IRSN
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE
Enhancing nuclear safety

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

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AMORAD project

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INVESTISSEMENTS D'AVENIR
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Context / Issues / Objectives

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

- Territories contaminated by atmospheric fallouts (Chernobyl, FDNPP accidents)

- ^{137}Cs half-life ~ 30 y X Forests High interception efficiency = persistence of products contamination
- Operationnal modeling needs for adressing 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}Cs inventories

- FDNPP accident case ▸ equilibrium not reached ▸ How assessing the ^{137}Cs root uptake?
  - Similar behaviour of rCs stable analogs K & ^{133}Cs (e.g. Yoshida et al., 2004 ; Sombré et al., 1994)
  - Competition of K vs. Cs (cf. Zhu & Smolders, 2000)
  - Scarce ^{133}Cs contents data sets

- OBJECTIVE
  - Assessing the Root Uptake of both K & stable Cs
  - Defining ^{133}Cs discrimination factors for a process-based modeling relying on K biogeochemical fluxes

QUANTIFICATION OF THE BIOGEOCHEMICAL RECYCLING

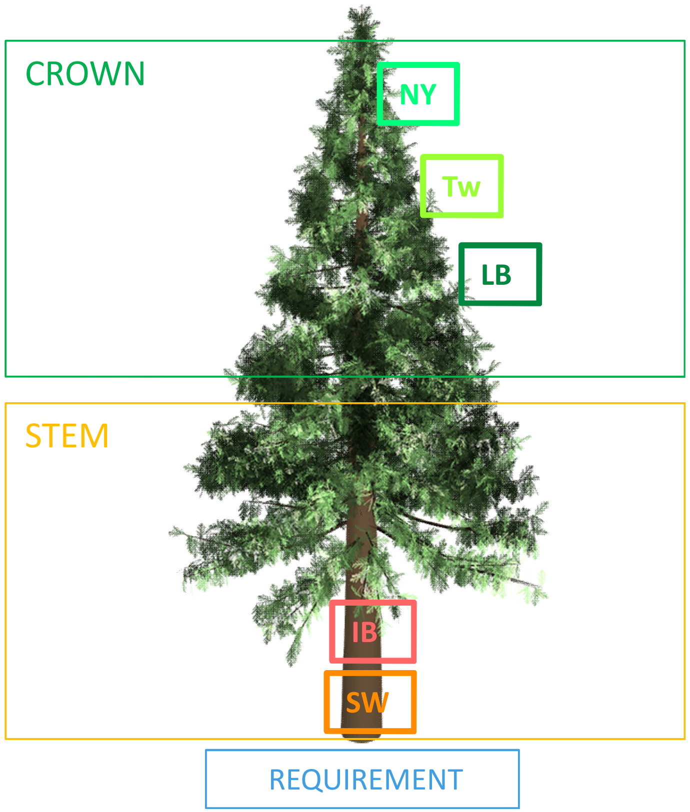
- Approach developed for ^{137}Cs by Goor & Thiry (2004) / derived from Cole & Rapp (1981)

- 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



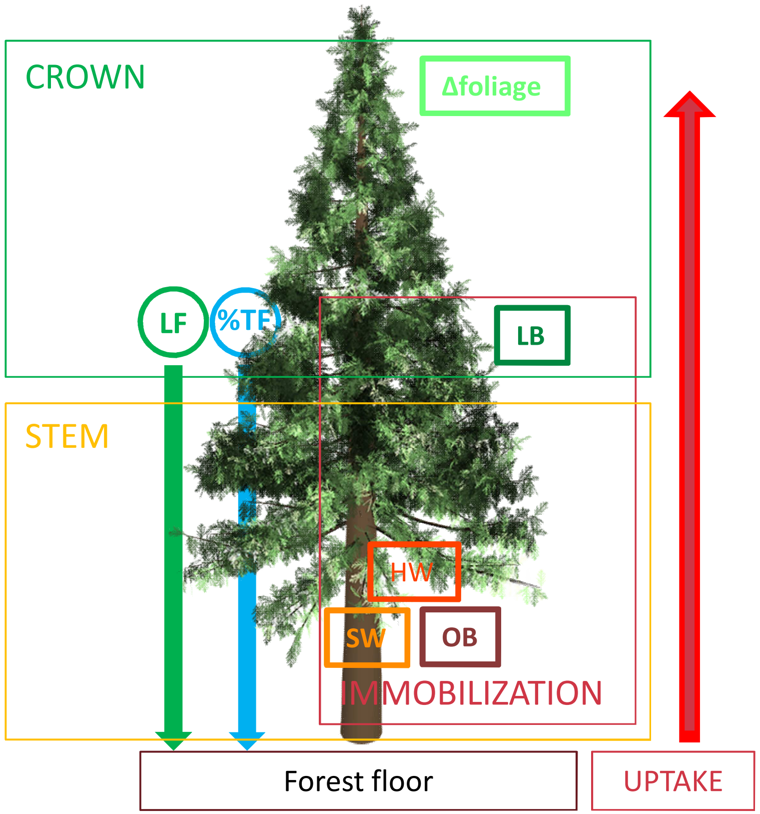
ROOT UPTAKE

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

UPTAKE = IMMOBILIZATION + RETURNS + 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

