

# Revisiting Radiocesium Retention in Japanese Cedar: Implications for Post-Accident Forest Recovery

## Presenter

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## 30 min Keynote Roadmap

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*Forest coverage, ecological & economic significance*
- 02 The Fukushima Context**  
*Accident, deposition patterns, chemical speciation*
- 03 Crown & Bark Dynamics**  
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- 04 Wood Compartments**  
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- 05 Species Comparison**  
*Cedar vs. pine, oak, cypress, larch*
- 06 Mechanistic Drivers**  
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- 09 Conclusions**  
*Synthesis, key messages, and open questions*
- 10 Closing Remark**

PART 1

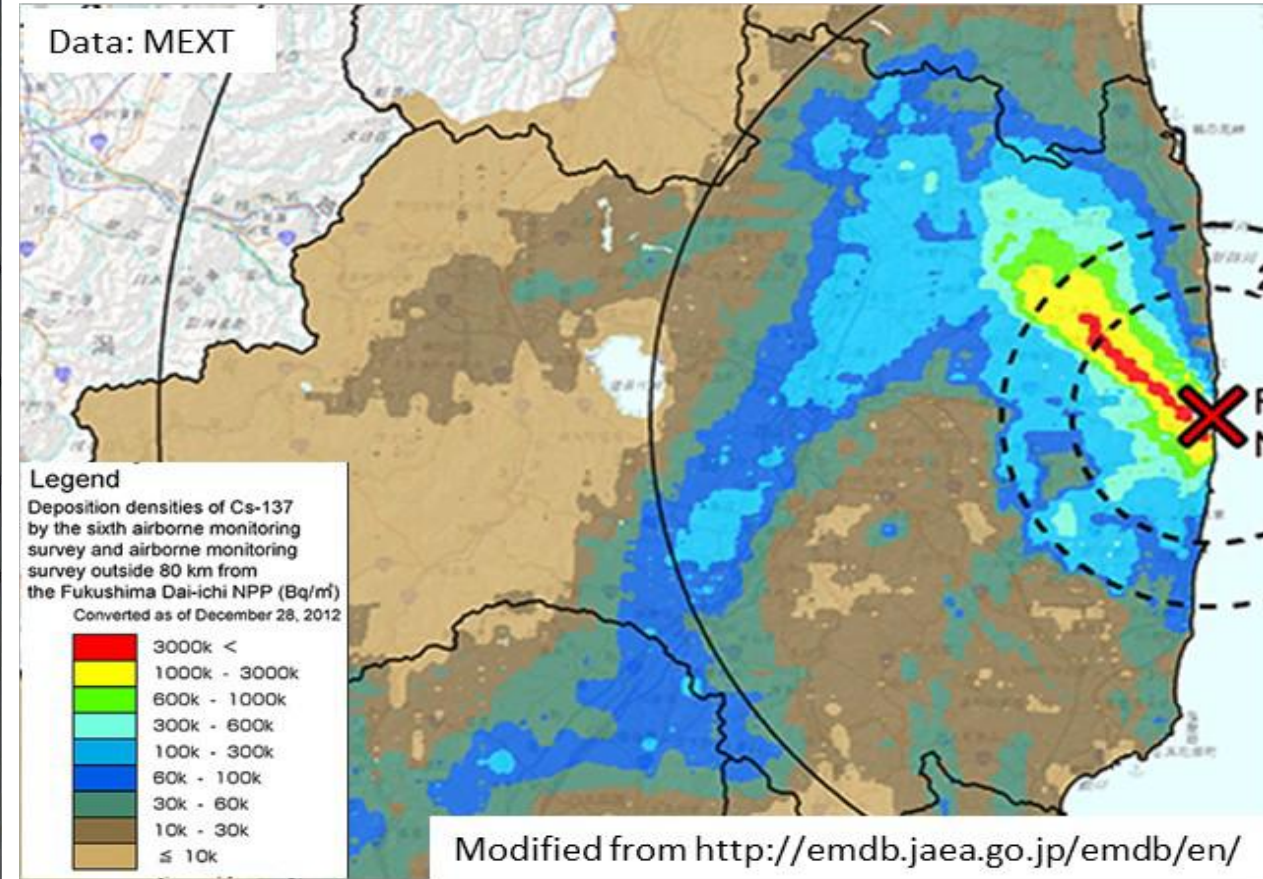
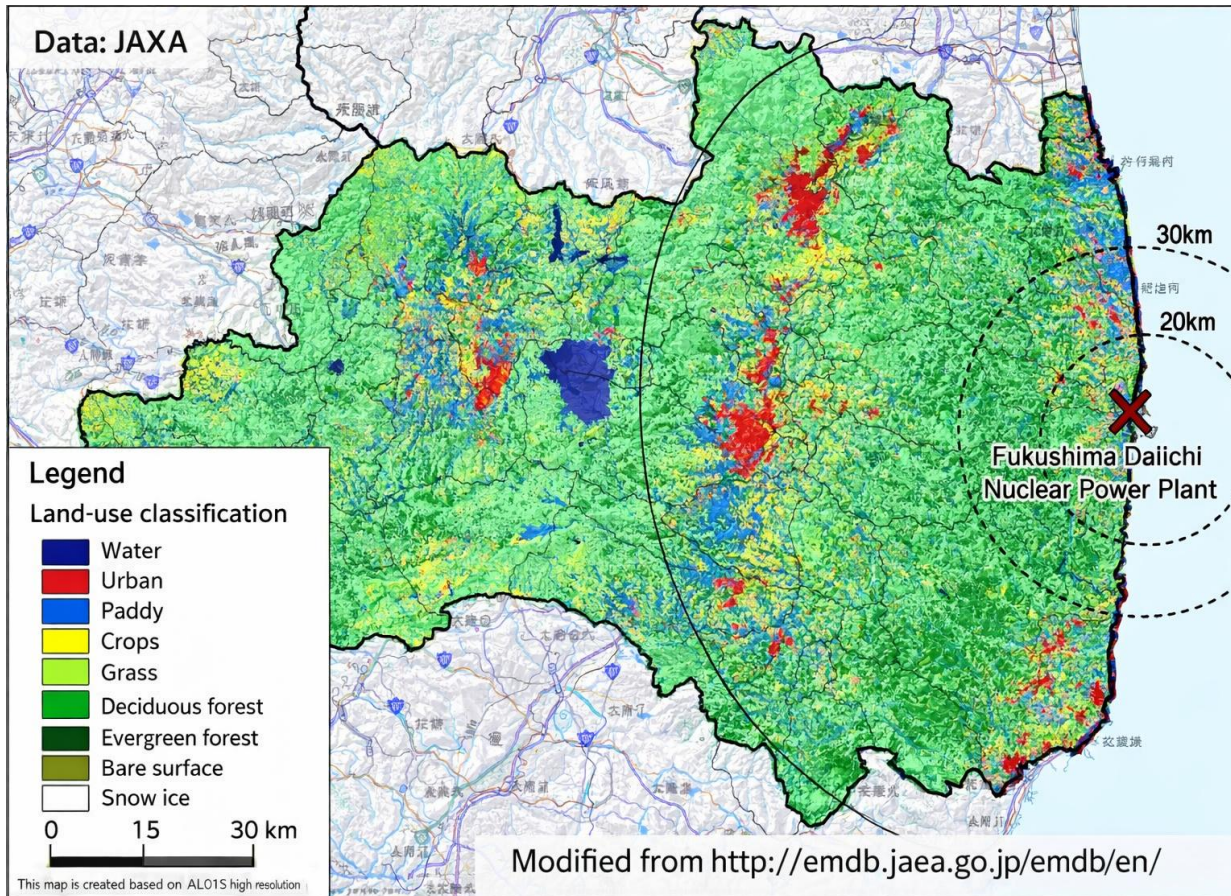
# Why Japanese Cedar Matters

