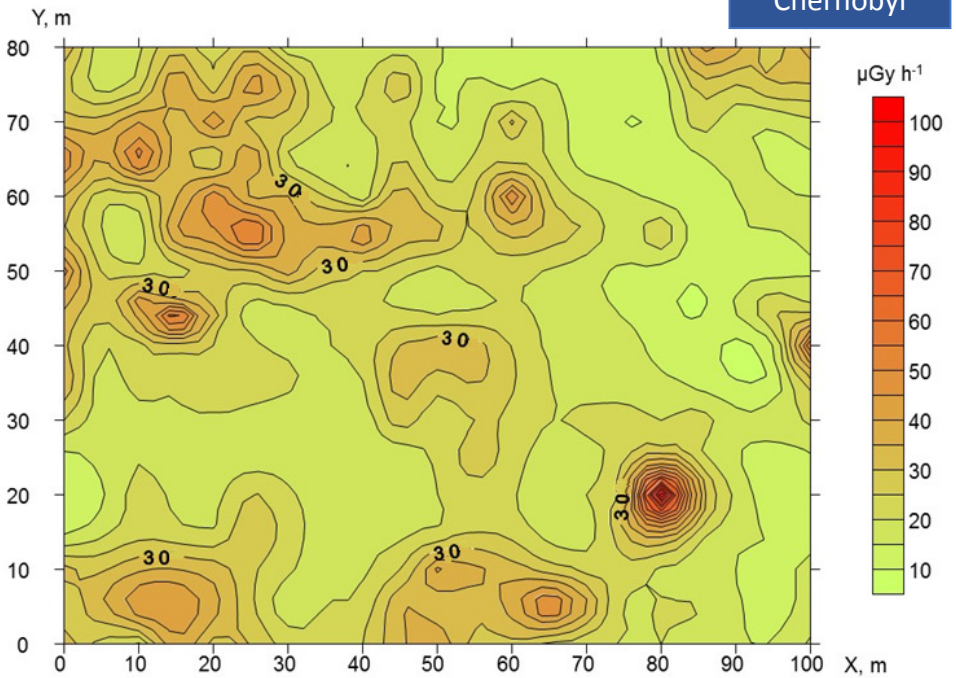


RN in aboveground biomass and litter:
-lower attenuation than for RN in soil profile
-species of interest can grow near to other plants with higher CR
Foliar contamination:
-lower attenuation than for RN in soil profile
-β and α emissions may be important
-initial interception and retention depend on species, period of the year, rain amounts etc

Sources of uncertainties of the dose estimates: external exposure

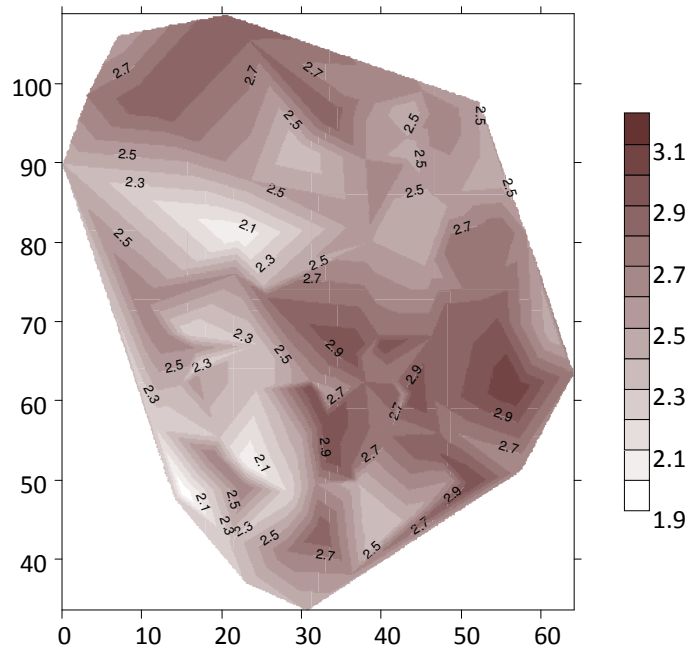
What is in practice? Measured values of DR_{ext} at the height of 1 m:

Chernobyl



(UIAR)

Fukushima



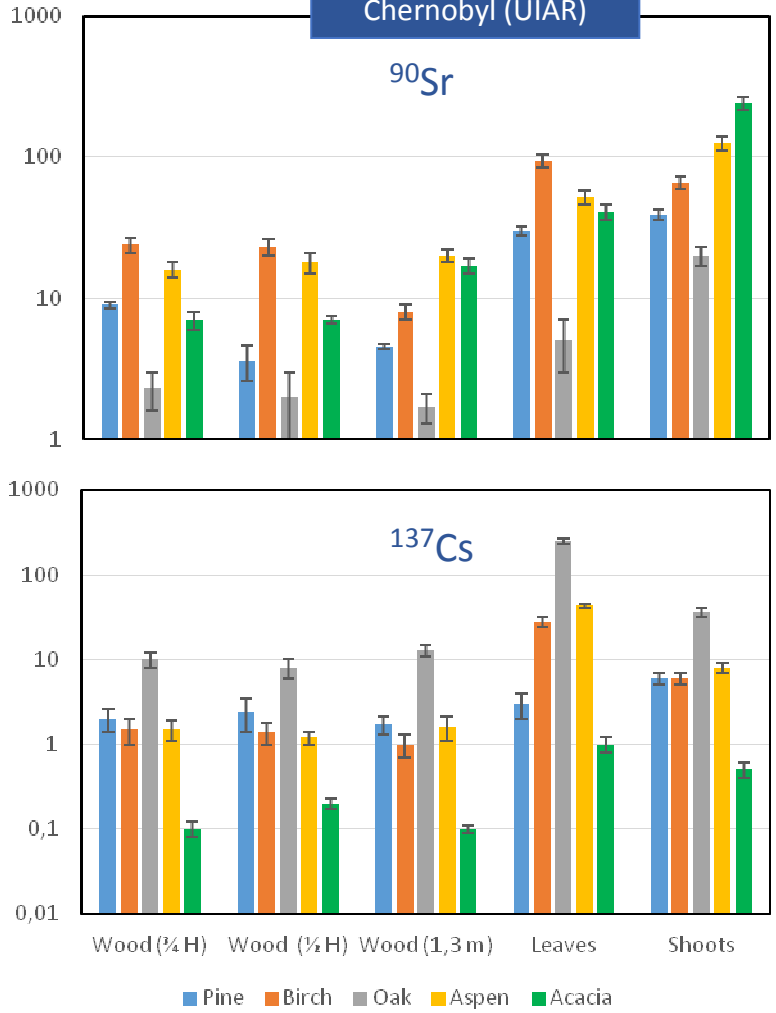
(IER)

DR_{ext} varies even within the comparable small areas. The accurate assessment of DR_{ext} for individual plants at such plots may require big efforts (both for characterization of the conditions and for calculations)

Sources of uncertainties of the dose estimates: internal exposure

CRs for various species may be very different!

Chernobyl (UIAR)



IAEA Handbook..., 2010

TABLE 38. RADIOCAESIUM TRANSFER FACTORS (T_{ag}, m^2 kg^{-1}, dry weight) TO FOREST TREES

(Measured under apparent steady state conditions)

Species	Wood		Needles/leaves		N
	Geometric mean	Range	Geometric mean	Range	
Spruce	1.5×10^{-3}	2.8×10^{-4}–3.9×10^{-3}	8.6×10^{-3}	5.7×10^{-4}–5.2×10^{-2}	7
Fir tree	1.2×10^{-4}	—	—	—	1
Pine	1.7×10^{-3}	1.1×10^{-4}–2.1×10^{-2}	1.0×10^{-2}	2.4×10^{-4}–9.2×10^{-2}	22
Oak	8.6×10^{-4}	1.1×10^{-4}–3.8×10^{-3}	1.2×10^{-2}	1.1×10^{-2}–1.2×10^{-2}	3
Beech	7.2×10^{-4}	1.8×10^{-4}–1.6×10^{-3}	2.5×10^{-3}	2.3×10^{-3}–2.7×10^{-3}	3
Birch	9.4×10^{-4}	2.4×10^{-4}–3.8×10^{-3}	8.7×10^{-3}	2.8×10^{-3}–3.0×10^{-2}	3
Willow	2.5×10^{-5}	1.0×10^{-5}–6.8×10^{-5}	2×10^{-2}	—	4

TABLE 39. RADIOSTRONTIUM TRANSFER FACTORS (T_{ag}, m^2 kg^{-1}, dry weight) TO FOREST TREES