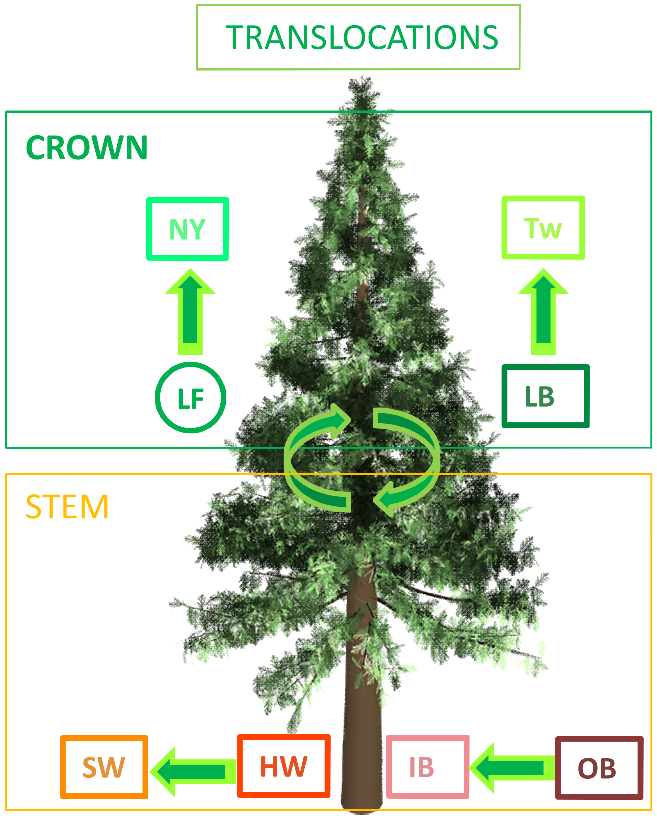
INTERNAL TRANSLOCATIONS

- Internal TRANSLOCATIONS (ΣT) ▸ Remobilization of elements from senescing to corresponding current biomass production

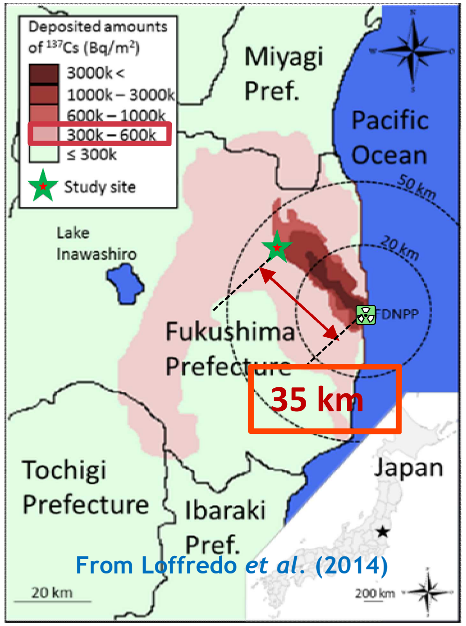
SOURCE – SINK relationship

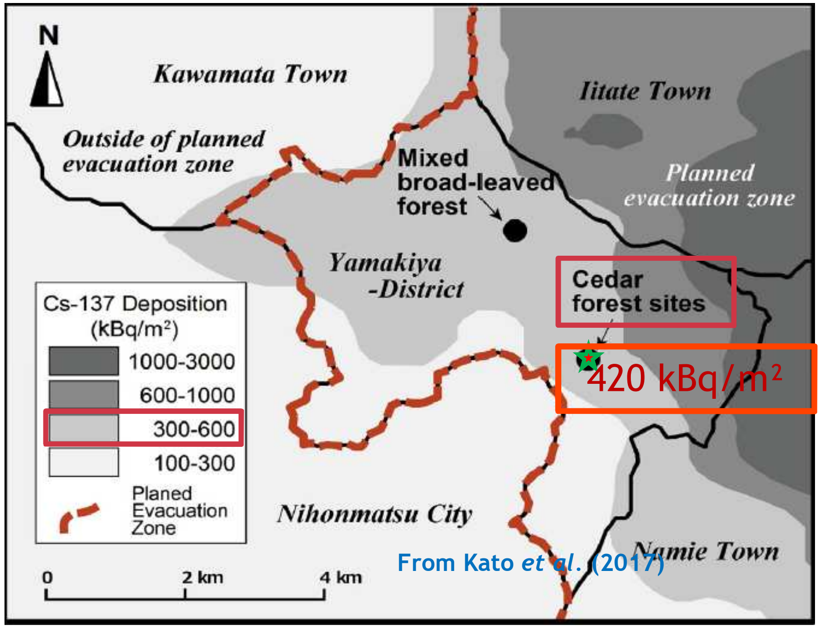
TRANSLOCATION = Biomass (SENESCING organ) x ([Element CURRENT PROD° organ] – [Element SENESCING organ])