Ecological & economic significance in Fukushima-contaminated Japan

# Why are the Cedar forests important?

## Land use

## Deposition Densities of Cs-137



## Forests in Fukushima prefecture:

972,000 ha, or 71% of the whole area (<http://www.pref.fukushima.lg.jp/>); Plantations ~ 339,000 ha, or ~34% of forests (MAFF, 2014). Annual production before 2011 ~ 697,000 m<sup>3</sup> (411,000 m<sup>3</sup> of cedar): Roundwood prices, 2012 (MAFF, 2012): cedar (Sugi) – ¥11,400 m<sup>-3</sup>, cypress – ¥18,500 m<sup>-3</sup> **Annual income (cedar only): ≈ ¥4.5 Billion (¥45 億)**

# Why Does *Cryptomeria japonica* Demand Our Attention?

70%

of Fukushima Prefecture  
is forested

#1

Most dominant conifer  
in Japanese plantations

30.2y

Physical half-life of  $^{137}\text{Cs}$   
— decades of concern

520 PBq

Total radioactive release  
(FDNPP, 2011)

## The Central Puzzle

Most conifers **retain  $^{137}\text{Cs}$  in sapwood** — the active, living xylem layer that transports water and nutrients.

**Japanese cedar is different.** It progressively enriches heartwood — the dead, non-living core — reaching HW/SW ratios of **2–3× by 2020.**

## Key Economic Stakes

- **Construction timber:** Japan's #1 plantation species — regulatory limit?
- **Firewood:** Limit 40 Bq/kg — heartwood persistence threatens markets
- **Bark disposal:** Insoluble Cs-bearing particles create administrative burden
- **Ecosystem services:** Soil, water, wildlife — decades of contamination storage

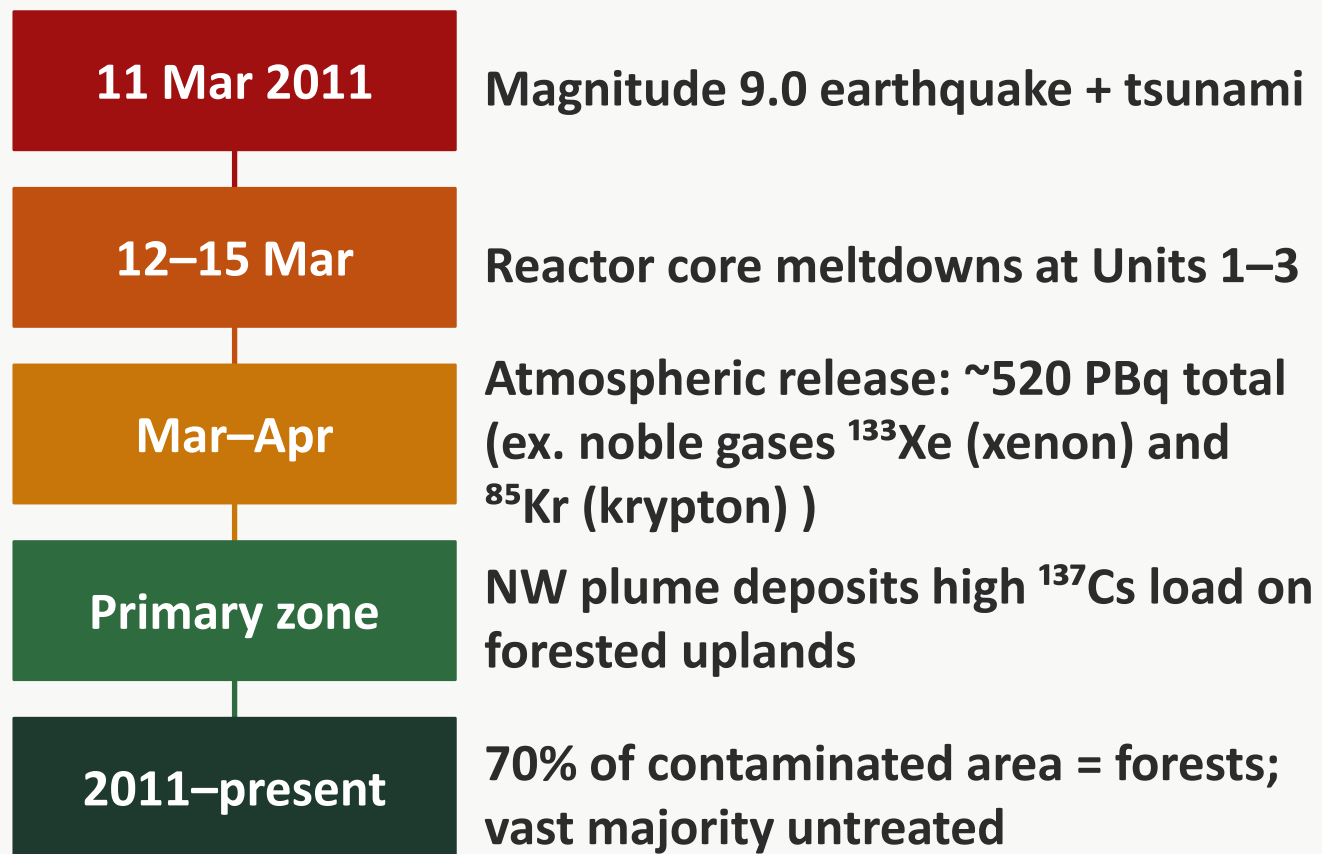
## PART 2

# The Fukushima Context

Accident, deposition patterns & chemical speciation of radiocesium



## The 1F Accident: Scale, Fallout, and Forest Impact



### Key Deposition Facts

- ▶  $^{134}\text{Cs}$  +  $^{137}\text{Cs}$  dominant long-term contaminants
- ▶ Deposition highly heterogeneous: NW corridor received highest loads
- ▶ Dry vs. wet deposition ratio varies by direction from plant (Gonze et al., 2014)
- ▶ IAEA (2015): complete forest remediation effectively unachievable
- ▶ UNSCEAR (2022): no discernible health effects in general public — but long-term ecological monitoring essential

