

**IRSN**

INSTITUT  
DE RADIOPROTECTION  
ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

# How knowledge on K and $^{133}\text{Cs}$ biocycling can be used to estimate $^{137}\text{Cs}$ root uptake in Japanese cedar stands contaminated by the Fukushima fallouts

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## AMORAD project



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### Why studying $^{137}\text{Cs}$ stable analogs recycling (K, $^{133}\text{Cs}$ )?

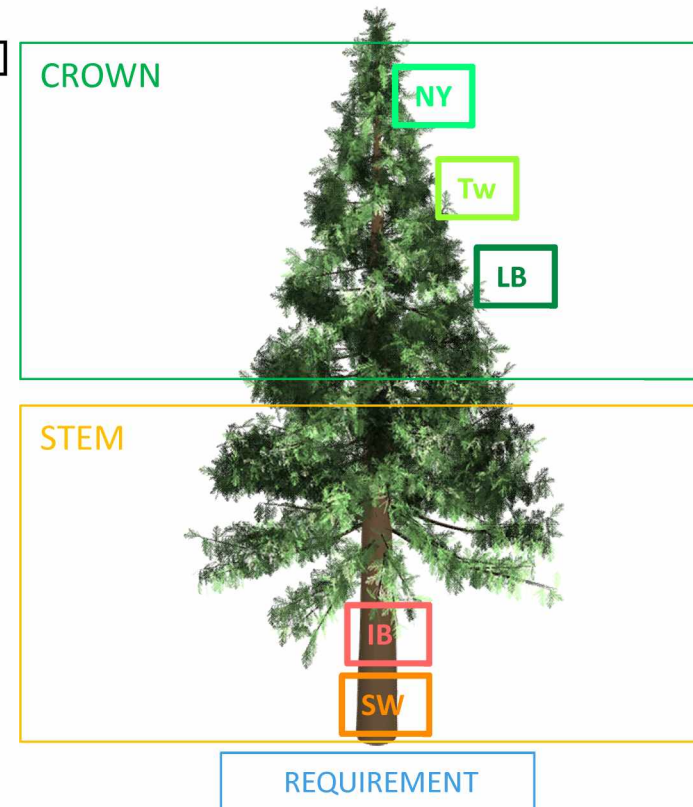
- ▶ Territories contaminated by atmospheric fallouts (Chernobyl, FDNPP accidents)
- ▶  $^{137}\text{Cs}$  half-life ~ 30 y X Forests High interception efficiency = persistence of products contamination
- ▶ Operational modeling needs for addressing Short & Long Term
- ▶ Short Term / Early stage ~ 5y ▶ Dynamics mainly driven by competition between initial uptake & depuration processes (cf. Gonze & Calmon, 2017)
- ▶ Long Term / Apparent Steady State ~ Decades ▶ Root Uptake is the major contributor to  $^{137}\text{Cs}$  inventories
- ▶ FDNPP accident case ▶ equilibrium not reached ▶ How assessing the  $^{137}\text{Cs}$  root uptake?
  - ▶ Similar behaviour of rCs stable analogs K &  $^{133}\text{Cs}$  (e.g. Yoshida et al., 2004 ; Sombré et al., 1994)
  - ▶ Competition of K vs. Cs (cf. Zhu & Smolders, 2000)
  - ▶ Scarce  $^{133}\text{Cs}$  contents data sets
- ▶ OBJECTIVE
  - ▶ Assessing the Root Uptake of both K & stable Cs
  - ▶ Defining  $^{133}\text{Cs}$  discrimination factors for a process-based modeling relying on K biogeochemical fluxes

## QUANTIFICATION OF THE BIOGEOCHEMICAL RECYCLING

- ▶ Approach developed for  $^{137}\text{Cs}$  by Goor & Thiry (2004) / derived from Cole & Rapp (1981)
- ▶ ANNUAL growing biomass **REQUIREMENT** is fed by **Root UPTAKE** & **internal TRANSLOCATIONS**
  - ▶  $R = U + \Sigma T$
- ▶ **REQUIREMENT (R)** ▶ Total quantity of element mobilized by the current biomass production

**REQUIREMENT** = Current Biomass Production x [Element]

- ▶ Current needles **NY**
- ▶ Twigs **Tw**
- ▶ Living Branches **LB**
- ▶ SapWood **SW**
- ▶ Inner Bark **IB**





ROOT UPTAKE

- ▶ Root **UPTAKE (U)** ▶ Quantity of elements taken up from the soil through absorption by roots

$$\text{UPTAKE} = \text{IMMOBILIZATION} + \text{RETURNS} + \text{FOLIAGE ANNUAL VARIATION}$$

- ▶ **IMMOBILIZATION** = Current Biomass Production x [Element]

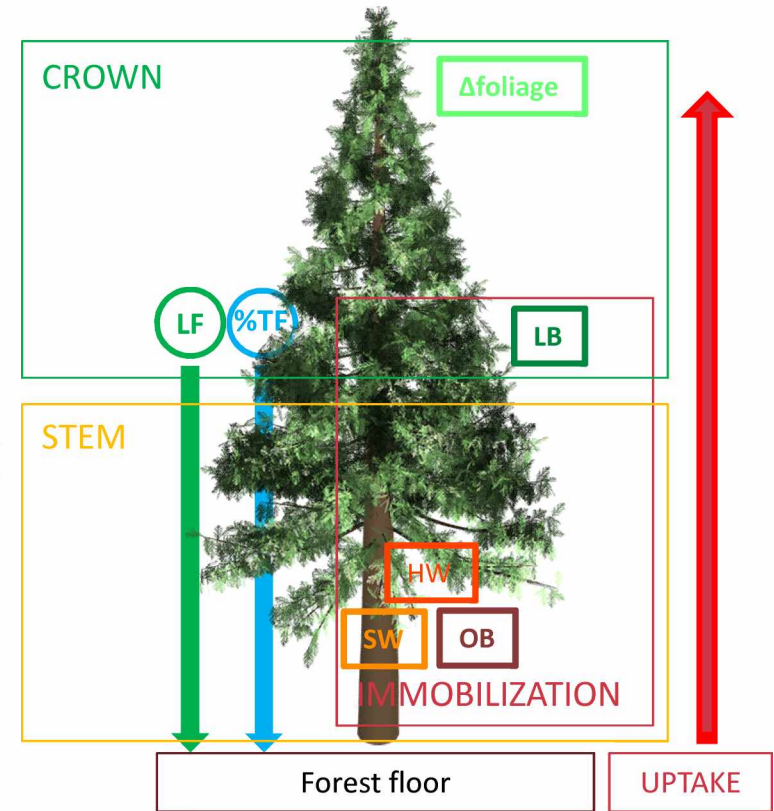
- ▶ STEMWood SW HW
- ▶ Living Branches LB
- ▶ Outer bark OB

- ▶ **RETURNS** = Annual Returned to Forest Floor Amount x [Element]

- ▶ LitterFall LF
- ▶ Canopy Leaching %TF

- ▶ **FOLIAGE ANNUAL VARIATION** = (Biomass Year n – Biomass Year n-1) x [Element Year n]