FOLIAGE	▸ LitterFall	LF	to	NY	Current Needles
BRANCHES	▸ Living Branches	LB	to	Tw	Twigs
BARK	▸ Outer Bark	OB	to	IB	Inner Bark
WOOD	▸ HeartWood	HW	to	SW	SapWood



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

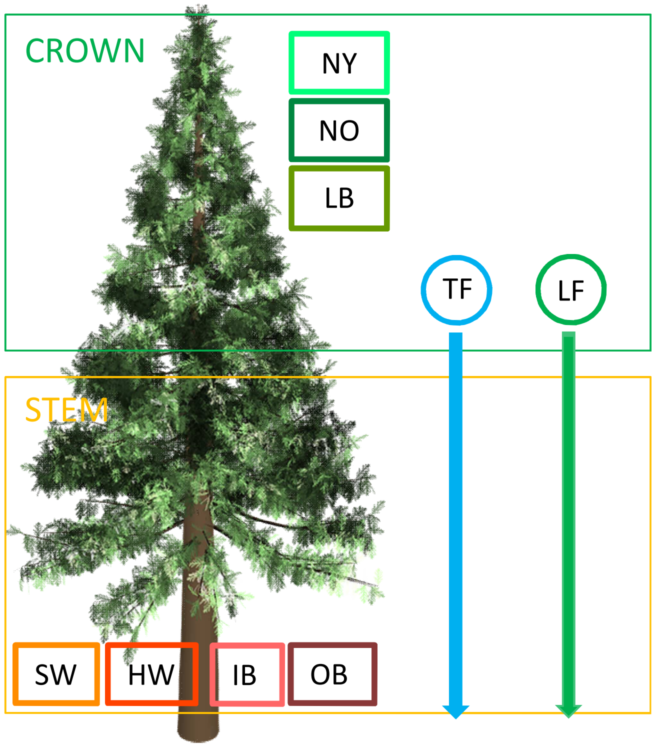
Stand	MC 2013-2018	YC 2013-2018
Stand age (years)	33 - 38	17 - 22
Stand density (stem ha^{-1})	800	2400
Plot area (m^2)	2900	2600
DBH (Average) (cm)	31.7 - 35.5	18.7 - 22.9
Stand density (stem ha^{-1})	800	2400
Height (Average) (m)	22 - 23	14 - 16
LAI (raw meas. 2013) (m^2 m^{-2})	4.2	10.3

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

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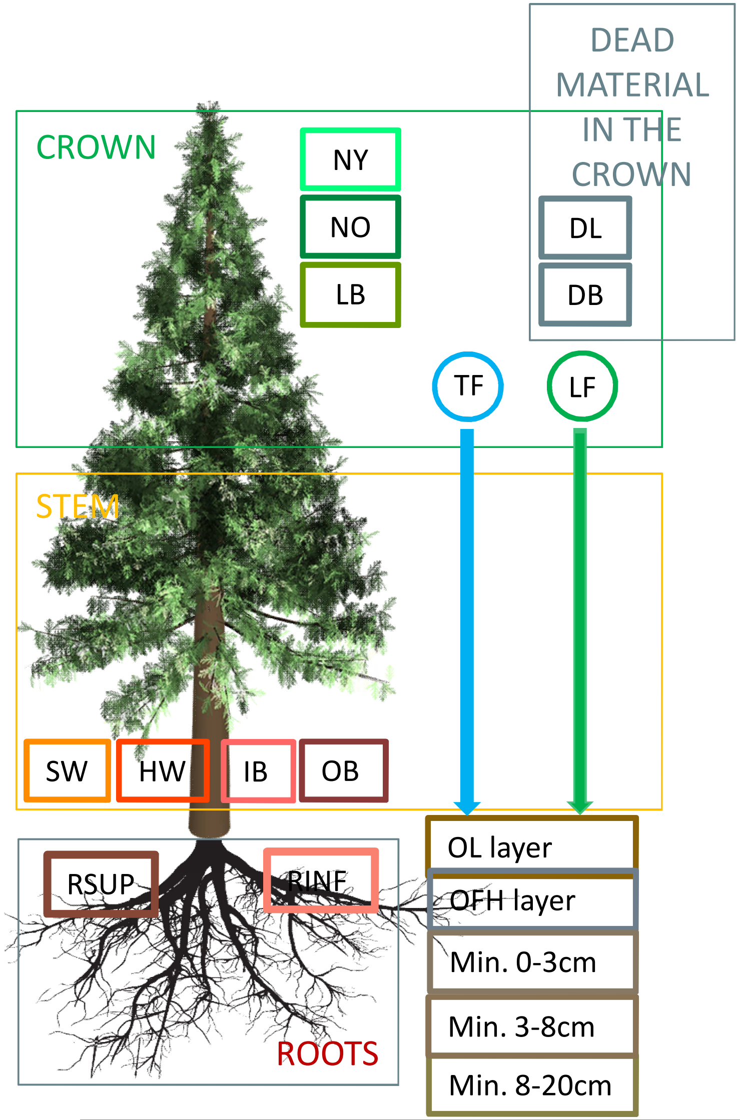
Sampling