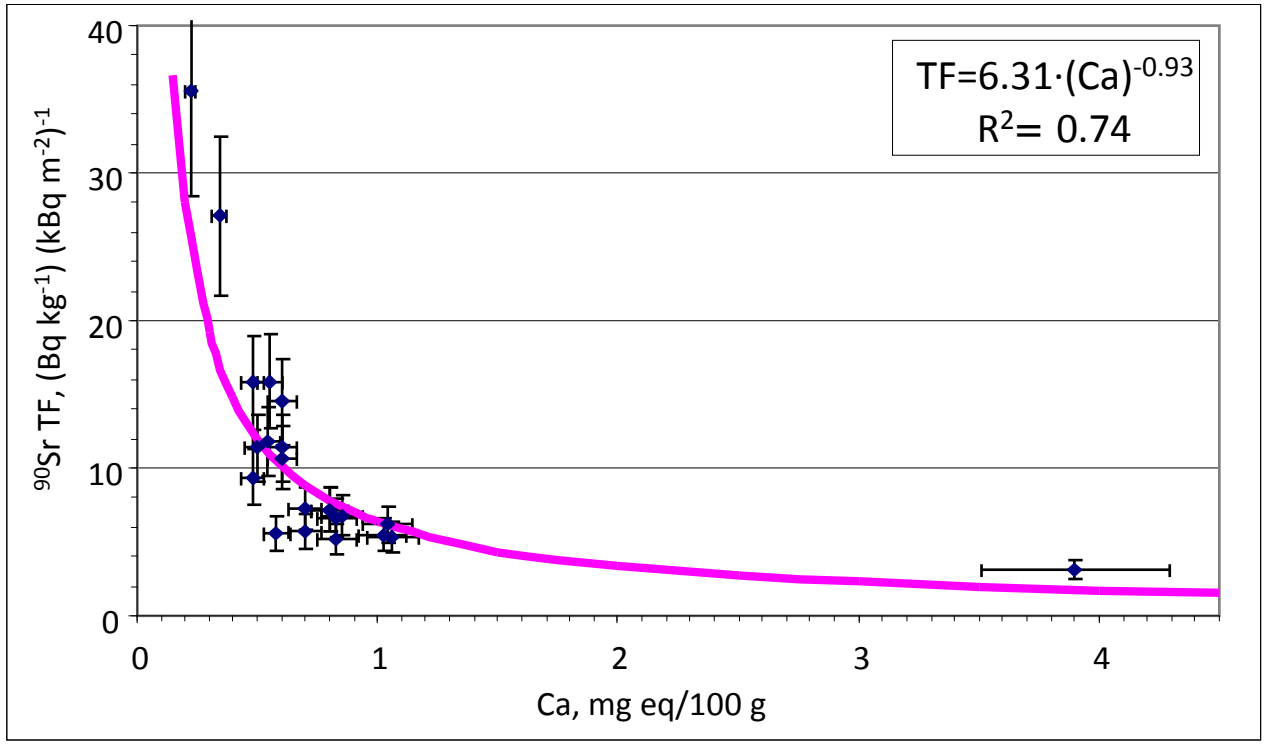
(measured following the Chernobyl (1991–1992) and Kyshtym (1966–1972) accidents; main reference: [157])

Species	Wood		Needles/leaves		N
	Geometric mean	Range	Geometric mean	Range	
Alder	9.5×10^{-4}	—	5.7×10^{-3}	—	1
Fir tree	4.4×10^{-3}	—	1.3×10^{-2}	—	1
Pine	1.6×10^{-3}	5.7×10^{-4}–1.0×10^{-2}	4.9×10^{-3}	1.5×10^{-3}–3.0×10^{-2}	5
Oak	1.3×10^{-3}	4.7×10^{-4}–2.8×10^{-3}	4.2×10^{-3}	1.9×10^{-3}–1.0×10^{-2}	3
Aspen	2.1×10^{-3}	—	1.7×10^{-2}	—	1
Birch	2.4×10^{-3}	5.8×10^{-4}–6.2×10^{-3}	1.8×10^{-2}	4.3×10^{-3}–7.8×10^{-2}	5

Sources of uncertainties of the dose estimates: internal exposure

CRs (TFs) for the given species depend on the soil conditions

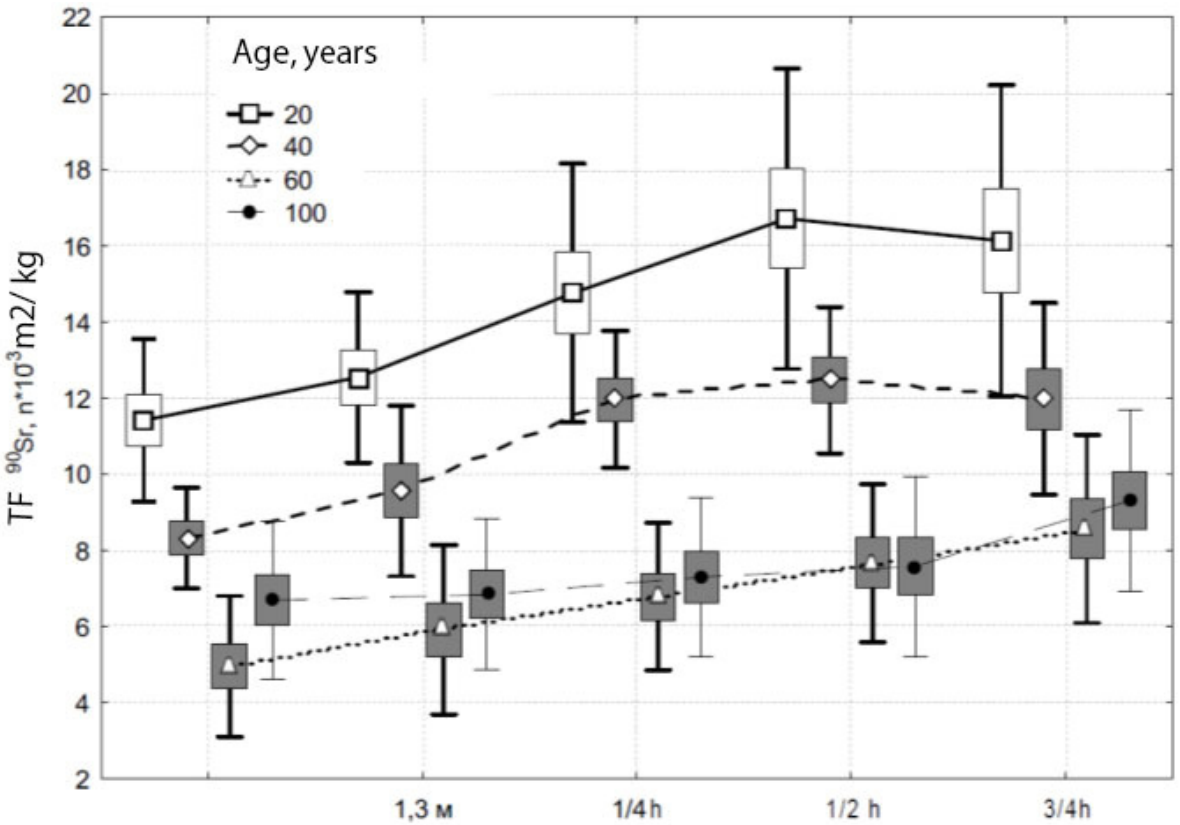
Example: ^{90}Sr transfer into wood of Scots pine vs content of mobile Ca in soil. Chernobyl zone (UIAR)



Sources of uncertainties of the dose estimates: internal exposure

CRs (TFs) for the given species depend on the age

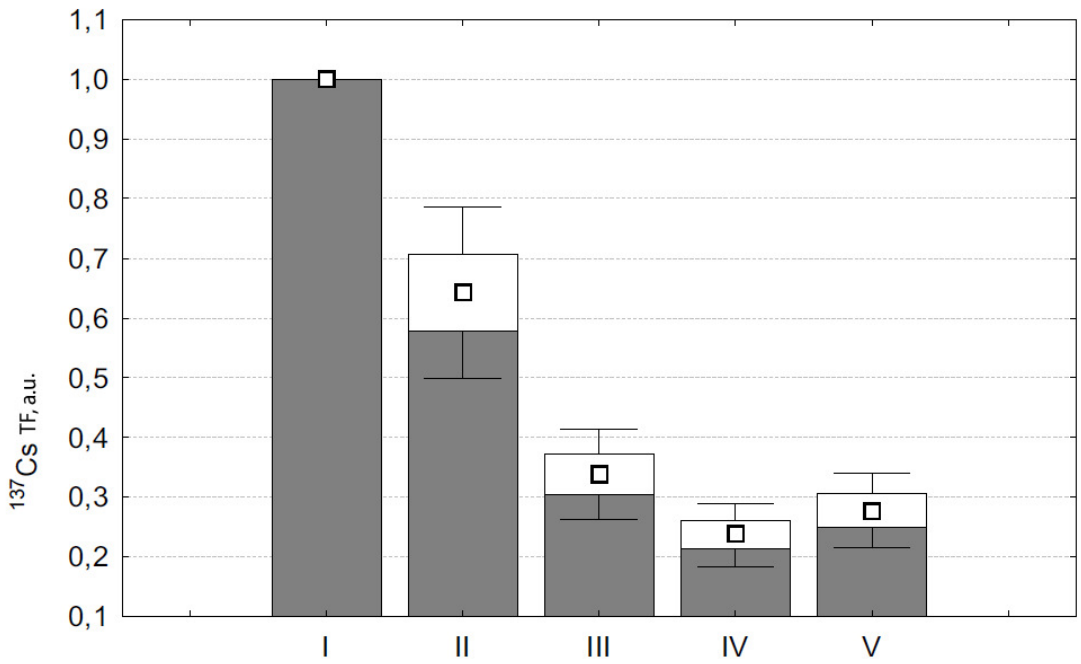
Example: ^{90}Sr transfer into wood of Scots pine at various age. Chernobyl zone (Perevolotsky, 2006)