- ▶ Δfoliage



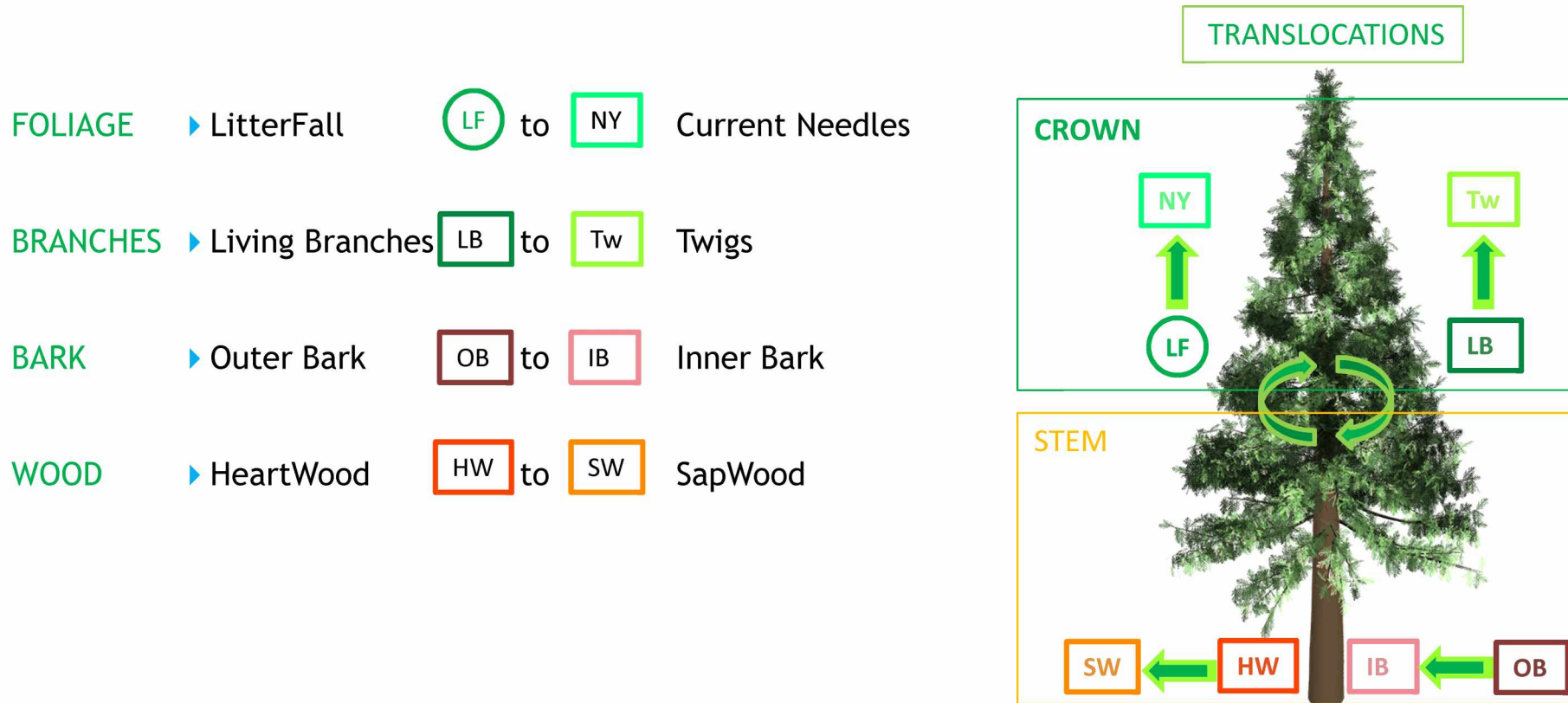


INTERNAL TRANSLOCATIONS

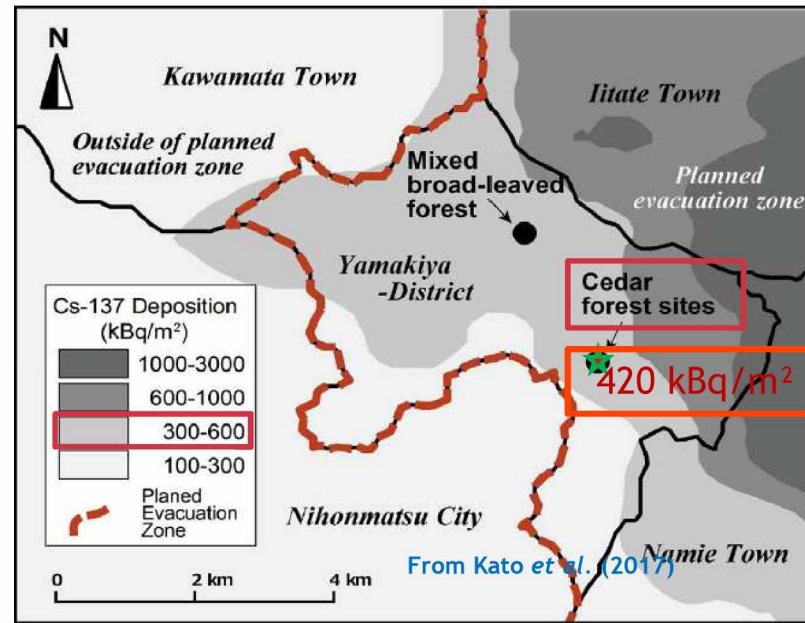
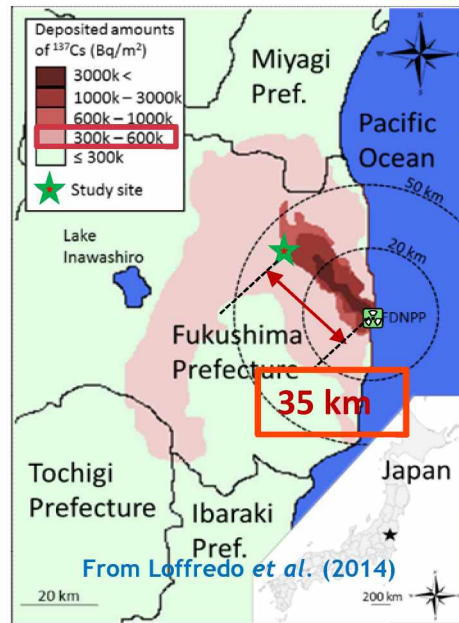
- ▶ Internal **TRANSLOCATIONS** ( $\Sigma T$ ) ▶ Remobilization of elements from senescing to corresponding current biomass production

SOURCE - SINK relationship

**TRANSLOCATION** = Biomass (SENESCING organ) x ([Element **CURRENT PROD**° organ] - [Element **SENESCING** organ])



Sampled sites



▶ *C. japonica* D. Don ▶ Mature (MC) and Young (YC)

Japanese cedars stands

▶ Sampling ▶ 1 Tree per DBH equal size class ▶ N=9

▶ Mid-November

▶ 2013 ▶ 2.8 y after FDNPP releases

▶ 2014 ▶ 3.8 y

▶ 2016 ▶ 5.8 y

▶ 2018 ▶ 7.8 y

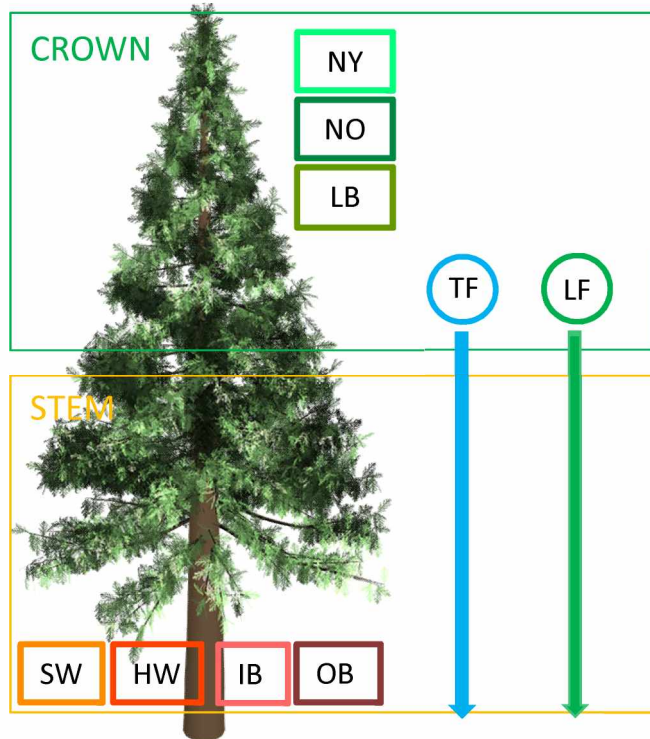
Stand	MC 2013-2018	YC 2013-2018
Stand age years	33 - 38	17 - 22
Stand density stem ha <sup>-1</sup>	800	2400
Plot area m <sup>2</sup>	2900	2600
DBH (Average) cm	31.7 - 35.5	18.7 - 22.9
Stand density stem ha <sup>-1</sup>	800	2400
Height (Average) m	22 - 23	14 - 16
LAI (raw meas. 2013) m <sup>2</sup> m <sup>-2</sup>	4.2	10.3