**SOLUBLE FRACTION (ionic <sup>137</sup>Cs)**

- Water-soluble & exchangeable forms
- Penetrates bark via passive diffusion
- Drives ALL internal translocation processes
- Absorbed by roots from soil exchangeable pool
- Translocated via xylem + phloem → wood
- Declining over time as soil fixation progresses

Only the soluble fraction causes heartwood enrichment in cedar

**INSOLUBLE FRACTION (RBMPs — 'Cesium Balls')**

- Radiocesium-Bearing Micro-Particles (RBMPs)
- Glassy silicate spherules from reactor combustion (Adachi et al., 2013)
- Deposited on outer bark surface ONLY
- Do NOT translocate internally
- Resistant to leaching; slow surface wash-off
- Cause persistent plateau in outer bark concentration below which further decline slows

**UNSCEAR (2022): RBMP proportion varies from a few % (<30km) to ~80% (>200km)**

**Soil Chemical Forms — Governing Root Uptake**



## PART 3

# Crown & Bark Dynamics

Interception, wash-off pathways, and inner vs. outer bark behaviour



## Canopy Interception: The Forest as a First Filter

**70–90%**  
 of total deposition  
 intercepted by crown  
 (Imamura et al., 2017)

**~2%**  
 of initial crown  $^{137}\text{Cs}$   
 remained in needles by 2015  
 (exponential decline)

**98%**  
 removed via throughfall,  
 litterfall, and rainwash  
 within 4 years

### Canopy Depuration Cascade

- 1** **Fallout interception**  
*70–90% retained in crown foliage & branches at impact*
- 2** **Throughfall dominates early**  
*Rain-driven wash-off most important in first months;  
 faster than defoliation*
- 3** **Litterfall transfer**  
*Contaminated needles/branches reach forest floor; litter Cs  
 >50% of floor input*
- 4** **Bark retention**  
*Bark slower to lose Cs than needles; outer bark retains  
 insoluble RBMPs persistently*

#### Inner Bark vs. Outer Bark — A Critical Distinction

##### Outer bark (phellem):

Direct surface deposition target  
 Retains insoluble RBMPs — persistent plateau  
 Initial high concentration then slow decline

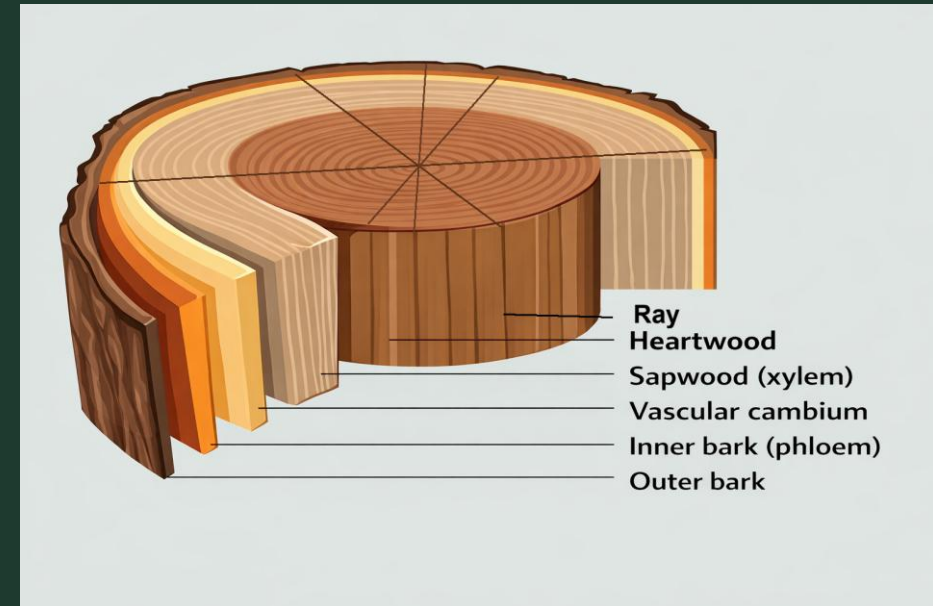
##### Inner bark (phloem):

Contamination = internal transfer only  
 More reliable proxy for internal redistribution dynamics  
 Lower activity than outer bark (Imamura et al., 2017)