Sources of uncertainties of the dose estimates: internal exposure

CRs (TFs) for the given species depend on the stand quality

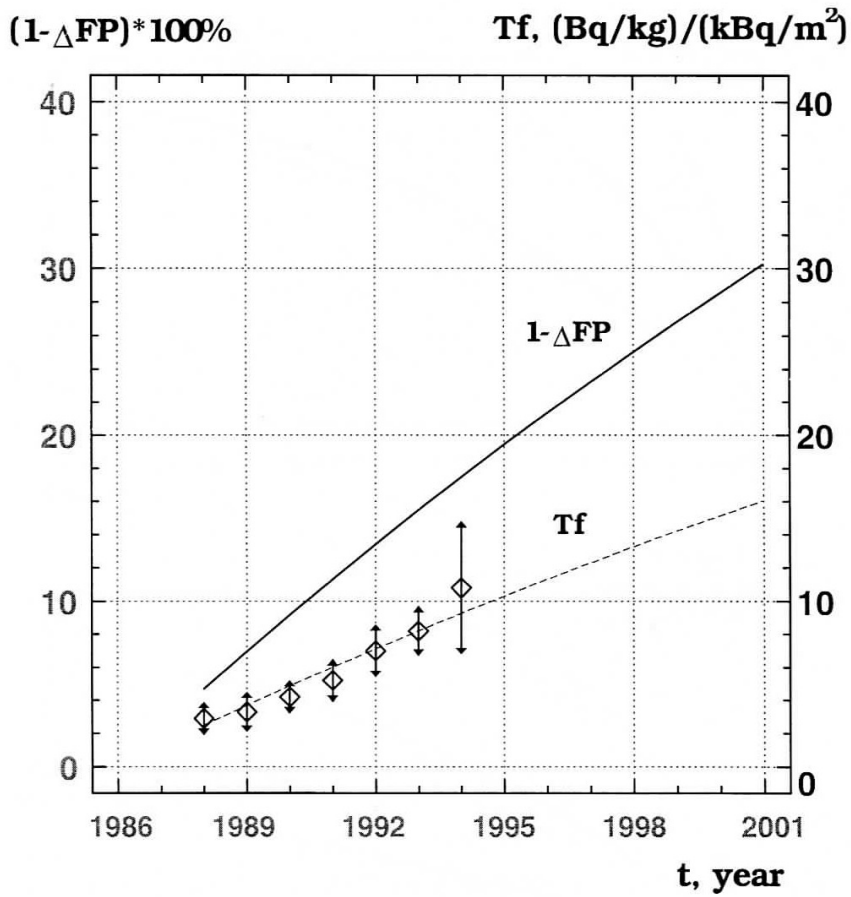
Example: ^{137}Cs transfer into wood of Scots pine of various quality classes. CEZ (Bulavik & Perevolotsky, 2003)



Sources of uncertainties of the dose estimates: internal exposure

CRs (TFs) depend on the RN forms and their evolution

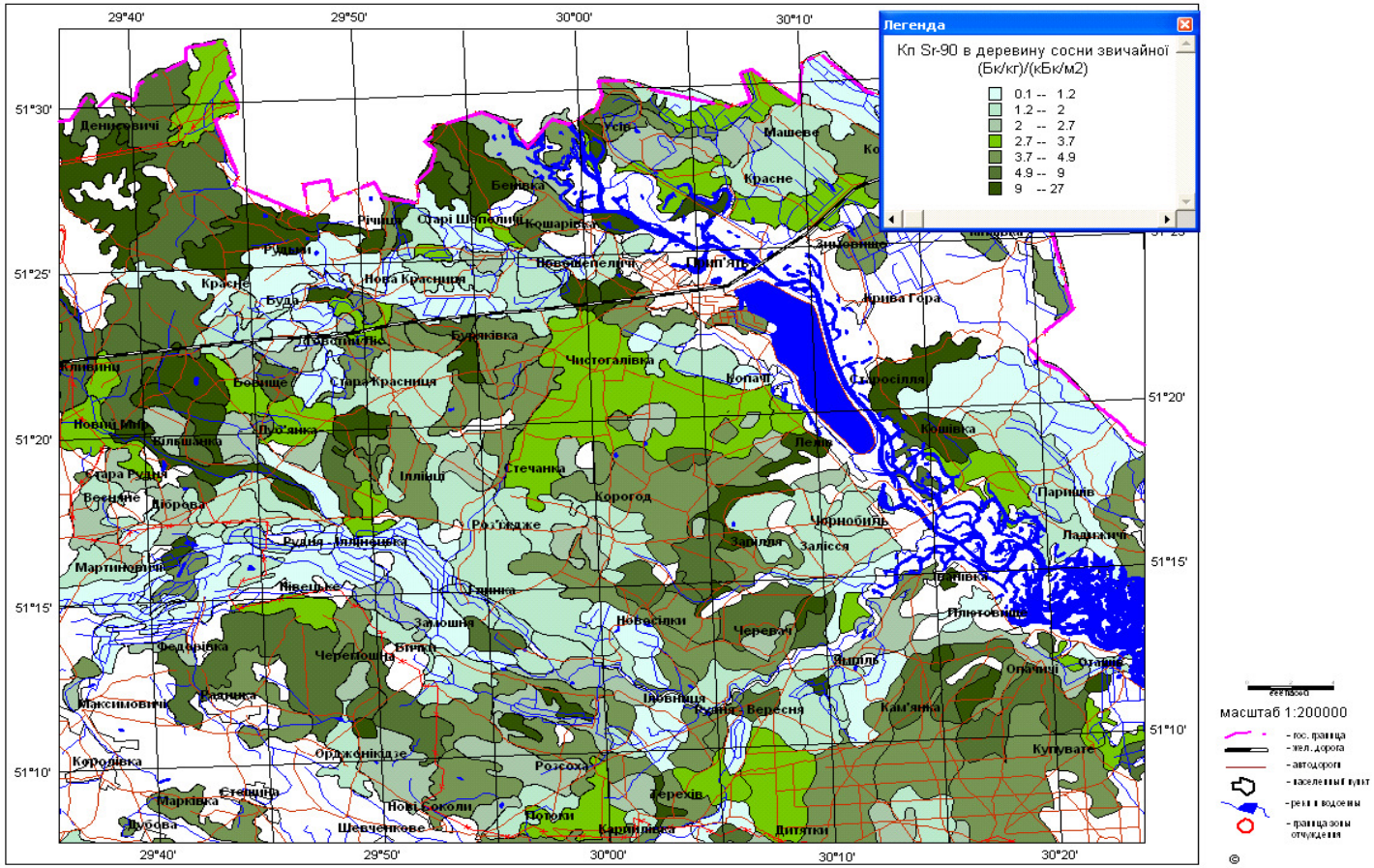
Example: FP dissolution and ^{90}Sr transfer into meadow plants. Chernobyl zone (Kashparov et al, 1999)



Sources of uncertainties of the dose estimates: internal exposure

CRs (TFs) for the given species depend on many factors and can significantly vary

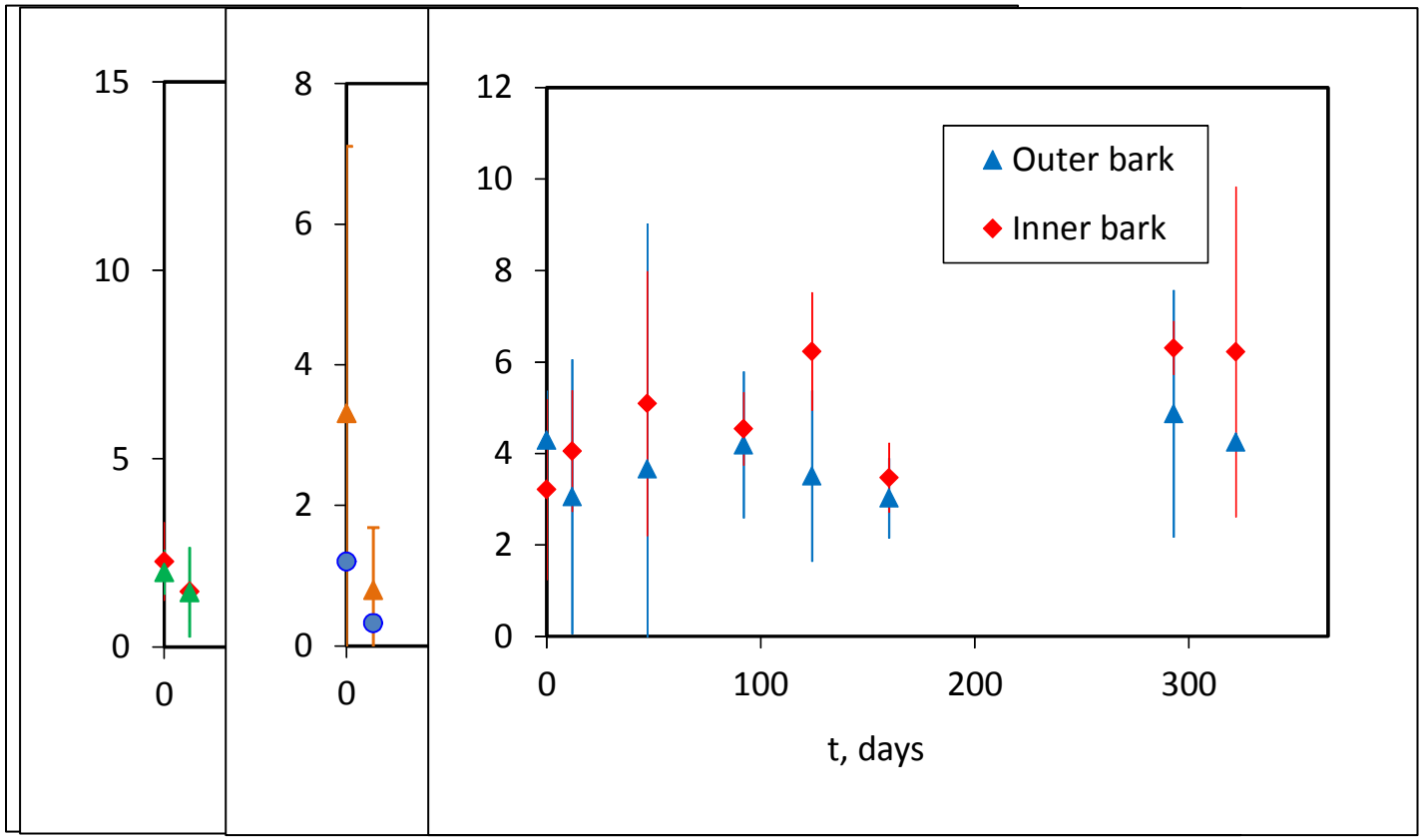
Example: predicted ^{90}Sr TF into Scots pine stemwood. Chernobyl zone (UIAR)