## Sampling

### ▶ Organs/compartments to feed the RUT approach

TF LF ▶ Kato et al. (in press, 2018)

▶ 2012-2016 series

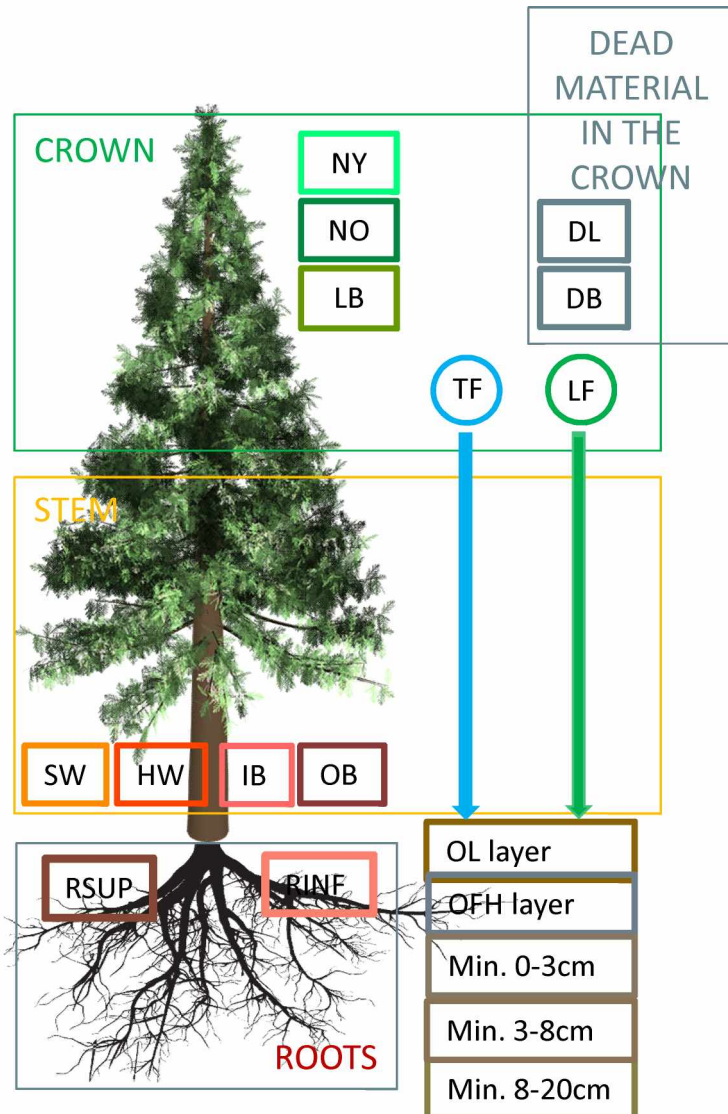


- NY ▶ Current needles
- Tw ▶ Twigs
- NO ▶ Needles > 1 year
- LB ▶ Living Branches
- OB ▶ Outer Bark
- IB ▶ Inner Bark
- SW ▶ SapWood
- HW ▶ HeartWood



Sampling

▶ Complementary Organs/Compartments to feed the INVENTORIES calculation



TF LF ▶ Kato et al. (in press, 2018)

▶ 2012-2016 series

- NY ▶ Current needles
- NO ▶ Needles > 1 year
- LB ▶ Living Branches
- OB ▶ Outer Bark
- IB ▶ Inner Bark
- SW ▶ SapWood
- HW ▶ HeartWood
- RSUP ▶ Coarse roots  $\phi > 2\text{mm}$
- RINF ▶ Fine Roots  $\phi < 2\text{mm}$
- DL ▶ Dead Needle
- DB ▶ Dead Branche

## Calculations based on observed data or literature

- ▶ Biomass stocks / annual increments (cf. Coppin et al., 2016)
  - ▶ Use of allometric relationships  $BM = a.DBH^b$  ▶ Lim et al. (2013)
  - ▶ DBH annual increment from biometrics on Wood Disk
  - ▶ No self-thinning taken into account over the study period
  - ▶ Dead material in crown ▶ allometric relationship  $BM = a.DBH^b$  ▶ (Yoshida & Hijii, 2006) MC/ regression from literature data (N=9) YC
  - ▶ Fine roots ▶ regression from literature data ▶ Fujimaki et al. (2007)
- ▶ Current needles production NY
  - ▶ Use of mean LF amounts from Kato et al. (in press, 2018) over 2012-2016 series
  - ▶ LFNeedles contribution to total LF amount ▶ (Yoshida & Hijii (2006))
  - ▶ Regular turnover equation  $NY = LFNeedles - \Delta foliage$
  - ▶ Needles turnover MC-YC is 4-5 years vs. 4.8 years mean value from Kiyono & Akama (2016)
- ▶ Returns to forest floor
  - ▶ Mean LF ( $kg/m^2$ ) & TF ( $L/m^2$ ) from 2012-2016 series (Kato et al., In press, 2018)
- ▶ RUT approach
- ▶ No trends over the study period for K &  $^{133}Cs$  contents in organs were observed (p-values > 0.05 /t)
  - ▶ use of mean values ( $\pm 1$  SD) for K &  $^{133}Cs$  fluxes (2013-2018)
- ▶ Specific adaptation for *C. japonica* = Tw integrated in NY ▶ No LB to Tw (T) flux (not taken into account)

**Lots of calculations  
& Literature review**

Derived values for Canopy Leaching %TF

- ▶ No observation for K contents in the TF

K

- ▶ TF+SF from Ohrui & Mitchell (1996) with SF contribution corrected from Sase et al. (2008)

- ▶ Wet & Dry Deposit vs. %TF contribution from Wu et al. (1996) / same watershed & period as O. & M. (1996)
  - ▶  $WD / DD / \%TF = 0.1 / 0.2 / 0.7$

▶ Correction of K Content in M&M (Yoshida 2019)  
**No observation for [Element] contents in TF  
%TF Calculation Hypotheses to further  
discuss**

- ▶ No observation for  $^{133}\text{Cs}$  contents in the TF

Cs

- ▶ Use of TF vs. LF  $^{137}\text{Cs}$  proportions after 1 needles lifespan ~ 5 y (year 2016 from Kato et al., In press)
  - ▶  $TF/LF = 0.4$  vs. ~ 0.3 for rCs (Yoschenko et al., 2018), ~ 0.5 for rCs (Goor & Thiry, 2004)
  - ▶ Implies stabilized ratio over time
- ▶ Application of DD/DD/%TF fractionation from Wu et al. (1996)
  - ▶ Implies Wu's et al. (1996) WD/DD/%TF fractionation is constant over time and Japan areas
  - ▶ Implies same K and  $^{133}\text{Cs}$  are in constant proportion in WD and DD