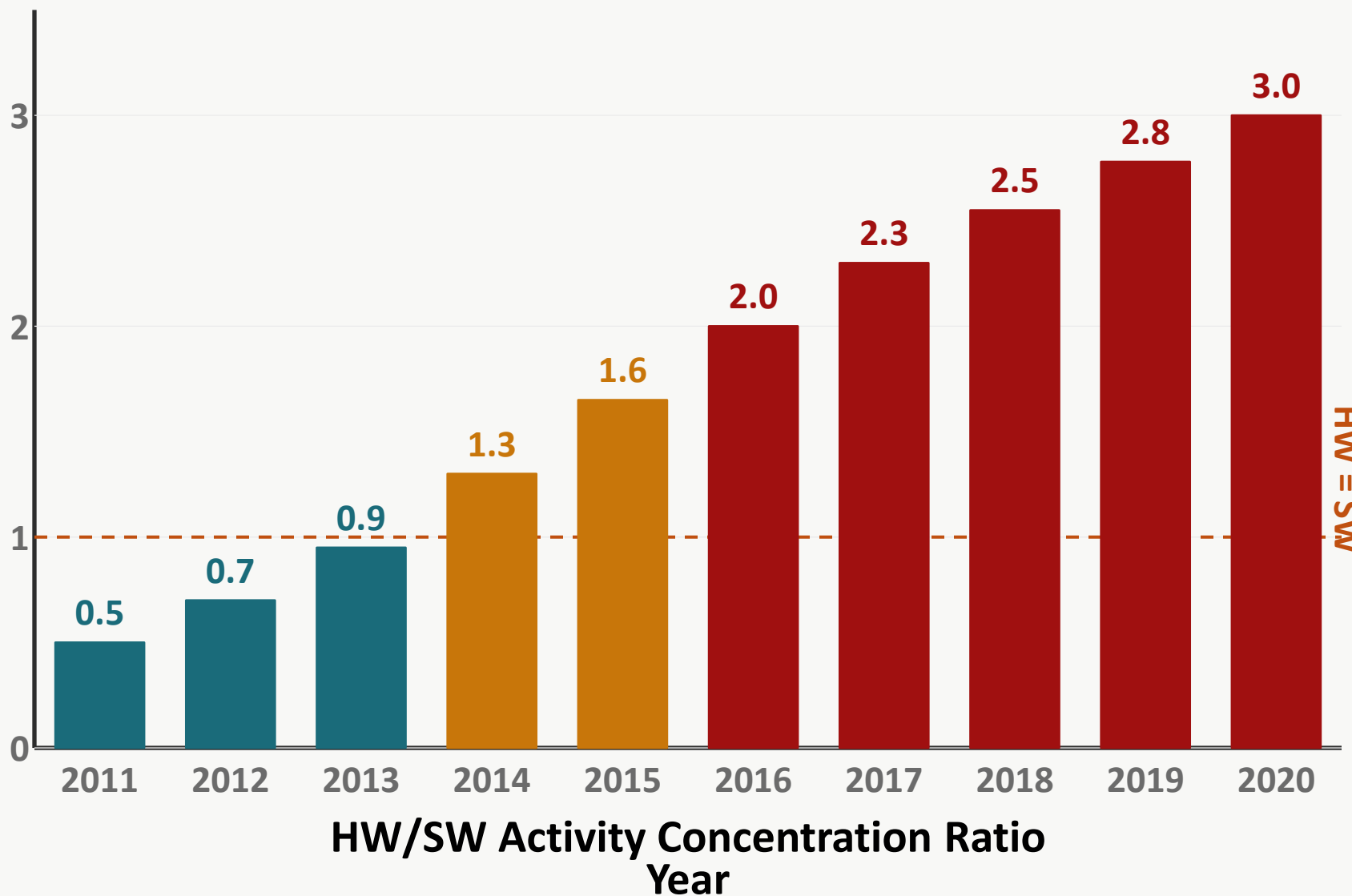
## PART 4

# Wood Compartments

The anomalous heartwood enrichment pattern in Japanese cedar



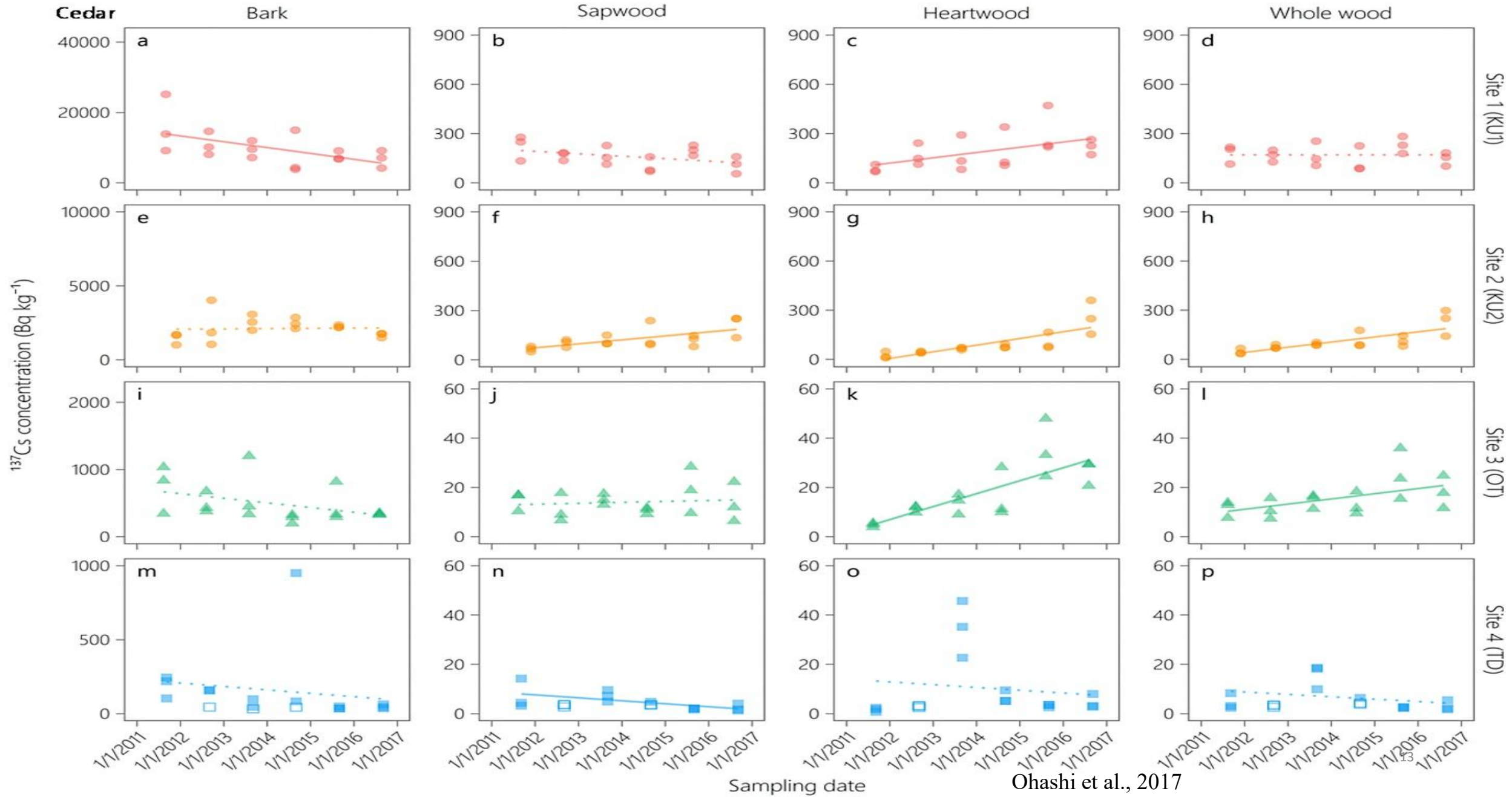
Cedar Heartwood Becomes the <sup>137</sup>Cs Sink — But Not Without a Ceiling



Key Observations

- 2011:** SW enriched; HW/SW ~0.5
  - 2012–2013:** Rapid SW→HW transfer; crosses unity
  - 2016:** HW/SW > 2 consistently
  - 2020:** ~3× in Yamakiya stand
- Plateau expected:  
*K<sup>+</sup> competition suppresses further Cs inflow to HW (Niizato et al., 2025; Yoschenko et al., 2022; Ohashi et al., 2017)*