▸ **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
- DL ▸ Dead Needle
- LB ▸ Living Branches
- DB ▸ Dead Branche
- OB ▸ Outer Bark
- IB ▸ Inner Bark
- SW ▸ SapWood
- HW ▸ HeartWood
- RSUP ▸ Coarse roots ø >2mm
- RINF ▸ Fine Roots ø < 2mm

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 ▸ regresssion 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 from reported values in Yoshida & Hijii (2006)
  - Regular turnover equation NY = LFNeedles - Δfoliage
  - 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 (± 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

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Derived values for Canopy Leaching %TF

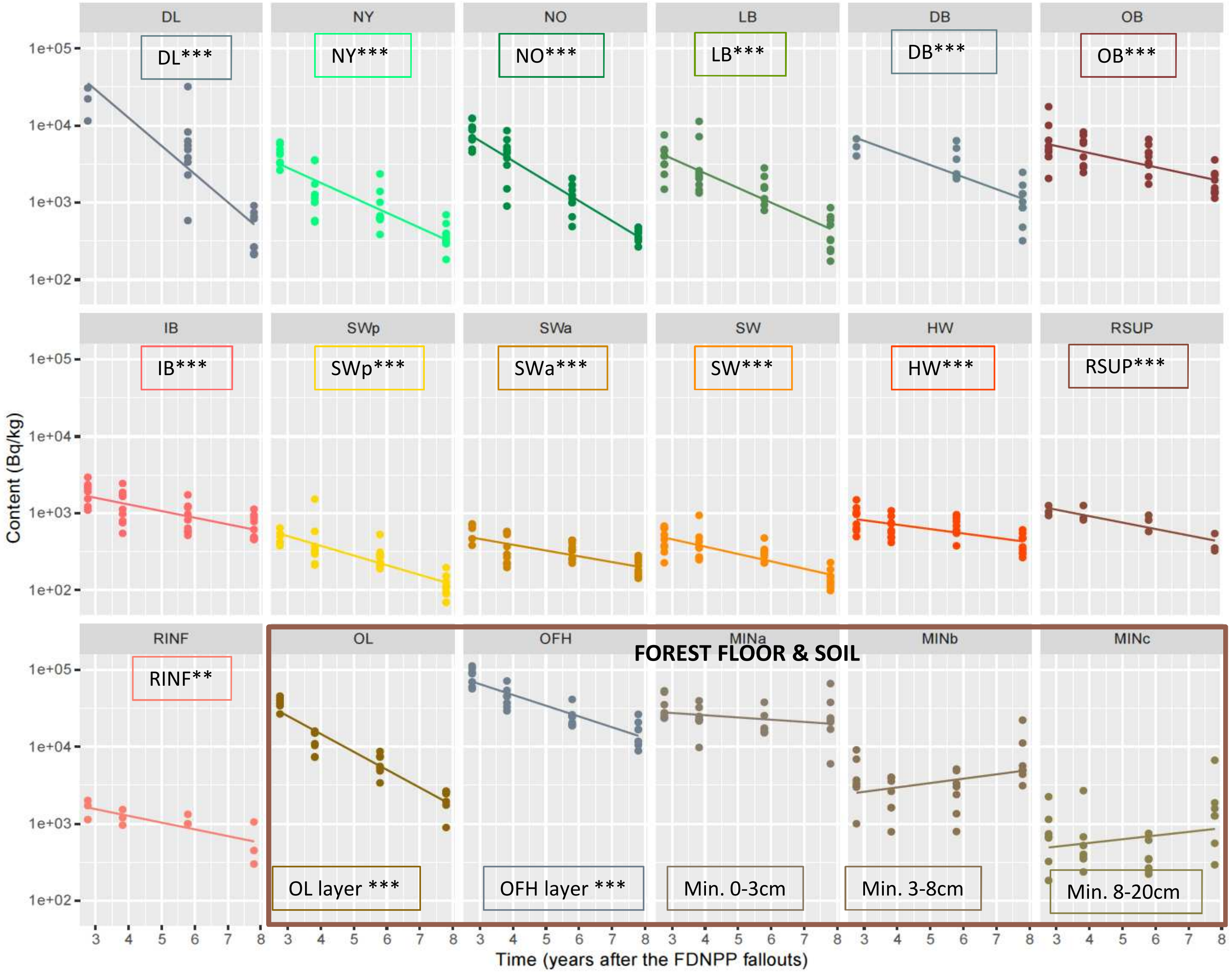
- No observation for K contents in the TF **K**
- TF+SF from Ohrui & Mitchell (1996) with SF contribution corrected from Sase et al. (2008)
- Wet & Dry Deposit vs. %TF contribution from Wu et al. (1996) (same watershed & period as O.&M. (1996)
  - WD / DD / %TF = 0.1 / 0.2 / 0.7
- Correction vs. K contents in WO & YO foliage