<sup>137</sup>Cs

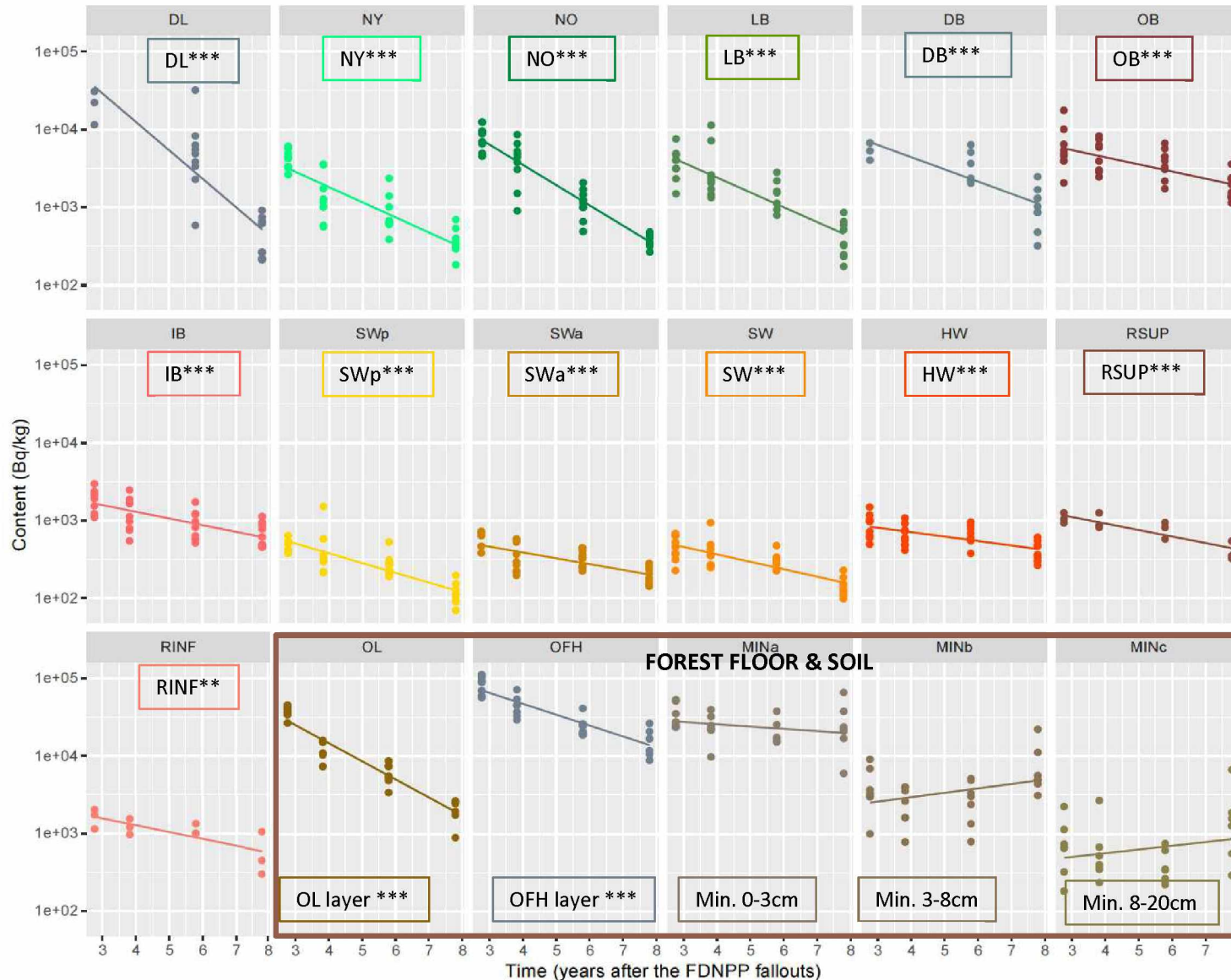
Slopes significance  
 \*\*\* p-value < 0.001  
 \*\* p-value < 0.01  
 \* p-value < 0.05

Fitting curves model  
 ▶ [Content] = a.EXP(b.t)

▶ ref date 2011/03/11  
 ▶ No radioactive decay taken into account

▶ Decrease of <sup>137</sup>Cs contents are all significant in biomass compartments

▶ Higher dispersion of values in CROWN compartments  
 ▶ The compartments the most exposed to fallouts



## [<sup>137</sup>Cs] Decreasing trends over the study period 2013-2018 / MC stand

<sup>137</sup>Cs

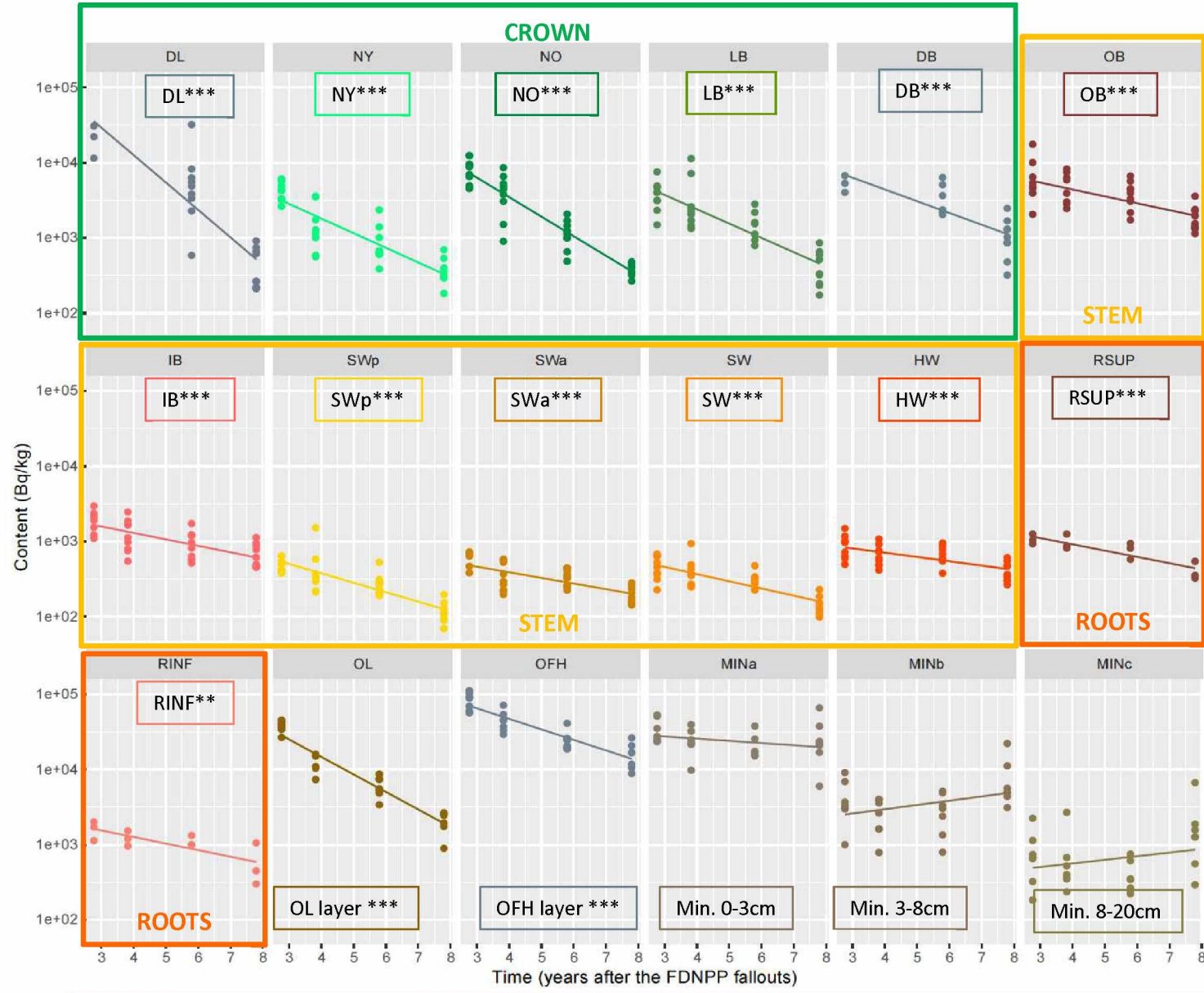
Slopes significance  
 \*\*\* p-value < 0.001  
 \*\* p-value < 0.01  
 \* p-value < 0.05

Fitting curves model  
 ▶ [Content] = a.EXP(b.t)  
 ▶ ref date 2011/03/11  
 ▶ No radioactive decay taken into account