# Early-stage radial distribution of $^{137}\text{Cs}$ in Japanese cedar



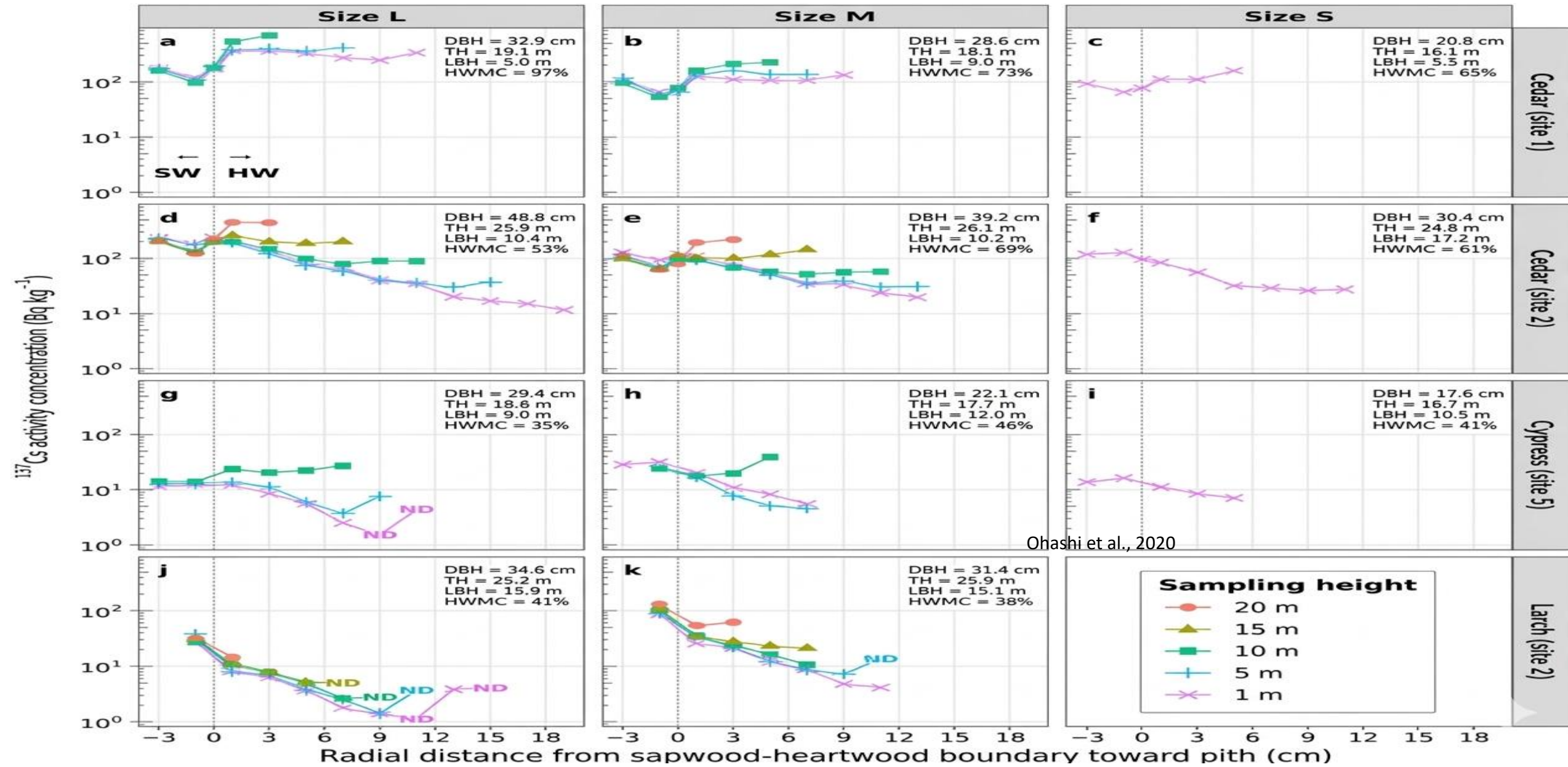
## PART 5

# Species Comparison

Cedar vs. pine, oak, cypress, larch — and lessons from Chernobyl



# Radial distribution of $^{137}\text{Cs}$ activity concentration in wood sampled at different vertical positions.



Ohashi et al., 2020

# No Other Species Shows Cedar's Degree of Heartwood Enrichment

*HW dominant — unique (Yoschenko et al., 2022; Ohashi et al., (2017))*

HW=SW

Japanese cedar (*C. japonica*)



3.00x

Japanese cypress (*C. obtusa*)



1.05x

*Near equilibrium — modest HW tendency (IAEA, 2020; Ohashi et al. 2020)*

Japanese larch (*L. kaempferi*)



1.00x

*Near equilibrium — uniform distribution (Ohashi et al. (2020))*

Japanese red pine (*P. densiflora*)



0.72x

*SW dominant — Cs stays in sapwood (Ohashi et al. (2014; 2017))*

Konara oak (*Q. serrata*)



0.68x

*SW dominant — typical for broadleaf (IAEA, 2020; Ohashi et al. (2014; 2017))*

Scots pine (*P. sylvestris*)  
[Chernobyl]



0.70x

*SW dominant even 10yr post-Chernobyl (IAEA, 2020; Ohashi et al. (2014; 2017))*

HW/SW <sup>137</sup>Cs Activity Concentration Ratio (~2020 for Fukushima species; ~2000 for Chernobyl scots pine)

## Two Distinct Phases of $^{137}\text{Cs}$ Distribution in Wood

Aspect	Early Phase (2011–2013)	Late Phase (2014–2022)
Concentration trends	Rapid decline in crown; sapwood initially enriched	Continued slower decline; HW stabilization begins
Radial distribution	HW/SW ratio < 1; sapwood dominant	HW/SW > 2 in cedar by 2016; > 3 in some stands by 2020
Dominant mechanism	Direct deposition + xylem upflow	Root uptake + ray-mediated radial transport
Transport driver	Atmospheric fallout, foliar absorption	Internal redistribution + $\text{K}^+$ -regulated heartwood loading
Influencing factors	Deposition density, chemical form of Cs	Soil $\text{K}^+$ competition, heartwood moisture, tree age

*Note: The temporal evolution of chemical forms (soluble → fixed) parallels these phase transitions and modulates the rate of change.*

## PART 6

# Mechanistic Drivers

K<sup>+</sup> competition · Ray parenchyma transport · Heartwood moisture · Molecular channels



# Four-Step Mechanism of $^{137}\text{Cs}$ Radial Transport in Cedar

1

## Foliar absorption & bark diffusion?

- Soluble fallout deposited on needles & outer bark
- Penetrates inner bark (phloem) through lenticels and bark discontinuities (cracks, wound sites)
- Insoluble RBMPs remain on the outer bark surface

2

## Xylem upflow (root uptake)

- Exchangeable soil  $^{137}\text{Cs}$  absorbed by shallow horizontal roots
- Upward transport with water via sapwood tracheids
- $\text{K}^+$  competes at root transporter sites