No observation for [Element] contents in TF
%TF Calculation Hypotheses to further discuss

- No observation for ^{133}Cs contents in the TF **Cs**
- Use of TF vs. LF ^{137}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/WD/%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}Cs are in constant proportion in WD and DD

^{137}Cs contents & dynamics

[^{137}Cs] Decreasing trends over the study period 2013-2018 / MC stand



^{137}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 ^{137}Cs contents are all significant in biomass compartments

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

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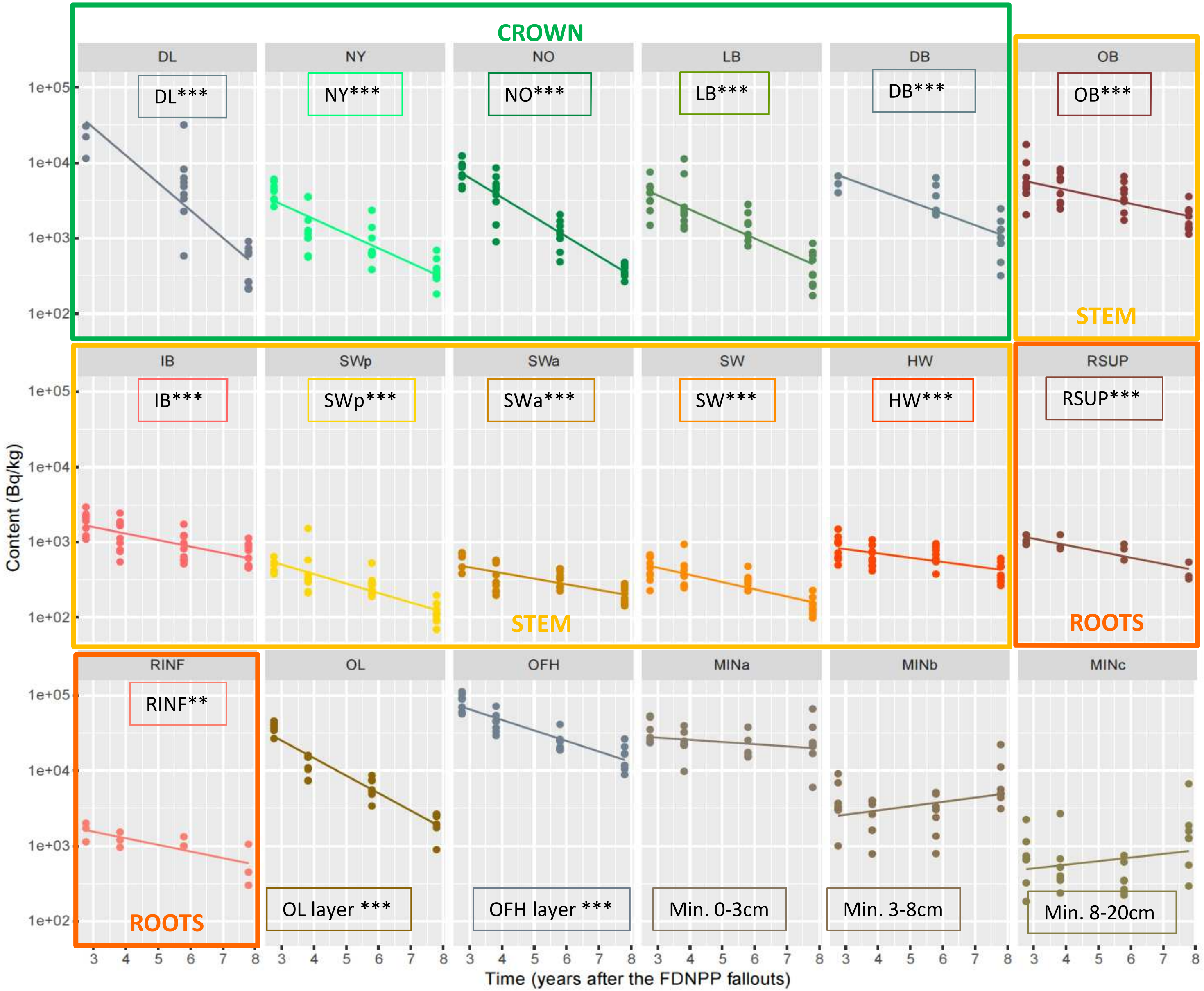
[^{137}Cs] Decreasing trends over the study period 2013-2018 / MC stand