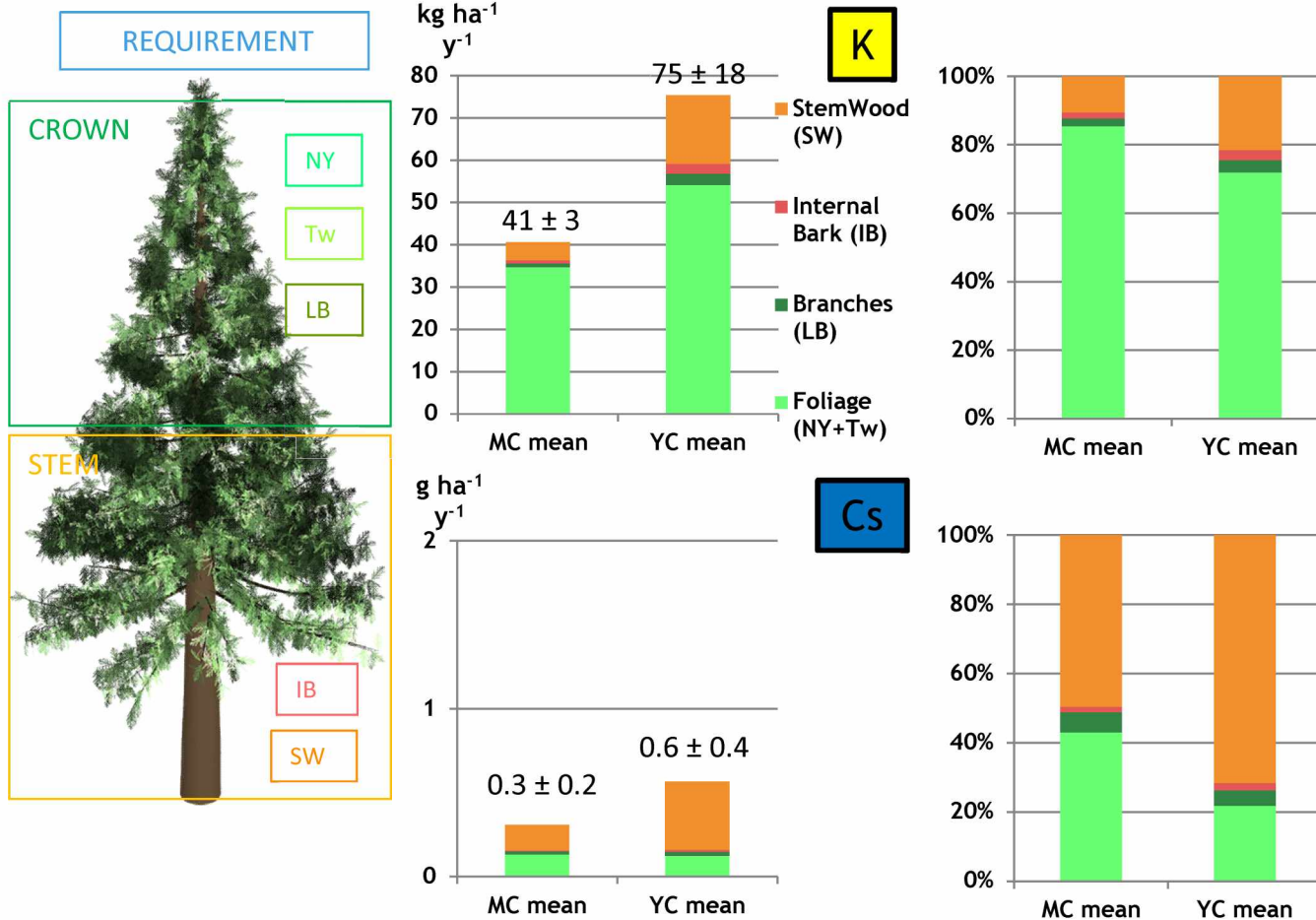
▶ CROWN DEPURATION  
 > STEM ≈ ROOTS

▶ RUT approach cannot be applied for <sup>137</sup>Cs

▶ Using stable analogs K & <sup>133</sup>Cs at equilibrium



## REQUIREMENT



▶ K vs. Stable Cs

▶ Distribution K ≠ Cs

▶ The FOLIAGE growth exhibits the HIGHEST K DEMAND

▶ REVERSE contributions for Cs FOLIAGE DEMAND

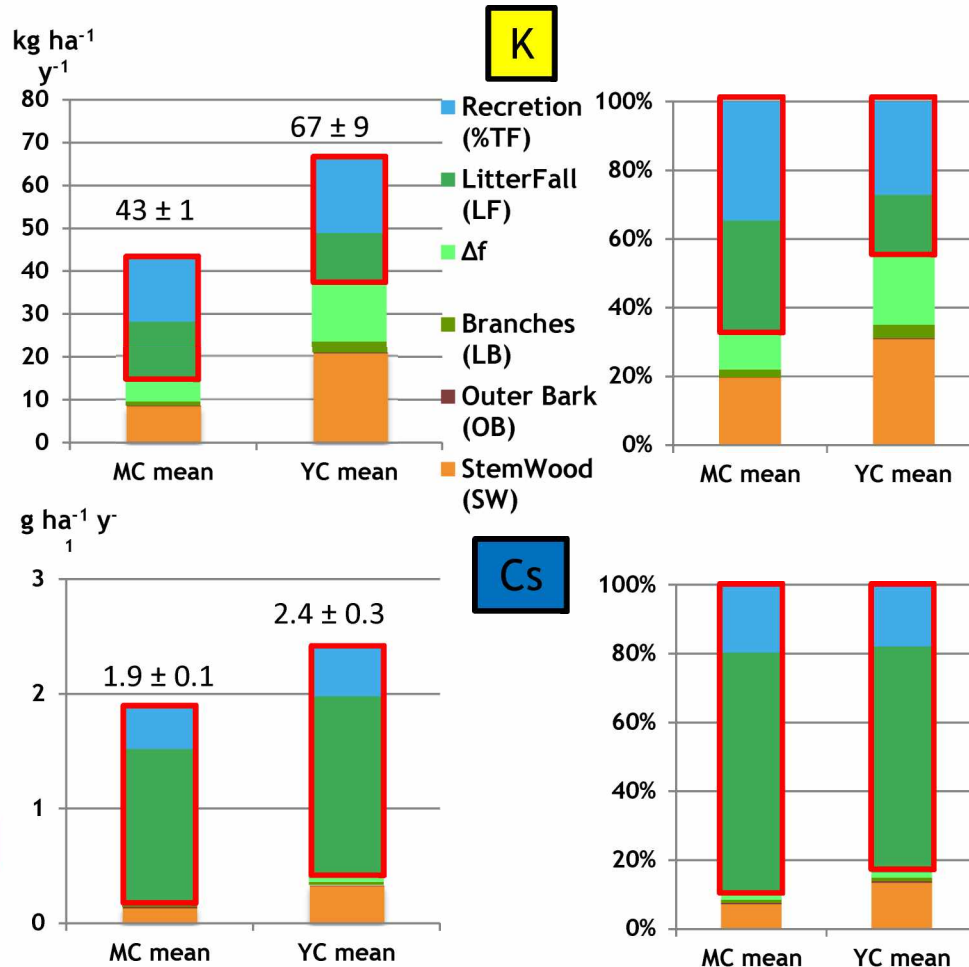
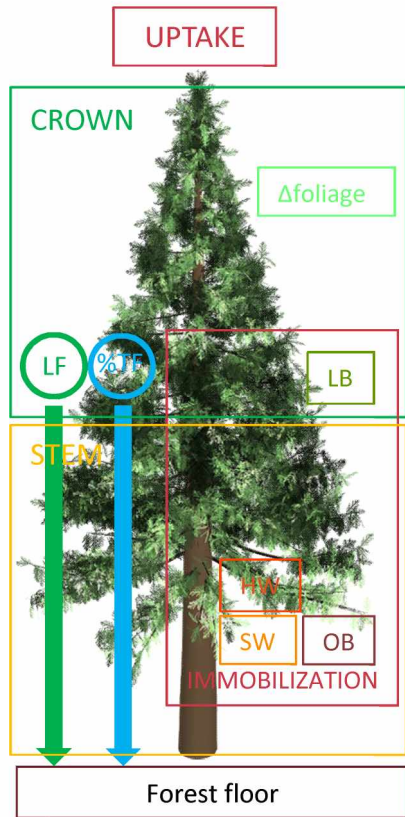
▶ MC vs. YC ▶ f(RGR)