3

## Ray parenchyma — active radial transport

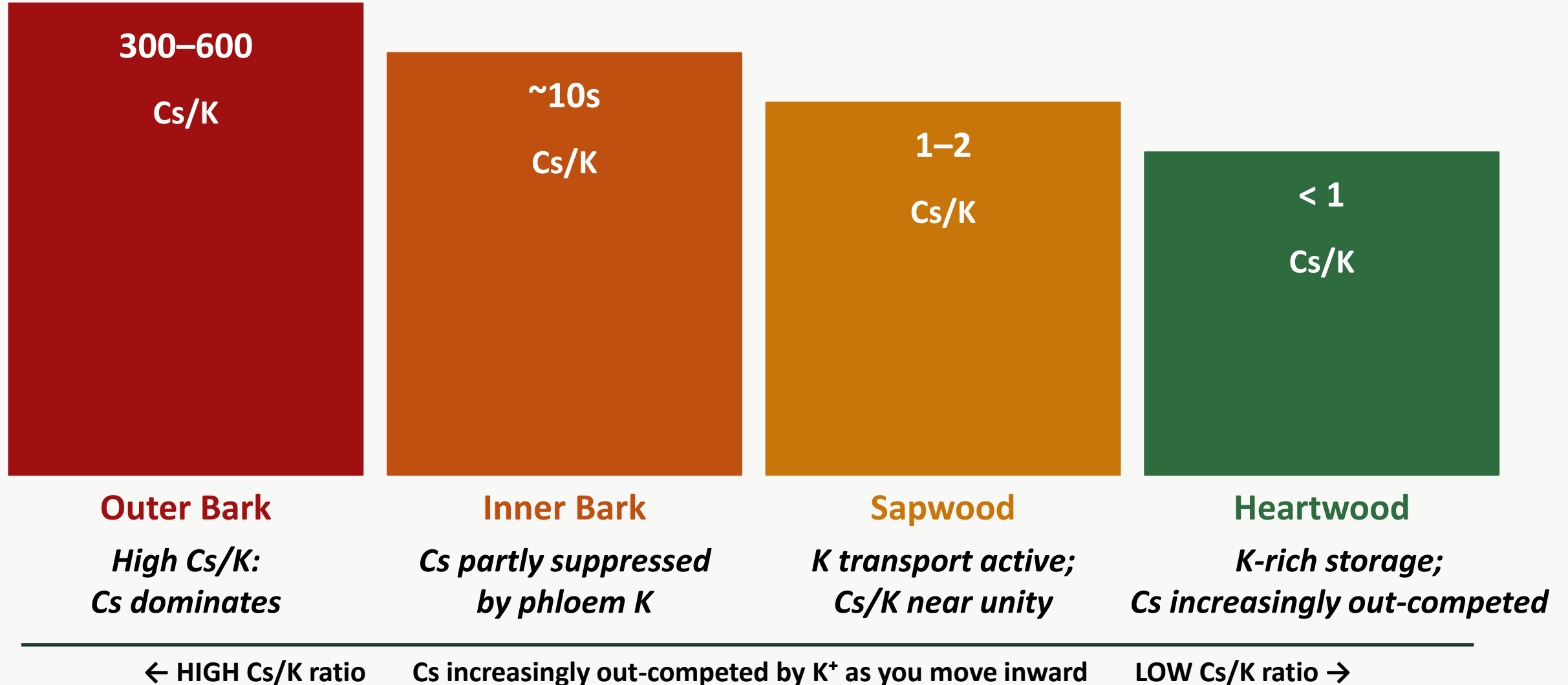
- Living ray cells carry Cs radially from xylem → heartwood
- Both xylem ray cells and phloem rays involved
- Cannot be explained by diffusion alone (Ogawa et al., 2016; Okada et al., 2012)

4

## Heartwood diffusion + retention

- Cs diffuses inward through moist heartwood along concentration gradient
- Also diffuses vertically from crown toward base
- **$\text{K}^+$ -rich environment progressively suppresses further inflow — PLATEAU**

# <sup>137</sup>Cs and K<sup>+</sup>: Competitors, Not Substitutes



Niizato et al. (2025): Cs/K gradient from outer bark (300–600) to heartwood (<1) confirms K<sup>+</sup> competitive suppression of Cs

# Physiological Regulators of Cesium Entry

## Molecular Ion Channels

### Voltage-gated K<sup>+</sup> channels (AKT/KAT family)

- Also facilitate Cs<sup>+</sup> entry — lower affinity than K<sup>+</sup>
- AKT1/AKT2 most relevant for root uptake

### H<sup>+</sup>/K<sup>+</sup> symporters

- Proton-coupled transporters accept Cs<sup>+</sup>
- Operate against concentration gradient

### Non-selective cation channels (NSCCs)

- Less discriminating — allow Cs<sup>+</sup> entry even at low concentrations

**Research gap:** *Specific channel identities in cedar ray parenchyma cells are UNKNOWN. Stable <sup>133</sup>Cs tracer studies urgently needed*

## Heartwood Moisture Content

### Key finding (Ongoing study):

HW/SW <sup>137</sup>Cs ratio is positively correlated with both heartwood K content AND heartwood moisture content

### Mechanism:

High moisture in cedar HW provides aqueous medium for Cs diffusion inward after active ray transport delivers Cs to HW boundary

### Kuro-shin (黒心) phenotype:

Anomalously high HW moisture → enhanced Cs entry  
 Black discolouration linked to elevated alkali metal (K, Cs) content  
 (Kubo & Ataka, 1998)

### Implication:

*Individual tree variation in HW moisture explains within-stand heterogeneity in <sup>137</sup>Cs accumulation*

## PART 7

# Management & Implications

Timber policy · Decontamination limits · Cedar as bioindicator



## From Science to Policy: What Does Heartwood Enrichment Mean in Practice?

### Timber Contamination Persists

Cedar heartwood inaccessible to physiological exchange  
→ cannot be remediated except by felling?.  
Timber may remain above regulatory limits decades post-accident?.  
Primary use = construction timber: 50 Bq/kg limit?.  
Bark disposal = administrative challenge at high  $^{137}\text{Cs}$  concentrations.

### Cedar as a Bioindicator

Clear, predictable sapwood → heartwood enrichment progression makes cedar excellent long-term biomonitor.  
 $^{137}\text{Cs}/^{133}\text{Cs}$  isotopic ratio measurable by increment borer — non-destructive, same-tree repeated sampling.  
HW/SW ratio encodes multi-year soil-plant dynamics.  
Yoschenko et al. (2025): isotopic ratio confirms root uptake dominance post-2017.