Sources of uncertainties of the dose estimates: internal exposure

RN specific activities are different in various organs and vary during the year

Example: ^{90}Sr in Scots pine. $q_g(t)$ normalized to $q_{stemwood}(t_0)$. (Yoschenko et al., 2009, 2011)



Sources of uncertainties of the dose estimates: internal exposure

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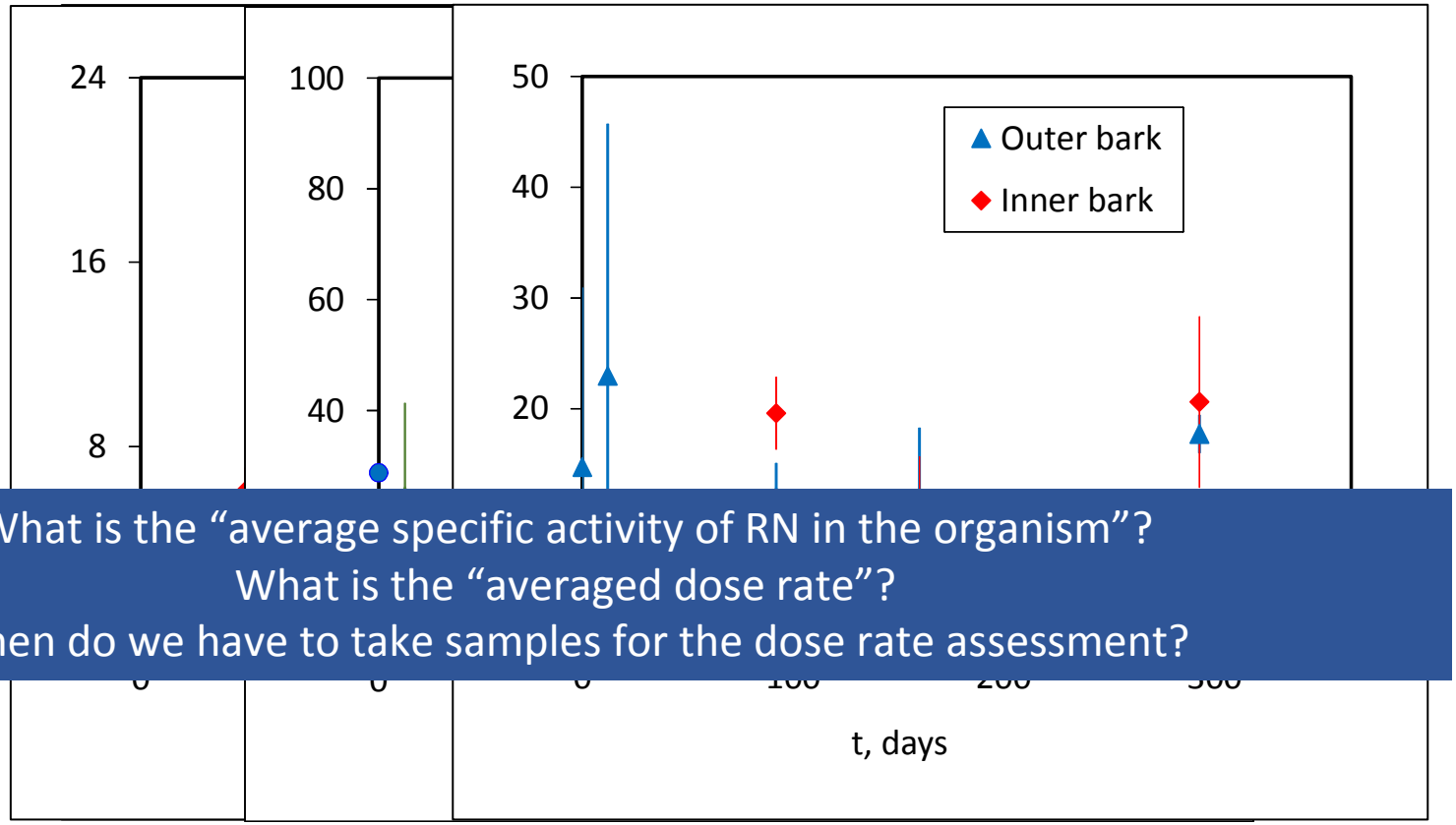
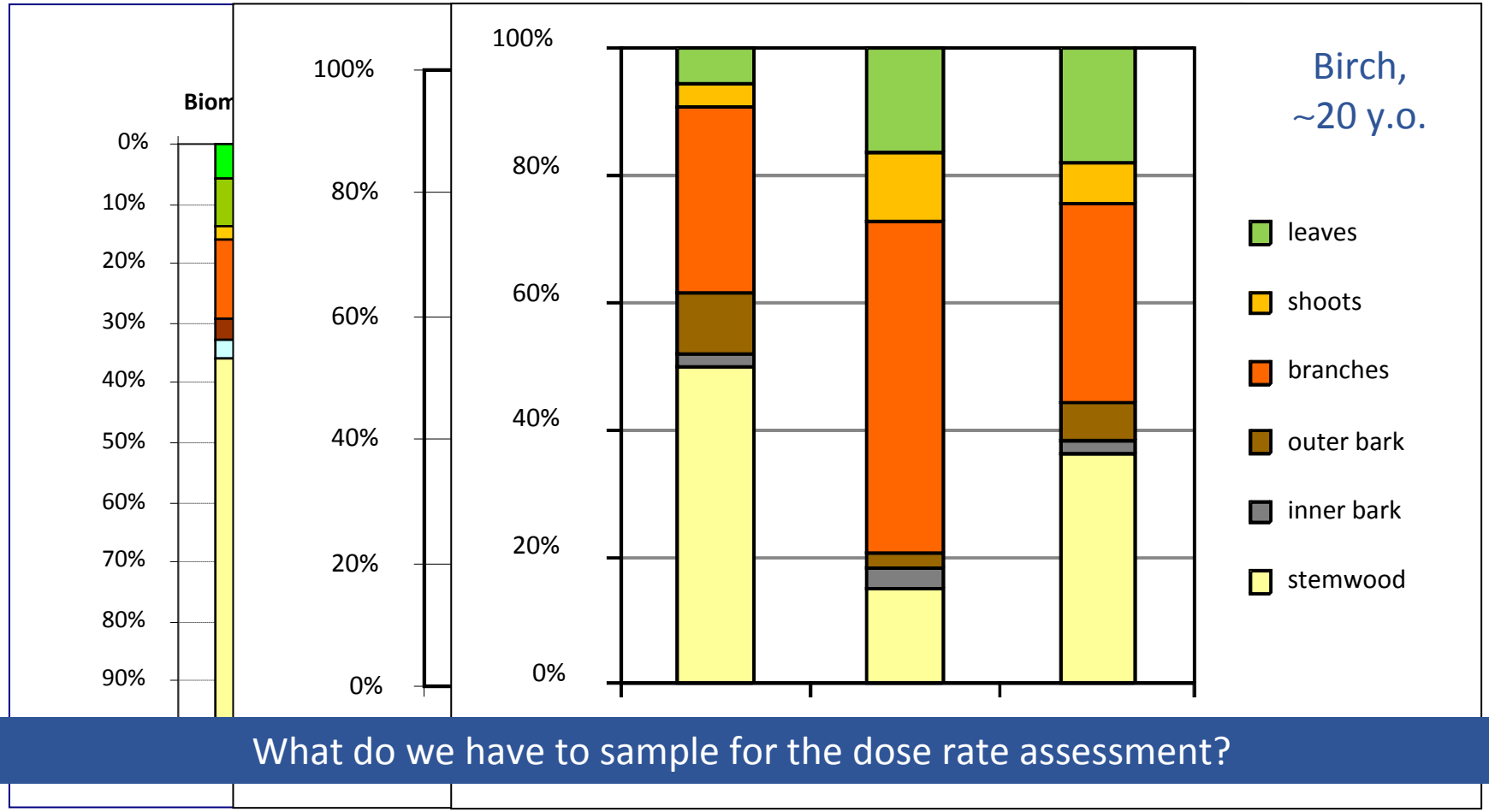


What is the "average specific activity of RN in the organism"?
What is the "averaged dose rate"?
When do we have to take samples for the dose rate assessment?