▶ Global HIGHER DEMAND for YC vs MC

▶ HIGHER SW biomass GROWTH RATE YC vs MC



## ROOT UPTAKE



### ▶ K vs. Stable Cs

▶ Contributions of RETURNS to forest floor are HIGHER for Cs vs K

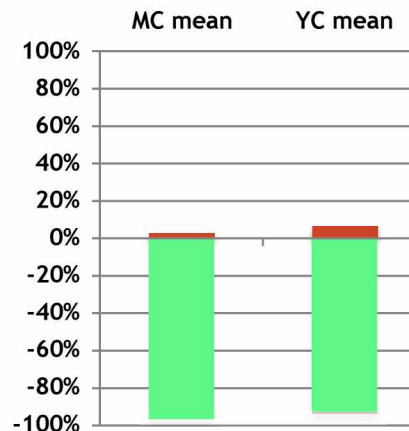
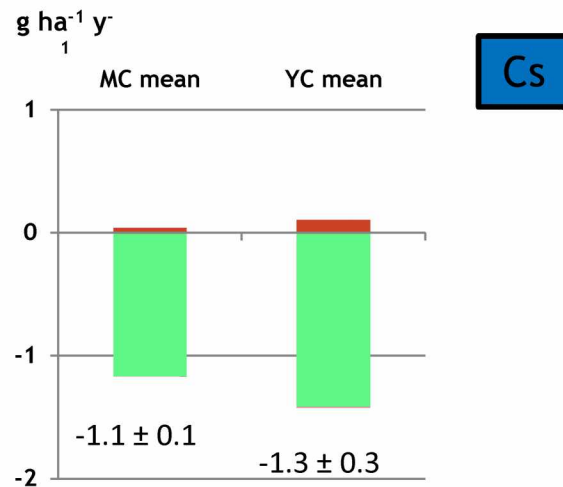
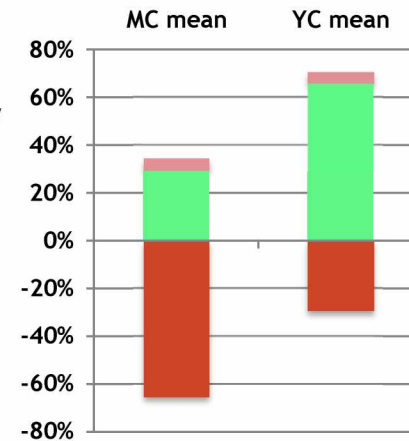
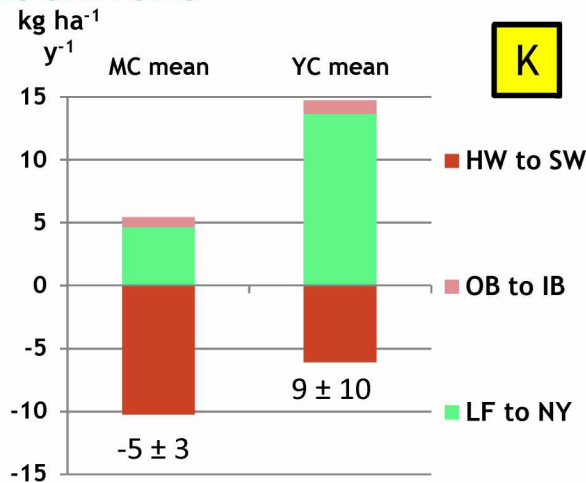
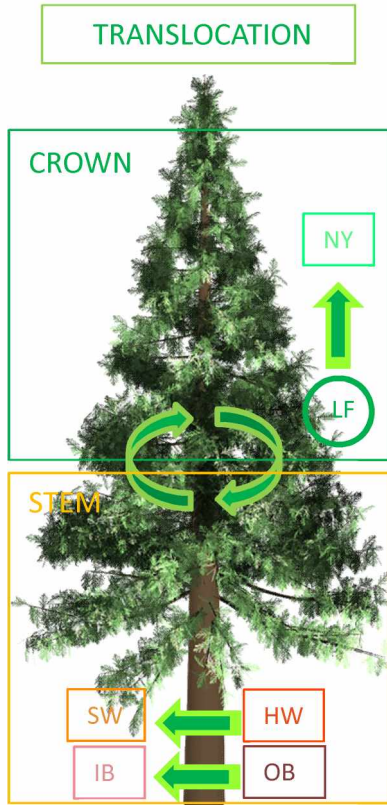
▶ HIGHER IMMOBILIZATION RATE in the perenial parts + foliage for K vs. Cs

▶ MC vs. YC ▶ f(RGR)

▶ SIMILAR fluxes of RETURNS to forest floor (LF, %TF) + SIMILAR CONTRIBUTIONS between stands MC & YC

▶ HIGHER UPTAKE YC vs. MC ▶ HIGHER SW biomass GROWTH RATE in the YC stand

## INTERNAL TRANSLOCATIONS



### ▶ K vs. Stable Cs

▶ REVERSE behaviour!

▶ HW to SW < 0 for K°

▶ Cs ▶ LF to NY

Translocation < 0 NOT in AGREEMENT with <sup>137</sup>Cs

Translocation seen in Scots pines after Chernobyl°

▶ Detoxification process suggested

▶ Iodine \*

▶ Chlorine \*\*

▶ Uranium \*\*\*

Ref.

° Momoshima & Bondietti (1994)

°° Goor & Thiry (2004)

\* Roulier et al. (2018)

\*\* Van den Hoof & Thiry (2012)

\*\*\* Thiry et al. (2005)

▶ MC vs. YC ▶ f(RGR)

▶ HIGHER NEEDLES TRANSLOCATION YC > MC

▶ FOLIAGE biomass GROWTH RATE YC > MC

## K & <sup>133</sup>Cs cycling fluxes

Balance between REQUIREMENT and RECYCLING FLUXES (U & Σ T)

		K kg ha <sup>-1</sup> y <sup>-1</sup>		Cs g ha <sup>-1</sup> y <sup>-1</sup>	
		MC	YC	MC	YC
REQUIREMENT	R	41 ± 3	75 ± 18	0.3 ± 0.2	0.6 ± 0.4
UPTAKE	U	43 ± 1	67 ± 9	1.9 ± 0.1	2.4 ± 0.3
TRANSLOCATION	Σ T	-5 ± 3	9 ± 10	-1.1 ± 0.1	-1.3 ± 0.1
RECYCLING Fluxes	U + Σ T	38 ± 3	76 ± 18	0.8 ± 0.2	1.1 ± 0.4
BALANCE	(U + Σ T)/R	0.95 ± 0.1	1.01 ± 0.1	3.0 ± 1.1	2.3 ± 0.8

▶ K cycle is balanced (U + Σ T)/R ~ 1

- ▶ Common situation for conifers \*
- ▶ A major nutrient reference cycle
- ▶ MC & YC ▶ U > T ▶ vs. T > U for K in Spruce, Scots pines\*
- ▶ Translocation to HW (T<sub>K</sub> flux < 0)
- ▶ *C. japonica* species effect?

▶ Cs cycle is unbalanced (U + Σ T)/R ~ 2-3

- ▶ <sup>133</sup>Cs cycle is imbalanced due to excess of Returns to forest floor and translocation
- ▶ Factor 2 observed for Beech with same flux distributions \*\*
- ▶ Specific recycling for Non Essential Elements?

Ref.