^{137}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 ^{137}Cs
- Using stable analogs K & ^{133}Cs at equilibrium

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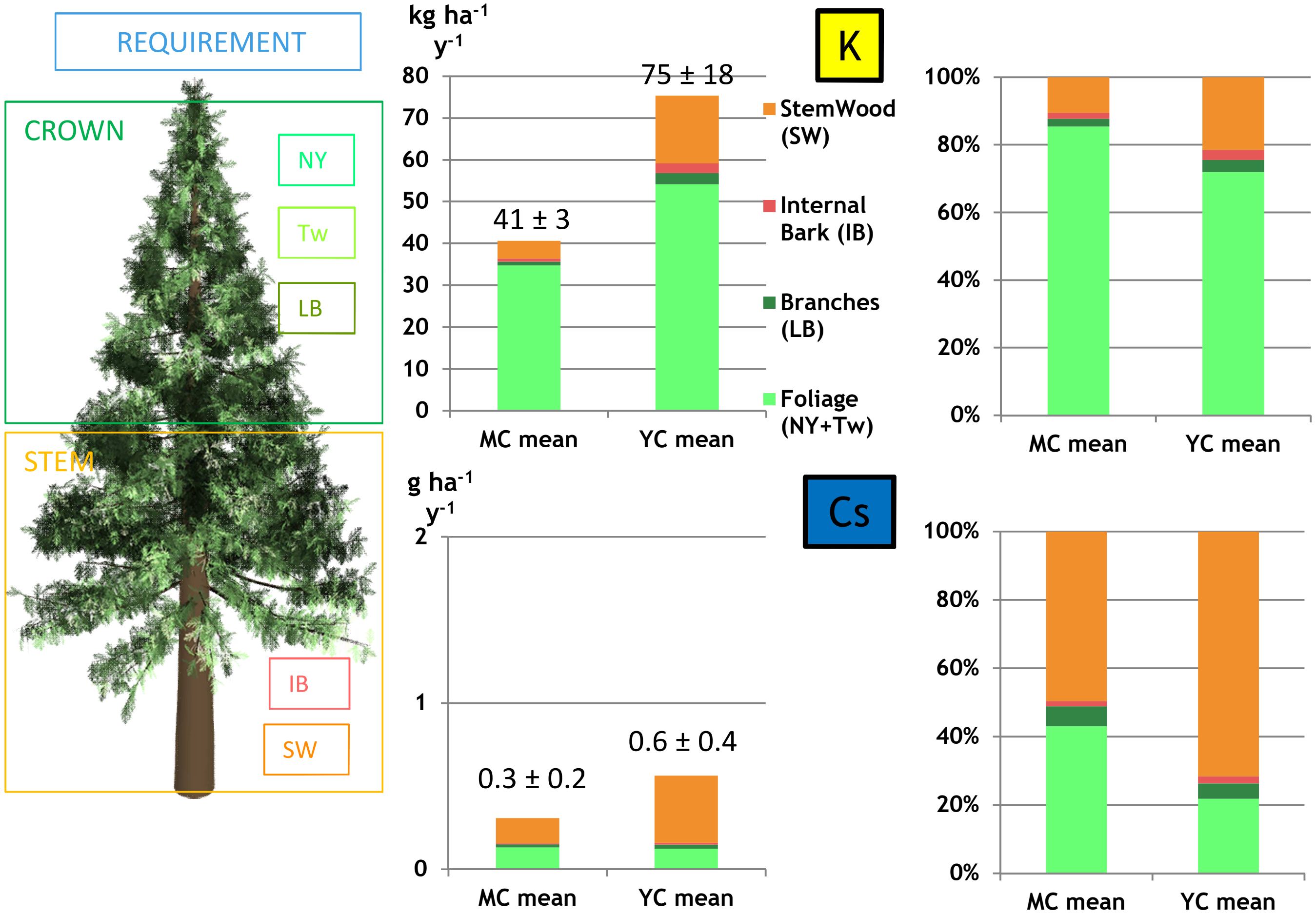
REQUIREMENT