Sources of uncertainties of the dose estimates: internal exposure

Distribution of RN inventories in the pine and birch plantations

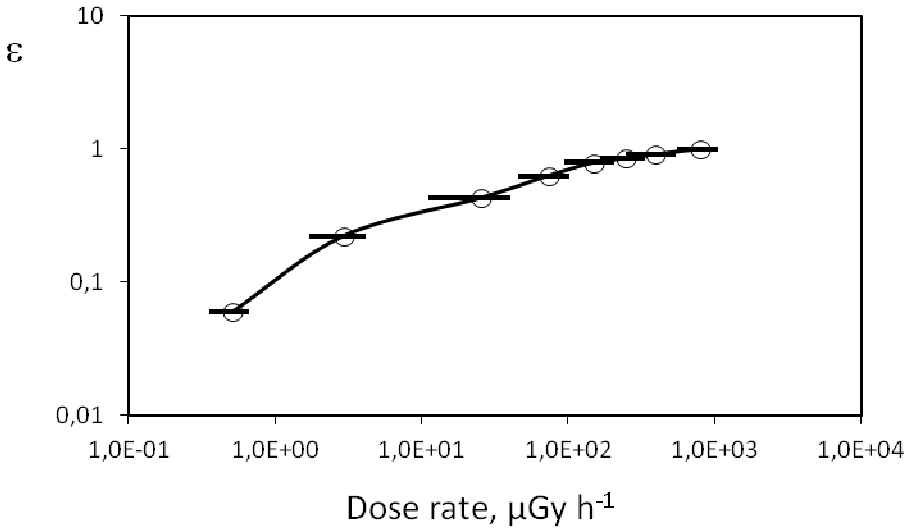
Chernobyl zone (Thiry et al., 2009; UIAR, 2005)

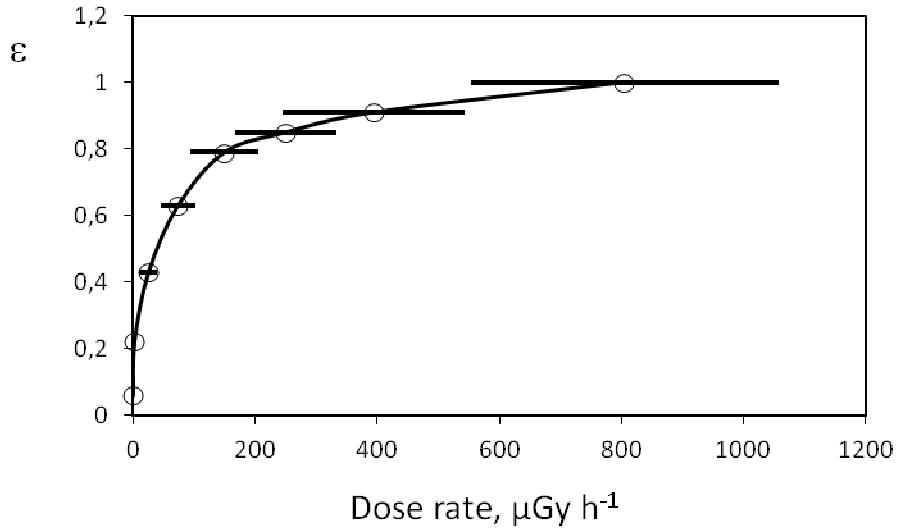


What do we have to sample for the dose rate assessment?

Needs for the dose assessments to plants

What should be an accuracy of the dose estimate?





Morphological changes in Scots pine (Yoschenko et al, 2011)

$EDR_{10} \approx 0.008$ Gy $y^{-1} \approx 0.9$ µGy h^{-1}
$EDR_{50} \approx 0.35$ Gy $y^{-1} \approx 40$ µGy h^{-1}

Example of the dose rate assessment

Typical morphological changes: cancelling the apical dominance. Chronic exposure

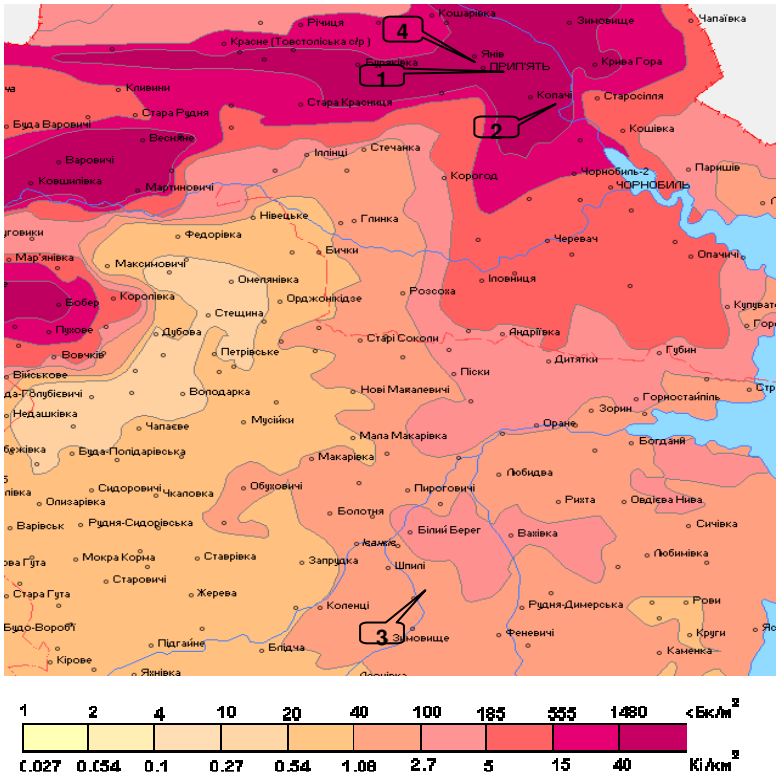
Example of the dose rate assessment

Experimental array: more than 1100 pine trees

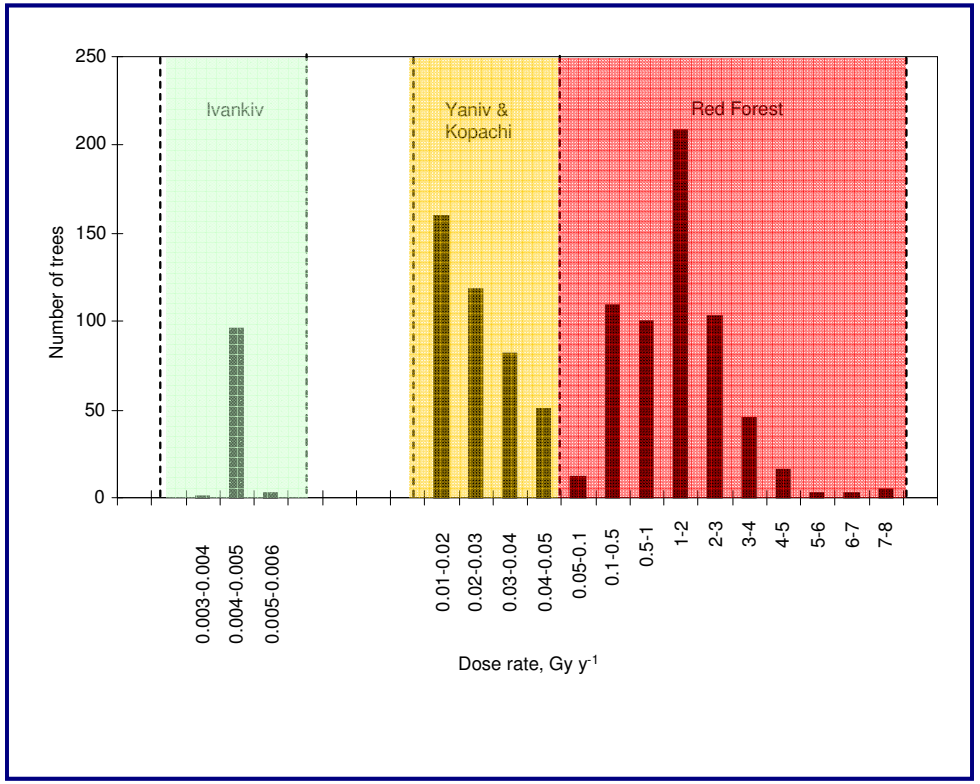
For each tree the morphological characteristics and dose rates from external sources and from incorporated radionuclides were determined

^{137}Cs contamination density

1 – Red Forest, 2 – Kopachi, 3 – Ivankiv, 4 – Yaniv



Dose rates to the trees



Example of the dose rate assessment

Species: *Pinus sylvestris*

Target organ: dominant bud

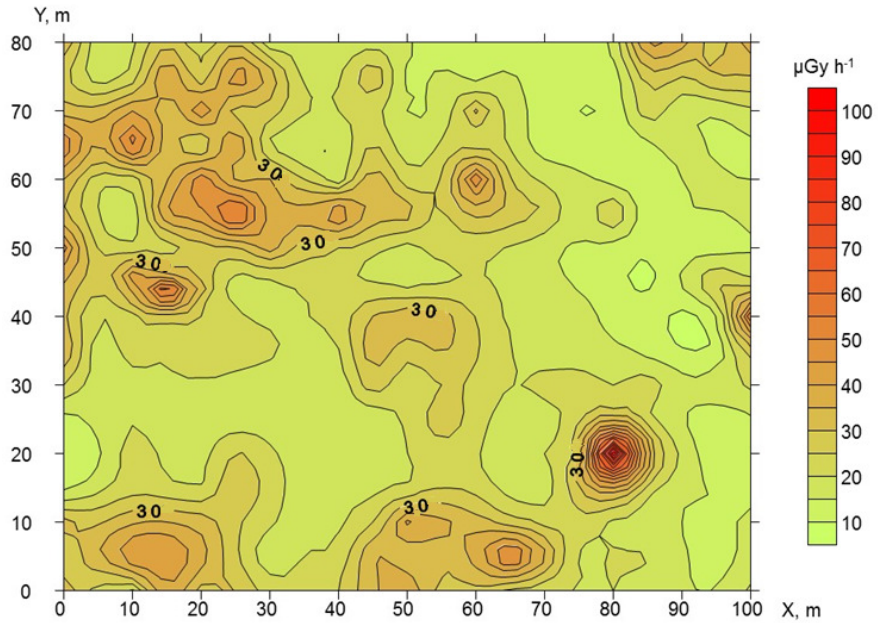
Exposure: chronic

Acute exposure during the accident: none

RN: ^{137}Cs and ^{90}Sr with progenies; other RN of the Chernobyl release for retrospective estimates