\* Cole & Rapp (1981), Dambrine et al. (1995), Goor & Thiry (2004)

\*\* M. Roulier (2018) PhD manuscript, unpub. Results

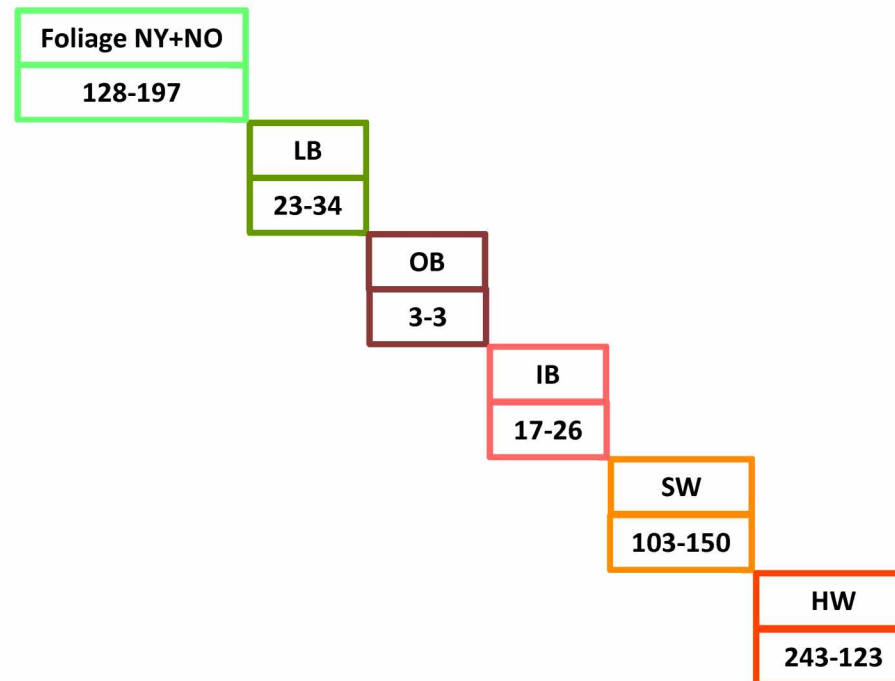


# Fluxes within stands

## K transfer rates



▶ Tree is described according to an Interaction Matrix

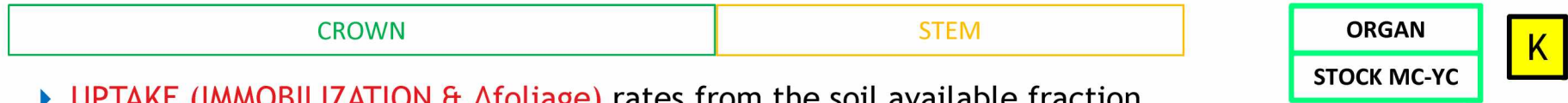


$$\text{FLUX (kg ha}^{-1} \text{ y}^{-1}) / \text{STOCK (kg ha}^{-1}) = \text{ANNUAL TRANSFER RATE (y}^{-1})$$

# Fluxes within stands

## K transfer rates

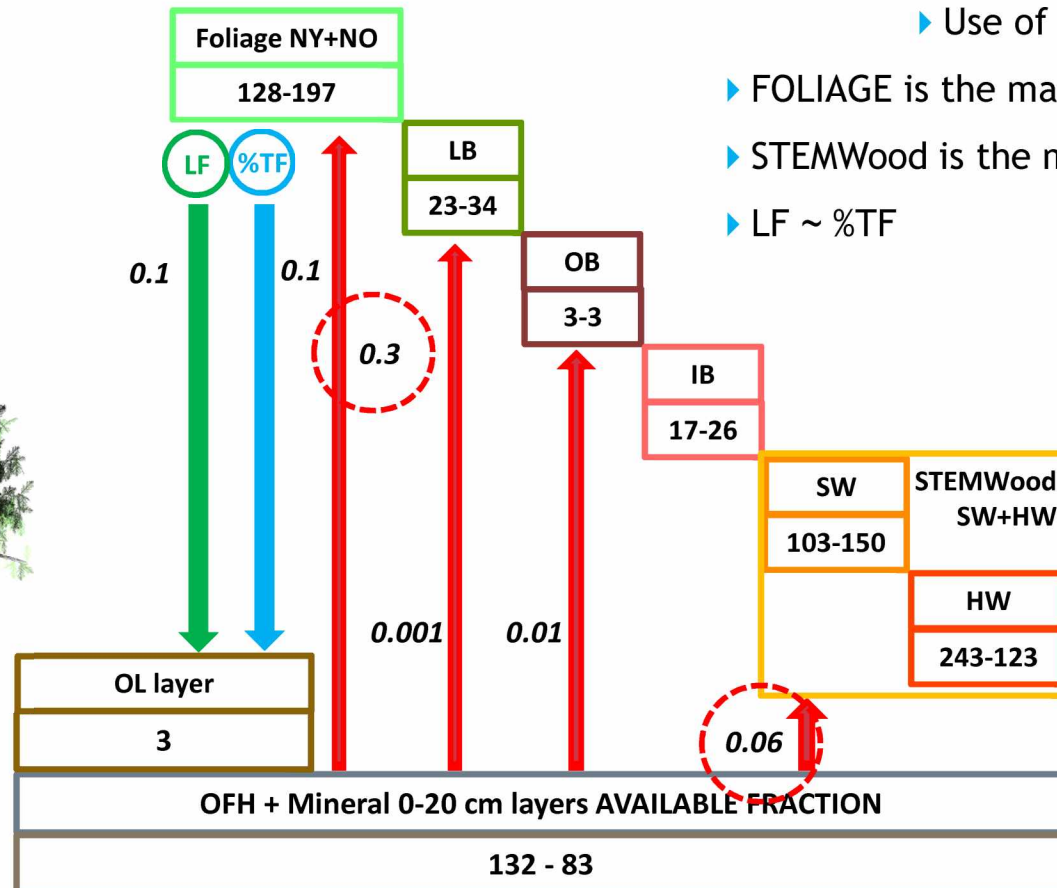
$$\text{FLUX (kg ha}^{-1} \text{ y}^{-1}) / \text{STOCK (kg ha}^{-1}) = \text{ANNUAL TRANSFER RATE (y}^{-1})$$



- ▶ UPTAKE (IMMOBILIZATION &  $\Delta$ foliage) rates from the soil available fraction
- ▶ COOCH<sub>3</sub>NH<sub>4</sub> extraction (exchangeable pool)
- ▶ 2-12 % soil K budget

→ Root UPTAKE

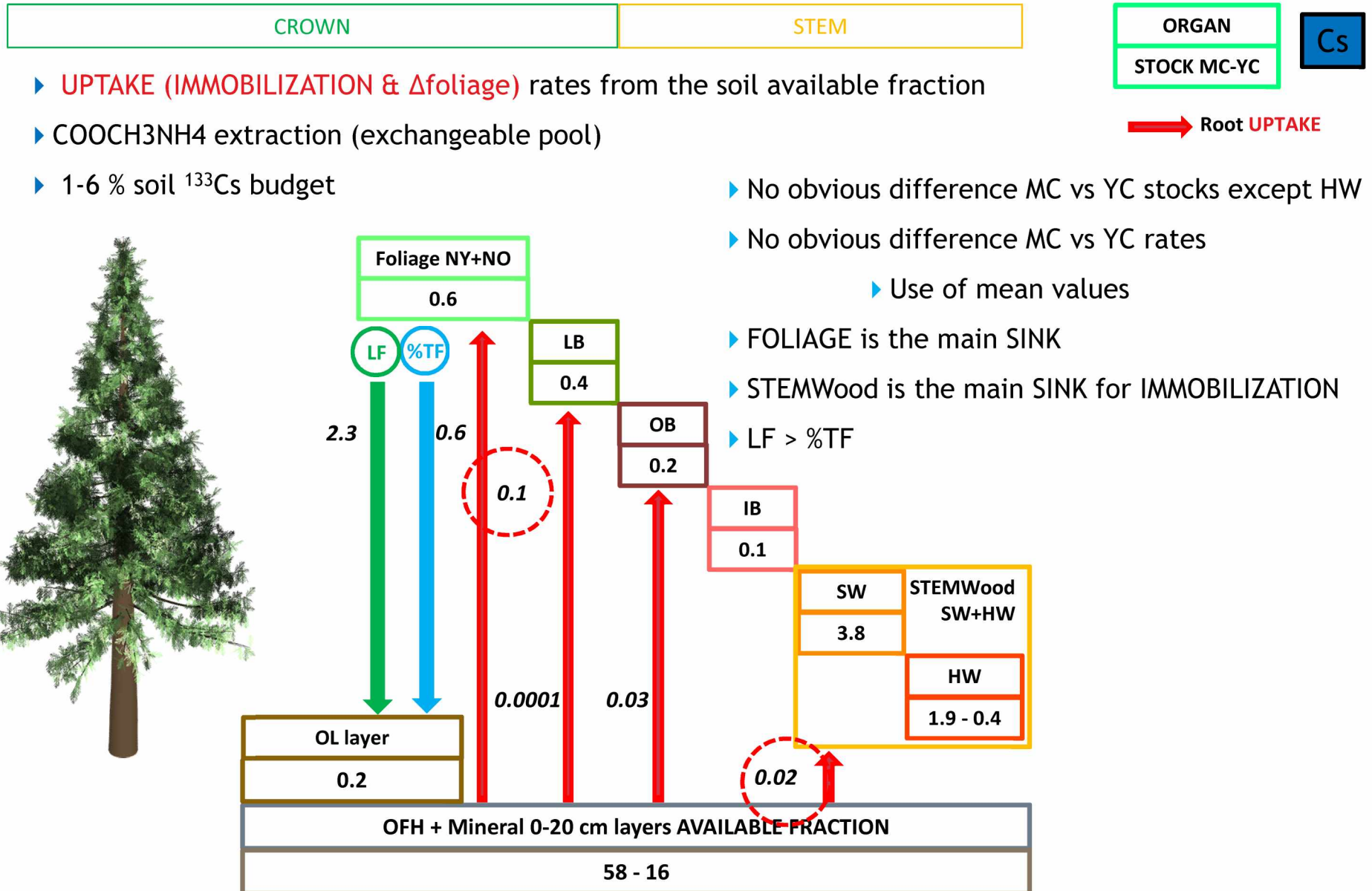
- ▶ No obvious difference MC vs YC rates
- ▶ Use of mean values
- ▶ FOLIAGE is the main SINK
- ▶ STEMWood is the main SINK for IMMOBILIZATION
- ▶ LF ~ %TF