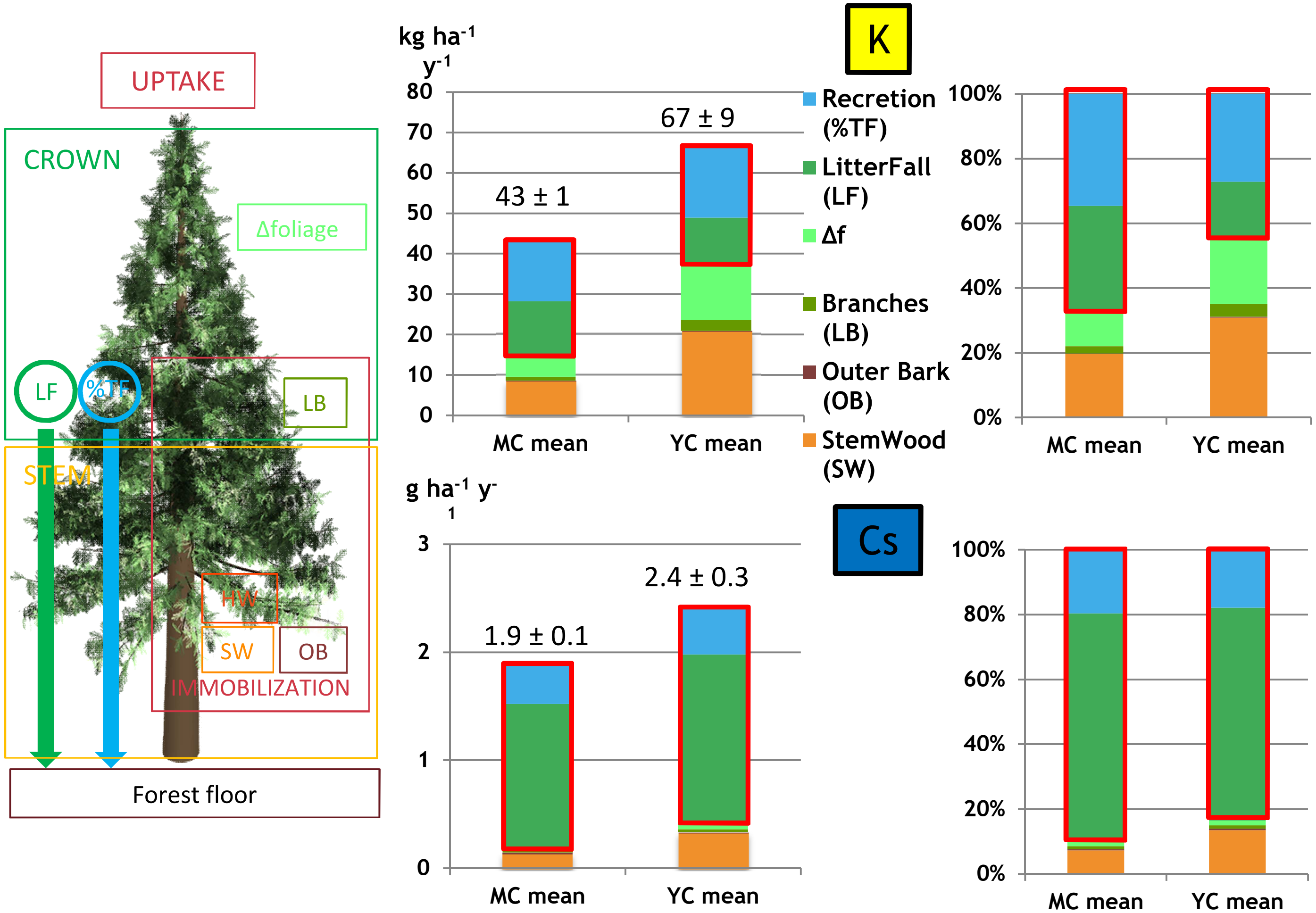


- **K vs. Stable Cs**
- Distribution K ≠ Cs
- The FOLIAGE growth exhibits the HIGHEST K DEMAND
- REVERSE contributions for Cs FOLIAGE DEMAND

- **MC vs. YC** ▸ f(RGR)
- Global HIGHER DEMAND for **YC** vs MC
- HIGHER SW biomass GROWTH RATE **YC** vs MC