Sources of radiation: soil, biomass and litter (external) and incorporated RN (internal)

External radiation: direct measurements because of essential spatial variability



Example of the dose rate assessment

Approach for calculation of the dose rates from incorporated RN (Yoschenko et al, 2009, 2011)

The model takes into account:

- ✓ β-emission of RN incorporated in the target organ and in other parts of the tree
- ✓ **actual distribution of RN** in the tree and **dynamics** of their specific activities in each organ during the year
- ✓ shape, location and growing of the organs during a year (changing geometry of irradiation)

Principal approach for DCC calculation:

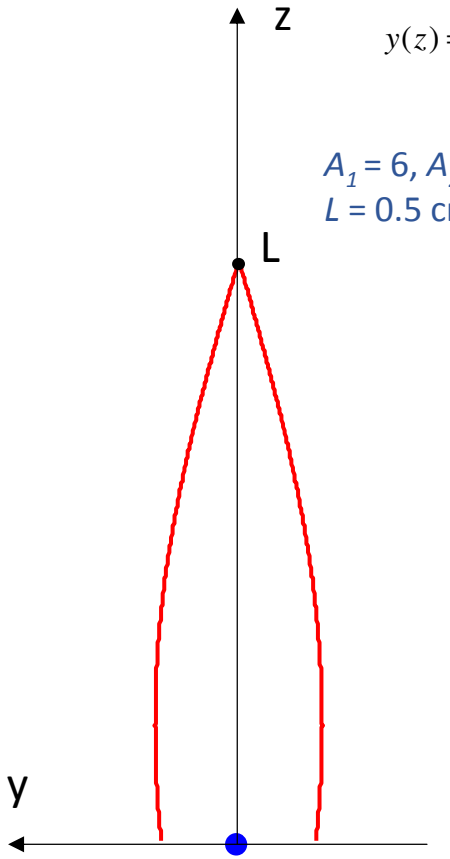
- ✓ integration of the **microdosimetric functions of the point sources** localized in the target organ in assumption of their uniform distribution inside the organ
- ✓ utilization of the **microdosimetric functions** and **geometrical factors** of irradiation of the selected point in the target organ by RN incorporated in other organs

Algorithm:

- ✓ calculation of the **individual dose coefficients** for each RN, source organ and month
- ✓ deriving the **integral dose coefficient** for unit specific activity of ^{90}Sr in wood in the moment t_0 (1 June)

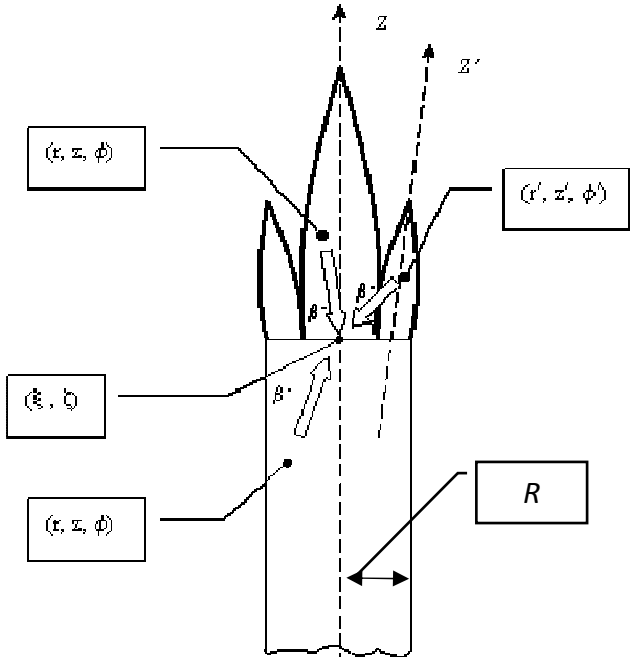
Example of the dose rate assessment

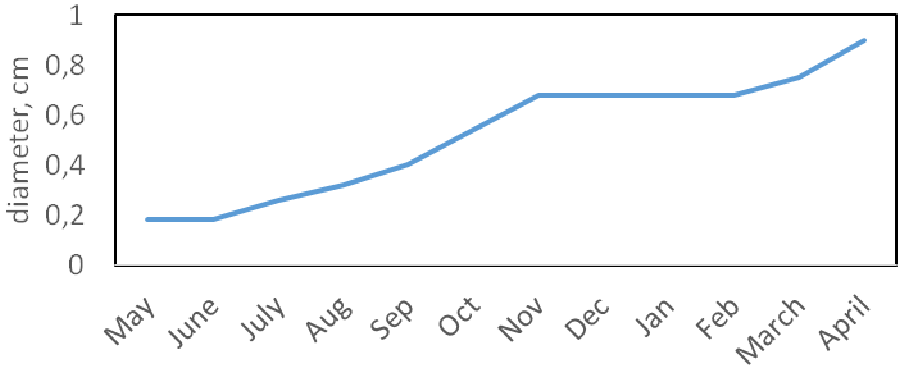
Actual shape of the target organ (apical bud) and its changes during the year



$$y(z) = L/A_1 \cdot \cos\left[(z - A_2 \cdot L) \cdot \frac{\pi}{2 \cdot (1 - A_2) \cdot L}\right]$$

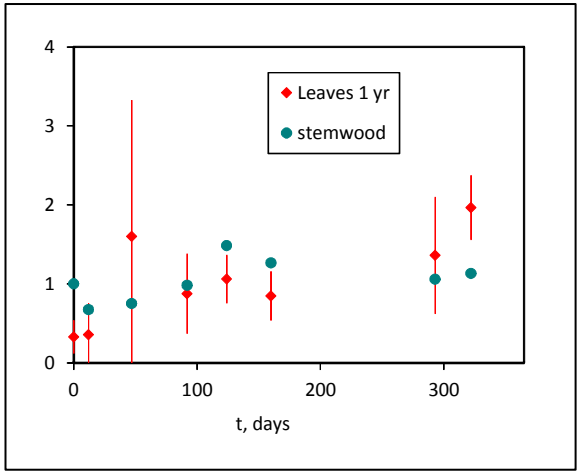
$A_1 = 6$, $A_2 = 0.2$
L = 0.5 cm (June) … 2.5 cm (April - May)

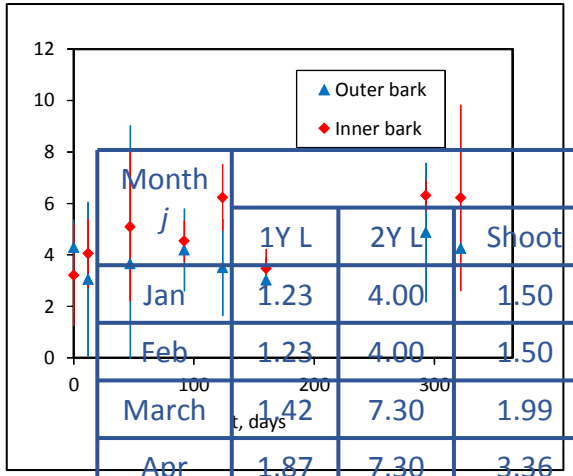




Example of the dose rate assessment

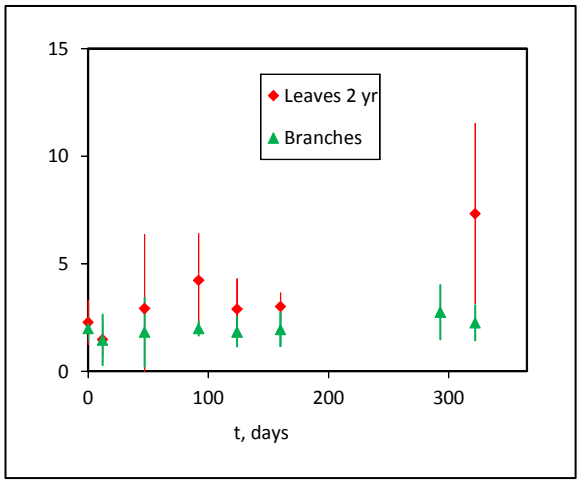
Actual distribution and dynamics of incorporated RN. ^{90}Sr:

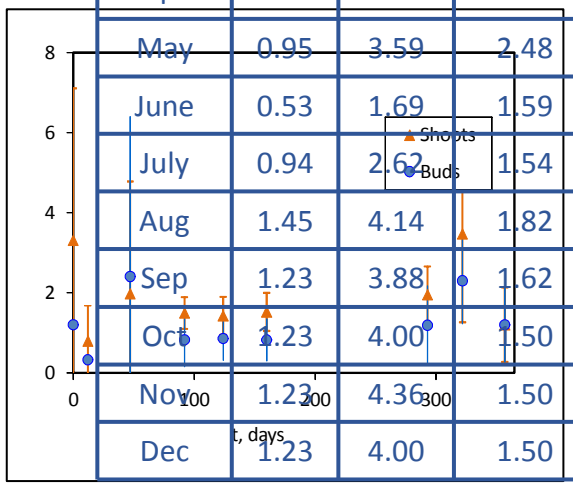




$$q_{i,j} = a_{i,j} \cdot q_{wood}(t_0)$$

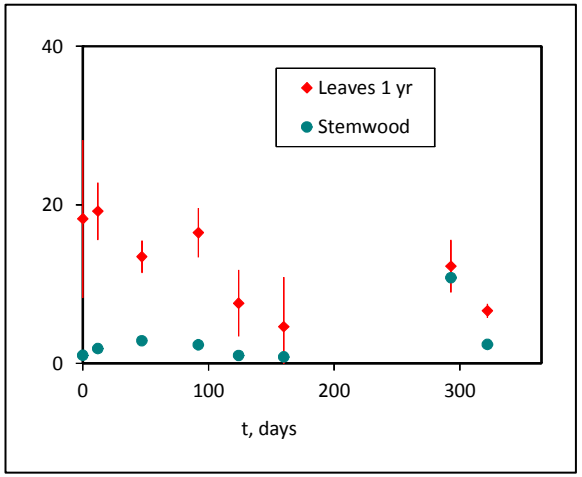
Month j	Organ i							
	1Y L	2Y L	Shoot	Branch	OB	IB	Wood	Buds
Jan	1.23	4.00	1.50	1.90	3.40	3.50	1.10	0.80
Feb	1.23	4.00	1.50	1.90	3.40	3.50	1.00	0.80
March	1.42	7.30	1.99	2.77	4.83	6.41	1.04	1.24
Apr	1.87	7.30	3.36	2.27	4.50	5.98	1.20	2.17
May	0.95	3.59	2.48	1.91	3.86	4.66	1.02	1.41
June	0.53	1.69	1.59	1.75	3.58	3.86	0.76	1.04
July	0.94	2.62	1.54	1.75	3.73	4.08	0.70	1.45
Aug	1.45	4.14	1.82	1.82	3.96	5.00	0.89	1.78
Sep	1.23	3.88	1.62	1.91	3.89	5.75	1.24	0.80
Oct	1.23	4.00	1.50	1.95	3.39	5.31	1.48	0.80
Nov	1.23	4.36	1.50	1.87	3.40	3.50	1.16	0.80
Dec	1.23	4.00	1.50	1.90	3.40	3.50	1.10	0.80

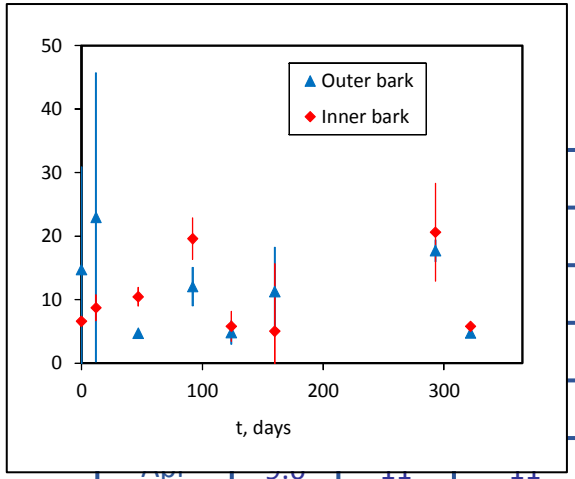


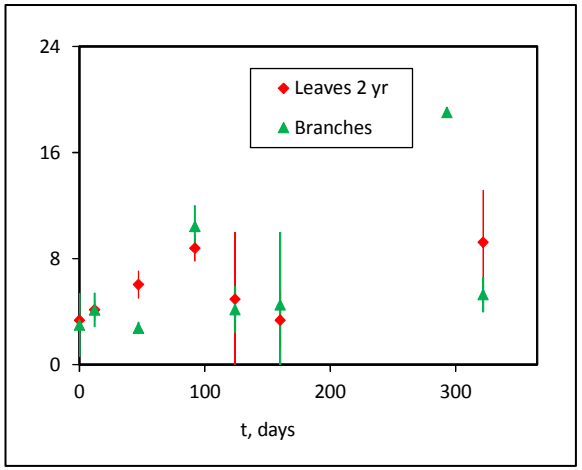


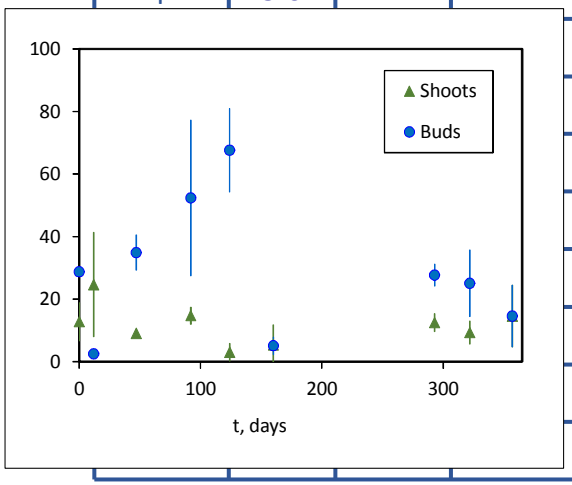
Example of the dose rate assessment

Actual distribution and dynamics of incorporated RN. ^{137}Cs:







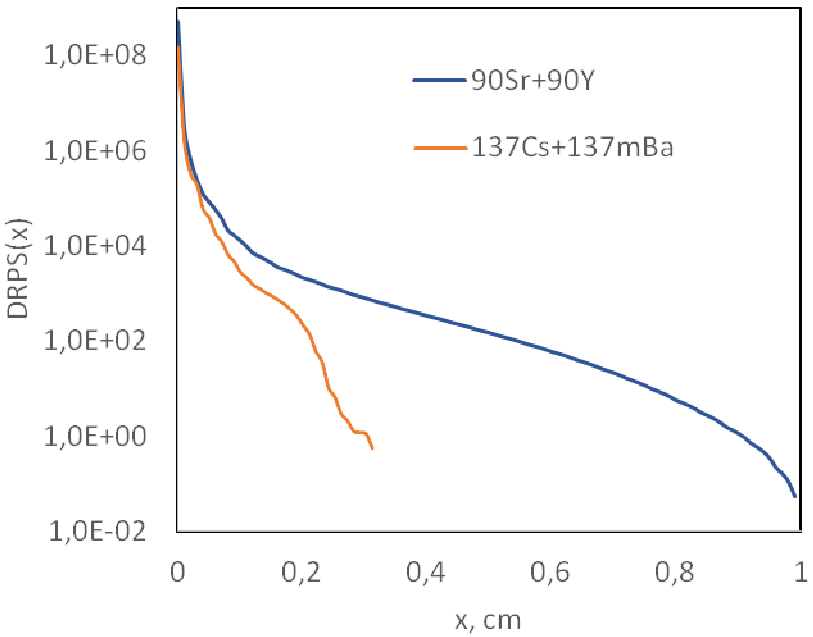


$$q_{i,j} = a_{i,j} \cdot q_{wood}(t_0)$$

	Organ *i*				
	Branch	OB	IB	Wood	Buds
	4.5	12	7	0.8	5
	4.5	12	7	1	5
	19	18	20	11	27
	7	5	8	3.2	28
	2.3	19	5	0.74	19
	3.1	17	8	1.65	16
	5.6	8	14	2.9	26
	7.2	9	17	3.1	47
	6.9	11	13	1.75	65
	5.3	5	5	1.0	55
	4.5	12	7	0.8	5
	4.5	12	7	0.8	5

Example of the dose rate assessment

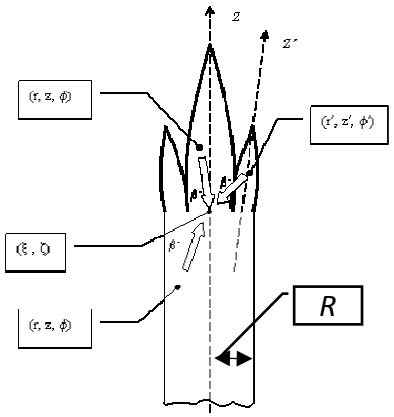
Dose functions of the point source, DRPS(x), in water, nGy h^{-1} Bq^{-1} (Cross et al, 1992)



Empirical expressions for DRPS(x) can be used, e.g. Loevinger formula

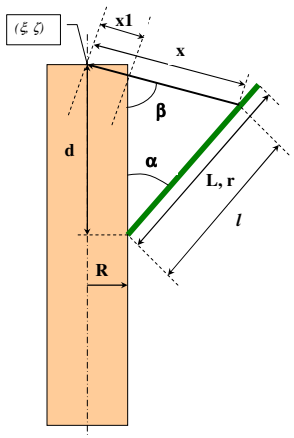
Example of the dose rate assessment

Dose rate coefficients calculations



RN incorporated the target organ

$$DH = \rho \cdot \iiint q(r,z) \cdot DPRS\left[\sqrt{(r-\xi\cdot\cos\phi)^2 + (\xi\cdot\sin\phi)^2 + (z-\zeta)^2}\right] \cdot r\ dr\ d\phi\ dz$$