### Decontamination Limitations

Only forests within 20 m of residences were systematically treated — <12,000 ha total (Onda et al., 2020).  
Vast majority of contaminated forest land was not treated.  
IAEA (2015): complete forest remediation effectively unachievable.  
Litter removal, thinning, and topsoil scraping have ecological costs (mycorrhizal disruption).

### Selective Harvesting Strategy

Lower-contamination stands: early selective harvest may reduce long-term heartwood loading.  
Higher-contamination stands: must wait until bark concentrations drop below regulatory limits.  
Increment borer monitoring of HW/SW trends = essential decision tool.  
K fertilisation in nearby agricultural fields: possible model for forest application (Kaunisto et al., 2002).



## PART 8

# Future Research Priorities

Six critical areas to address over the next decade



*Increment borer sampling at  
Yamakiya, Fukushima*



## A Decade of Targeted Research Will Resolve These Critical Gaps

1

### Increment Borer Monitoring

Non-destructive, same-tree sampling every 3–5 years; stratified by initial dry/wet deposition ratio (Gonze et al., 2014); 10-year minimum commitment to resolve whether HW/SW plateaus

4

### Bark & RBMP Speciation Analysis

Temporal trends in outer bark critical for timber disposal planning; RBMP fraction quantification needed to explain persistent outer bark activity plateaus

2

### Stable $^{133}\text{Cs}$ Tracer Experiments

Elucidate  $\text{Cs}^+/\text{K}^+$  competitive kinetics at membrane level; quantify xylem, phloem and ray contributions without radioactive constraints; minimum 10-year study

5

### Cs–K Competitive Dynamics

Quantify the temporal approach to Cs/K equilibrium in heartwood; determine whether K-based countermeasures (K fertilisation) applicable in contaminated forest context

3

### $T_{ag}$ -Based Long-Term Monitoring

Normalize concentrations to local deposition density; determine whether  $T_{ag}$  for cedar wood is still increasing, plateauing, or declining beyond 2022

6

### Integrative Forest Process Models

Link species-specific physiology + soil chemistry + climate drivers; predict timber safety decades ahead; incorporate dry/wet deposition heterogeneity to validate Chernobyl-derived frameworks

## PART 9

# Conclusions

Five key messages from this review



# Five Key Conclusions

1

## Cedar is uniquely heartwood-enriched

Unlike pine, oak, cypress or larch — driven by within-tree K distribution, high HW moisture and ray-mediated active transport

2

## A competitive $K^+$ -imposed plateau limits enrichment

$^{137}\text{Cs}$  concentrations in heartwood will NOT increase indefinitely;  $K^+$  competition suppresses inward transport as HW Cs accumulates.

3

## Chemical speciation governs bark dynamics

Insoluble RBMPs create persistent outer bark plateau; the Chernobyl speciation-dependent fuel-particle pattern is less pronounced at Fukushima — internal biological processes buffer deposition heterogeneity

4

## Forest soils are highly effective long-term $^{137}\text{Cs}$ repositories

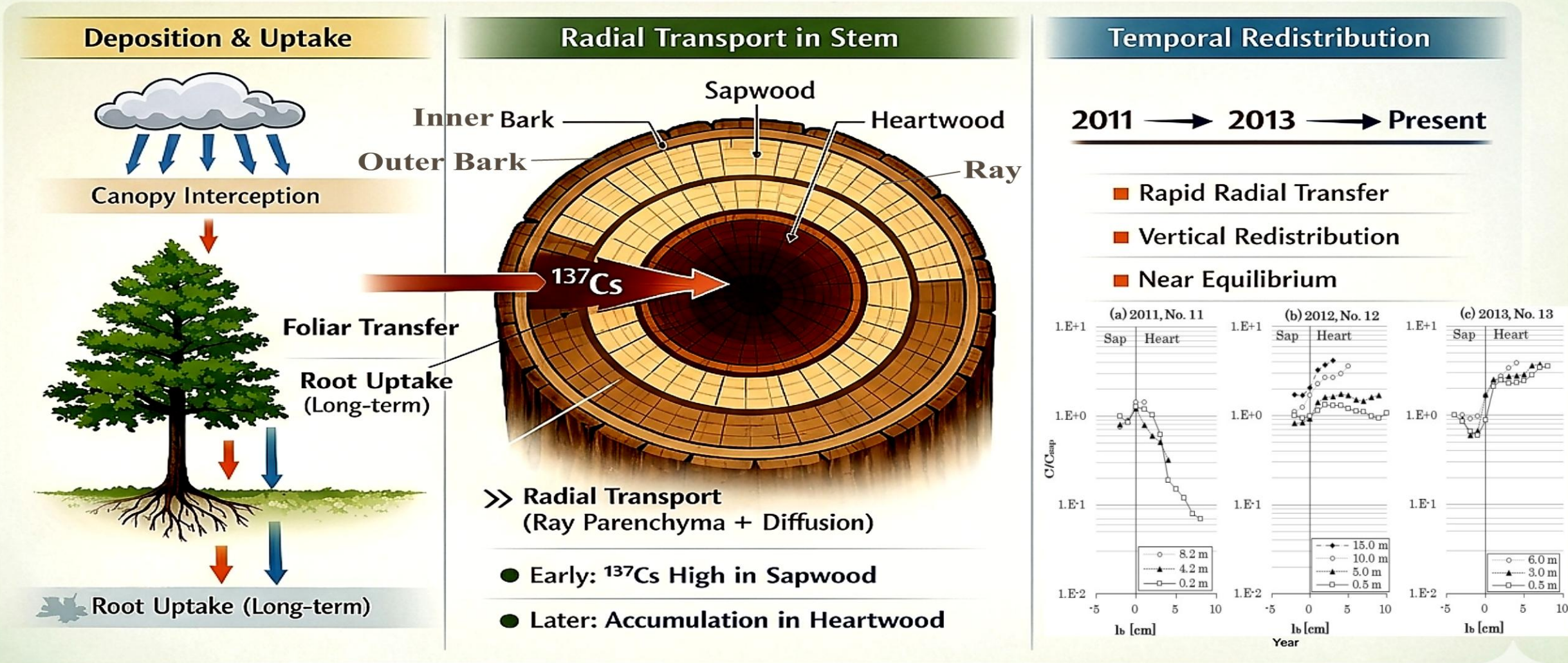
Forests remain a persistent secondary source of  $^{137}\text{Cs}$  on decadal timescales