# Fluxes within stands

## Cs transfer rates

$$\text{FLUX (g ha}^{-1} \text{ y}^{-1}) / \text{STOCK (g ha}^{-1}) = \text{ANNUAL TRANSFER RATE (y}^{-1})$$

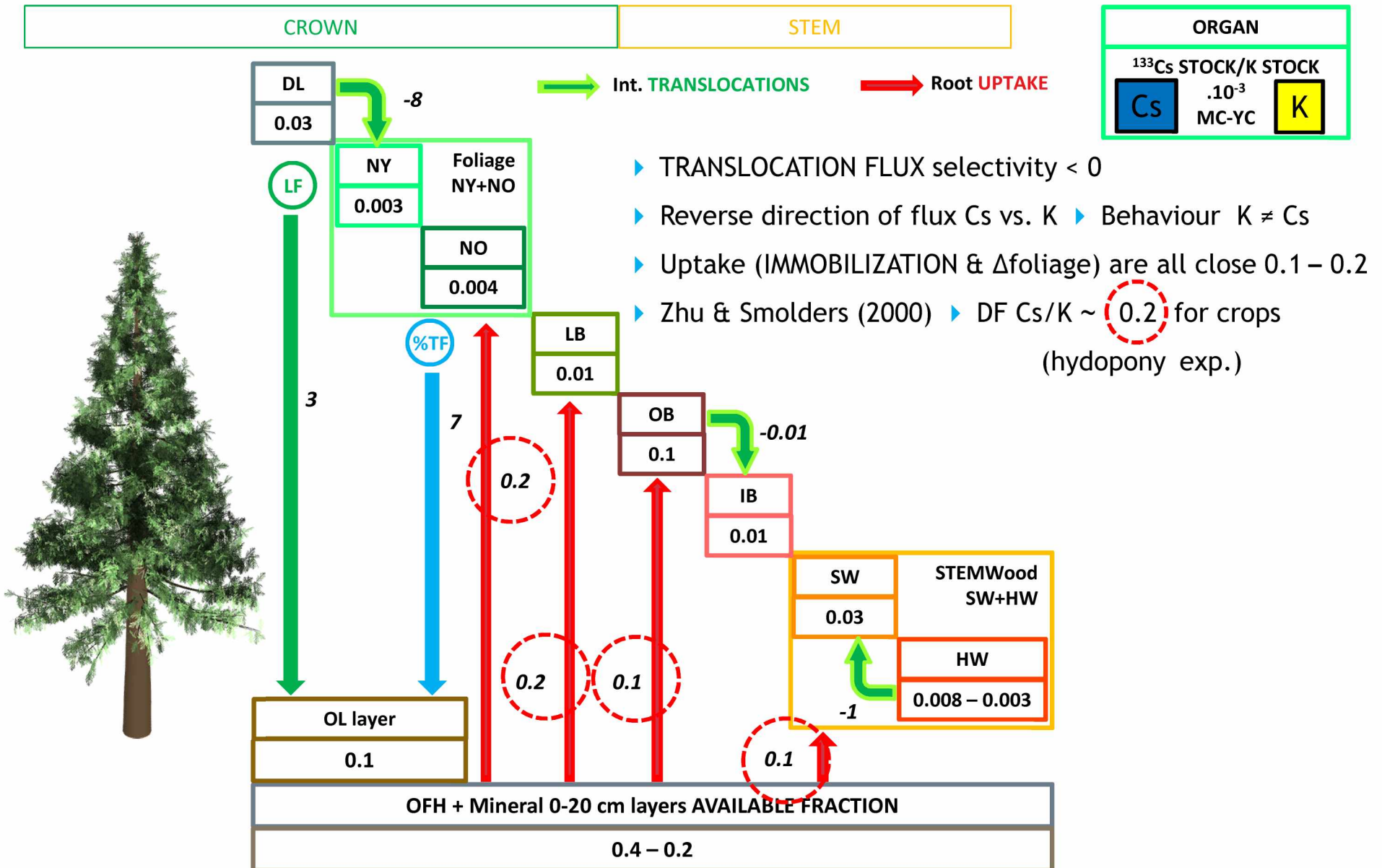




# Fluxes within stands

## Cs selectivity vs. K

$$^{133}\text{Cs rate (y}^{-1}) / \text{K rate (y}^{-1}) = ^{133}\text{Cs SELECTIVITY vs. K (dimensionless)}$$



### Behaviour of stable analogs K & $^{133}\text{Cs}$

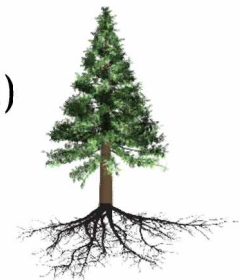
- ▶  $^{133}\text{Cs}$  and K exhibit different dynamics
- ▶ K is at equilibrium  $U + \sum T = R$
- ▶  $^{133}\text{Cs}$  is recycled in excess  $U + \sum T = 2 R$
- ▶ Detoxification process for a non essential element?

### Is the $^{133}\text{Cs}$ a good surrogate for assessing the rCs root uptake?

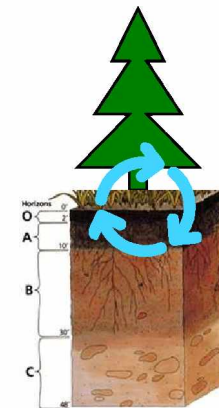
- ▶  $^{133}\text{Cs}$  selectivity coefficients vs. K
- ▶ Feeding of  $^{137}\text{Cs}$  transfers process-based modeling parameterization relying on K BGC fluxes
- ▶ Assessment through model run
- ▶ Hypothesis on  $^{133}\text{Cs}$  Canopy leaching
- ▶ Selectivity is uncertain (SD ranges 60-80% value)
- ▶ Observations datasets of paired stable analogs needs

### Remaining questions & prospects

- ▶ Monitoring of  $^{137}\text{Cs}$  still required...  
... in parallel with K and  $^{133}\text{Cs}$  observations  
... for comparing modeling outputs with observations  $f(t)$
- ▶ Roots ~10-25% rCs inventory in biomass (2013-2018) ▶ Neglectible?
  - ▶ What about tranlocations TO and FROM roots?



Thanks for your attention



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