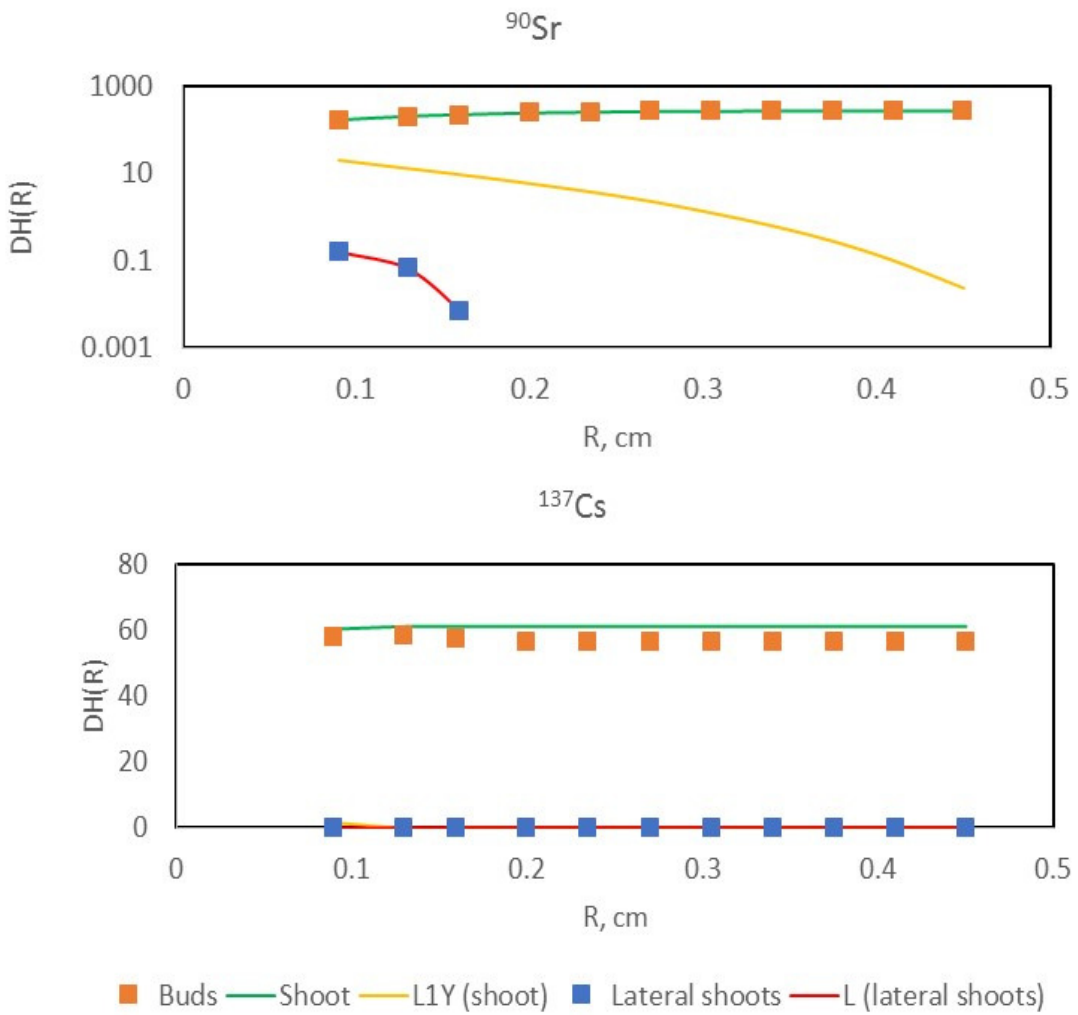


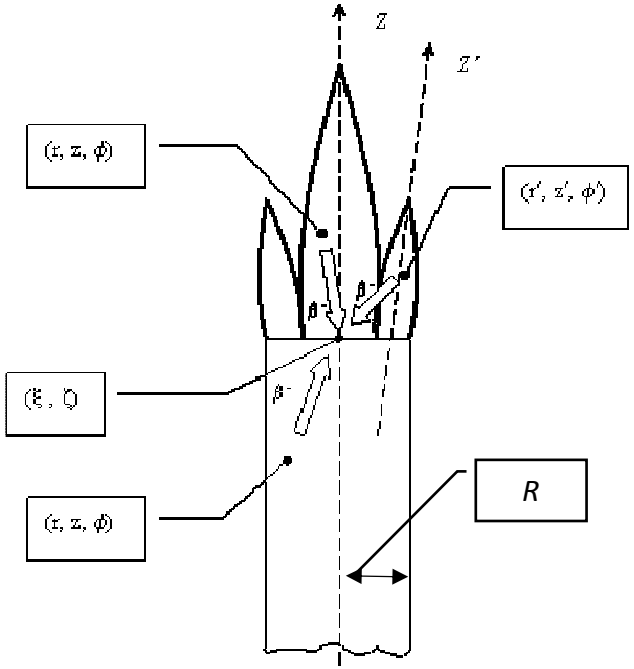
RN incorporated in the adjacent organs

$$DH(d) := aL \cdot \int_0^L \frac{DRPS\left[R \cdot \frac{\sqrt{(R + l\cdot\sin(\alpha))^2 + (d - l\cdot\cos(\alpha))^2}}{R + l\cdot\sin(\alpha)}\right]}{\left[(R + l\cdot\sin(\alpha))^2 + (d - l\cdot\cos(\alpha))^2\right]}\, dl$$

Example of the dose rate assessment

Partial dose rate coefficients DH(R), nGy hr^{-1} per Bq g^{-1} in the source organ





Similar to what we would have when if the concept of absorbed fraction was applied

Example of the dose rate assessment

Integral dose rate coefficients

ERICA Tool: µGy hr^{-1} per Bq kg^{-1} in "tree"
Our model: µGy hr^{-1} per Bq kg^{-1} in stemwood of Scots pine

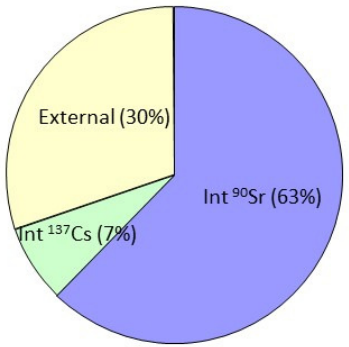
RN	ERICA Tool	Our model
^{137}Cs	3.2×10^{-4}	2.1×10^{-3}
^{90}Sr	6.5×10^{-4}	7.1×10^{-4}

ERICA Tool ignores the RN distribution and dynamics

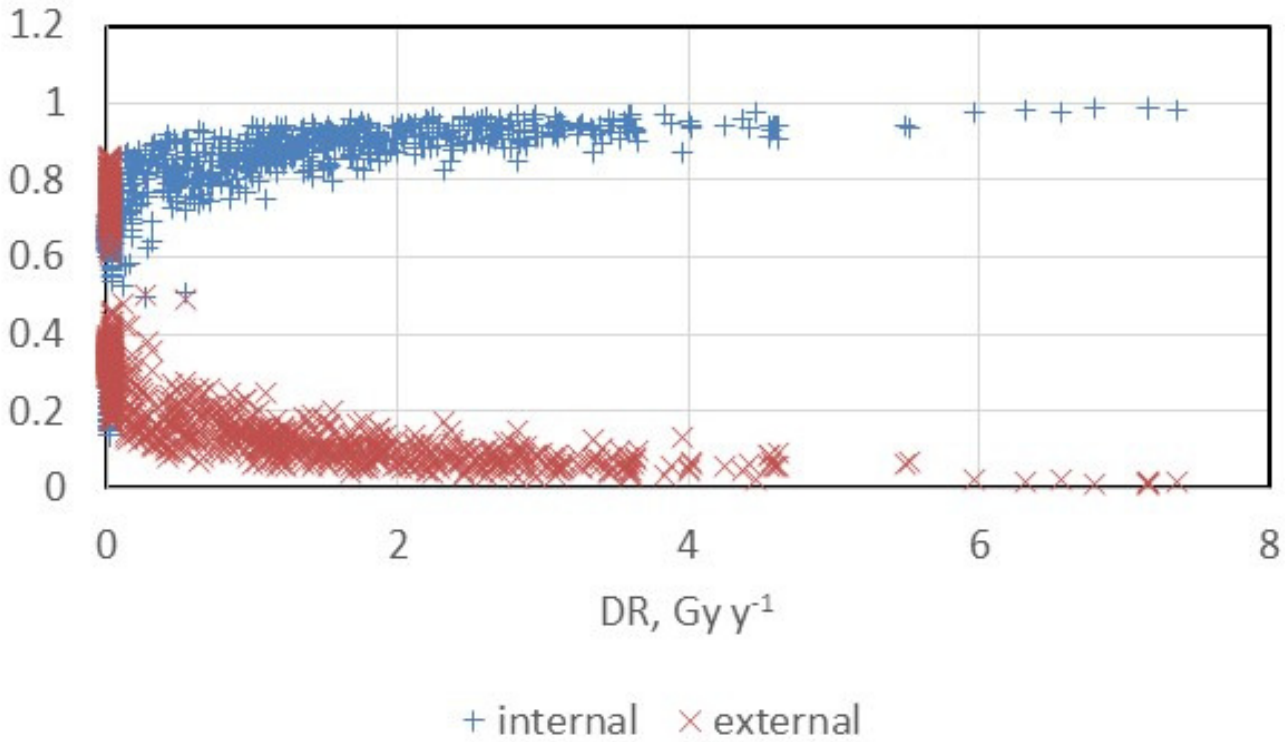
Example of the dose rate assessment

Contributions of various sources into the total dose rates (Scots pine, various sites)

Yaniv, CEZ



Red Forest, CEZ



Summary

External exposures:
-difficult to consider all sources and their actual geometries
-possible essential heterogeneity of the dose rates within the comparable small areas
-variations of the dose rates in time

Internal exposures:
-CR and the incorporated RN activities may widely vary depending on the species, age, environmental factors etc
-heterogeneity of the incorporated RN distribution in the organism/organs
-variations of the incorporated RN activities in time

Thank you for your attention!