5

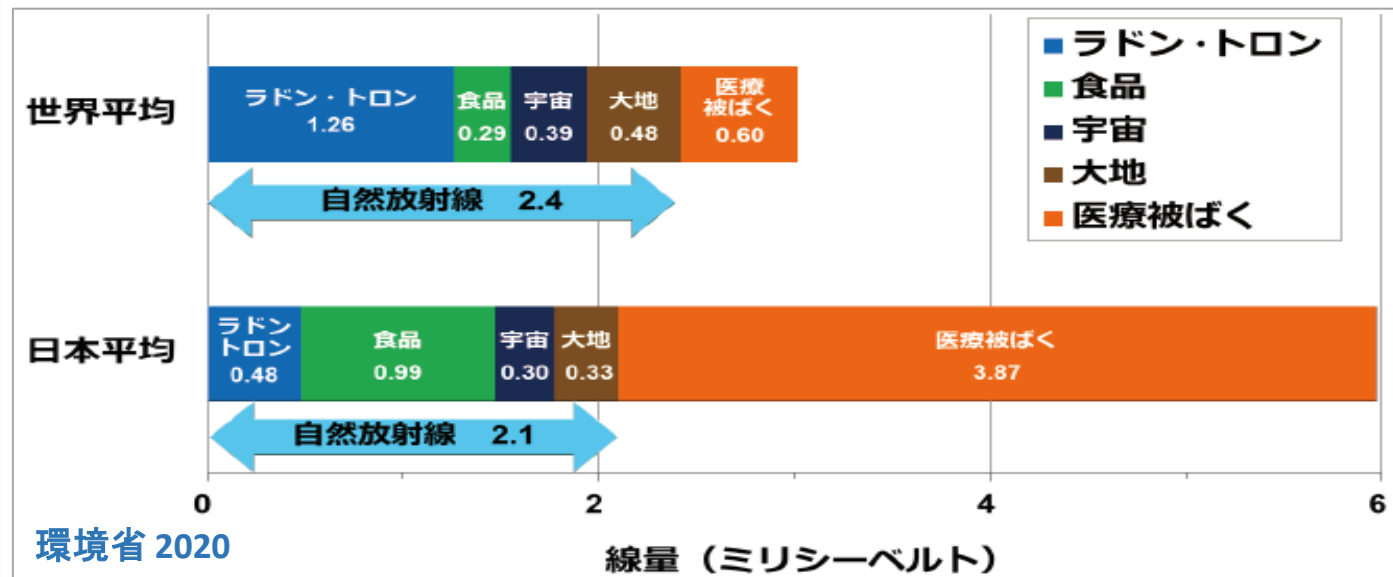
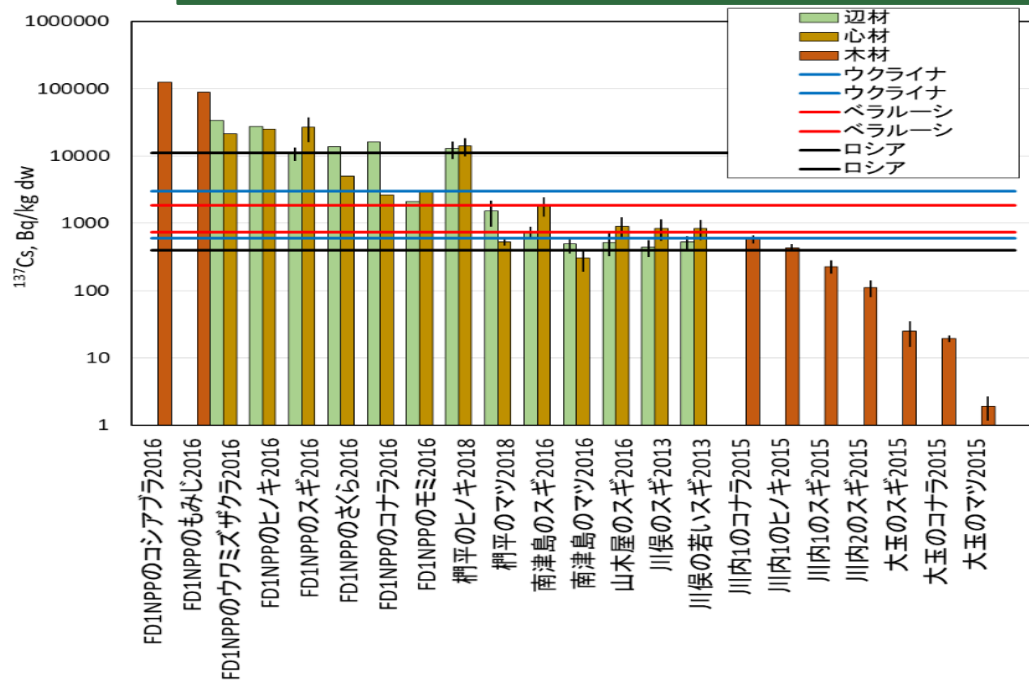
## $T_{\text{ag}}$ for Japanese cedar remains inadequately characterised

Systematic, deposition-normalised, long-term monitoring extending beyond 2022 is the single most pressing gap — without it, long-term timber risk projections cannot be validated

# Radiocesium ( $^{137}\text{Cs}$ ) Redistribution in Japanese Cedar



# What does the accumulation of $^{137}\text{Cs}$ in cedar heartwood mean for human health?



ACCORDING TO THE INTERNATIONAL STANDARDS, WOOD FROM MANY FORESTS IN FUKUSHIMA CAN BE SAFELY USED FOR CERTAIN INDUSTRIAL NEEDS. THE STANDARDS PROTECT CONSUMERS (PREVENT IRRADIATION IN THE HARMFUL DOSES) AND MINIMIZE LOSS IN FORESTRY.

ESTABLISHING THE STANDARDS FOR WOOD FOR INDUSTRIAL NEEDS WOULD HELP TO CLARIFY THE FORESTRY PERSPECTIVES IN FUKUSHIMA. THE STANDARDS MUST BE BASED ON THE ACCURATE DOSE CALCULATIONS FOR DIFFERENT UTILIZATIONS OF WOOD.

シナリオ SCENARIO	線量係数 DOSE COEFFICIENT, mSv/y	南津島のスギ 約 1300 Bq/kg
	$^{137}\text{Cs}$ in wood, Bq/kg	
PERSON IN WOODEN HOUSE (ROOM AREA 7 M X 7 M, CEILING 3 M, WALLS OF 20 CM, 11 HRS/DAY)	$2 \times 10^{-5}$	0.026 mSv
WORKER AT SAWMILL/WORKER IN FOREST (8 HRS/DAY, 200 DAYS/YEAR, UPTO $3 \mu\text{Sv/h}$ )	$1.5 \times 10^{-4}$	0.2 - 4.8 mSv




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### Radiocesium uptake and distribution in Japanese cedar (*Cryptomeria japonica* D. Don): A review of current knowledge and future perspectives

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**PART 10**

**ARIGATO GOZAIMASU – THANK YOU FOR LISTENING!!**



Fukushima University  
**INSTITUTE OF  
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