K & ^{133}Cs cycling fluxes

ROOT UPTAKE

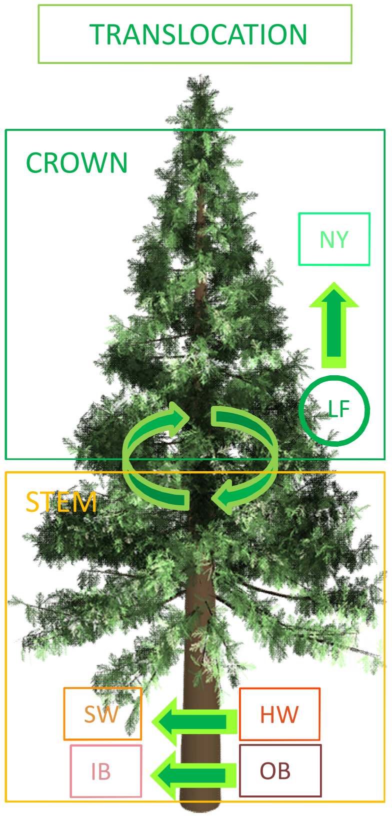


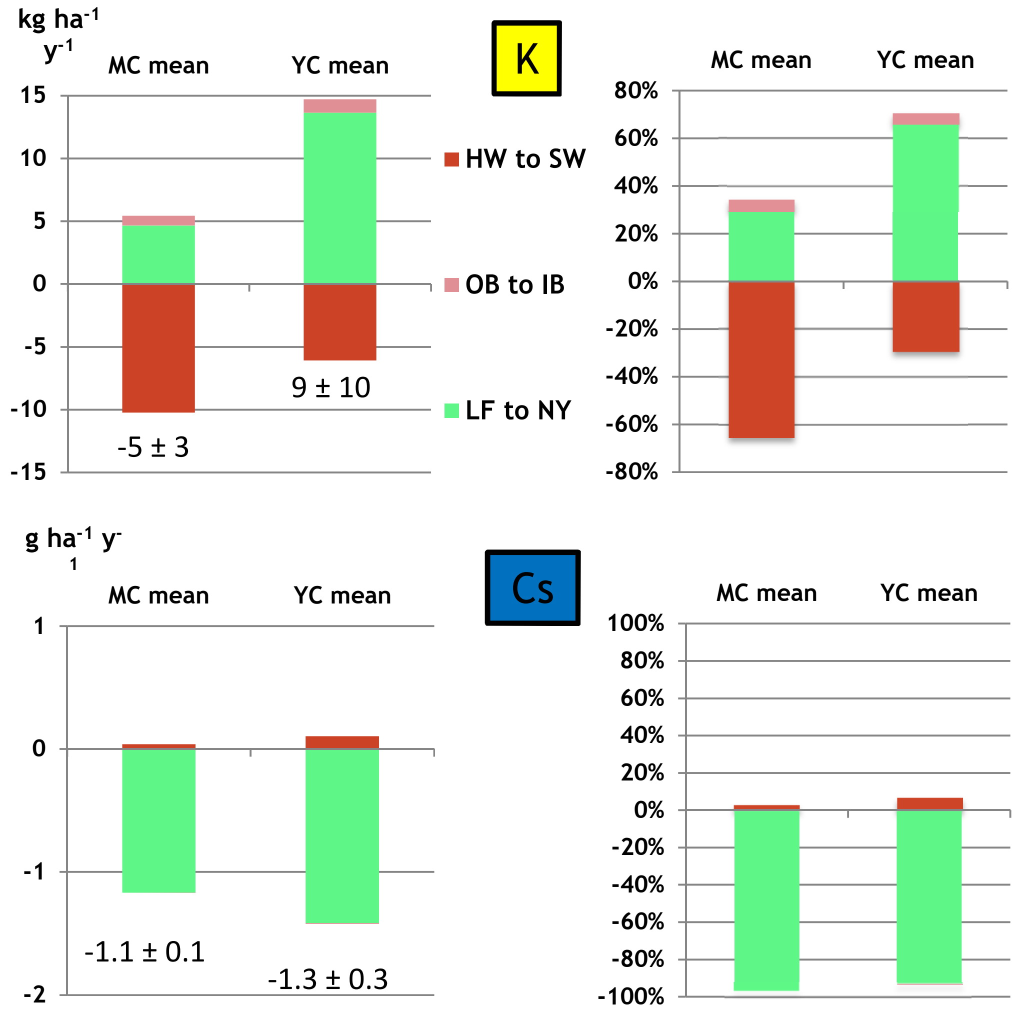
- **K vs. Stable Cs**
- Contributions of RETURNS to forest floor are HIGHER for **Cs** vs K
- HIGHER IMMOBILIZATION RATE in the perenial parts + foliage for **K** vs. Cs

- **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

K & ^{133}Cs cycling fluxes

INTERNAL TRANSLOCATIONS





- **K vs. Stable Cs**
- REVERSE behaviour!
- HW to SW < 0 for K°

- Cs ▸ LF to NY

Translocation < 0 NOT in AGREEMENT with ^{137}Cs

Translocation seen in Scots pines after Chernobyl°°

- Detoxification process suggested
  - Iodine *
  - Chlorine **
  - Uranium ***

- **MC vs. YC** ▸ f(RGR)
- HIGHER NEEDLES TRANSLOCATION **YC > MC**
- FOLIAGE biomass GROWTH RATE **YC >MC**

Ref.
° Momoshima & Bondietti (1994)
°° Goor & Thiry (2004)
* Roulier et al. (2018)
** Van den Hoof & Thiry (2012)
*** Thiry et al. (2005)

K & ^{133}Cs cycling fluxes

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

		K kg ha^{-1} y^{-1}				Cs g ha^{-1} y^{-1}			
		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_K flux < 0)
  - *C. japonica* species effect?

- Cs cycle is unbalanced (U + Σ T)/R ~ 2-3
  - ^{133}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

K transfer rates

CROWN | STEM

ORGAN / STOCK MC-YC | K

- Tree is described according to an Interaction Matrix

Organ	Stock MC-YC
Foliage NY+NO	128-197
LB	23-34
OB	3-3
IB	17-26
SW	103-150
HW	243-123

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

Fluxes within stands

K transfer rates

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

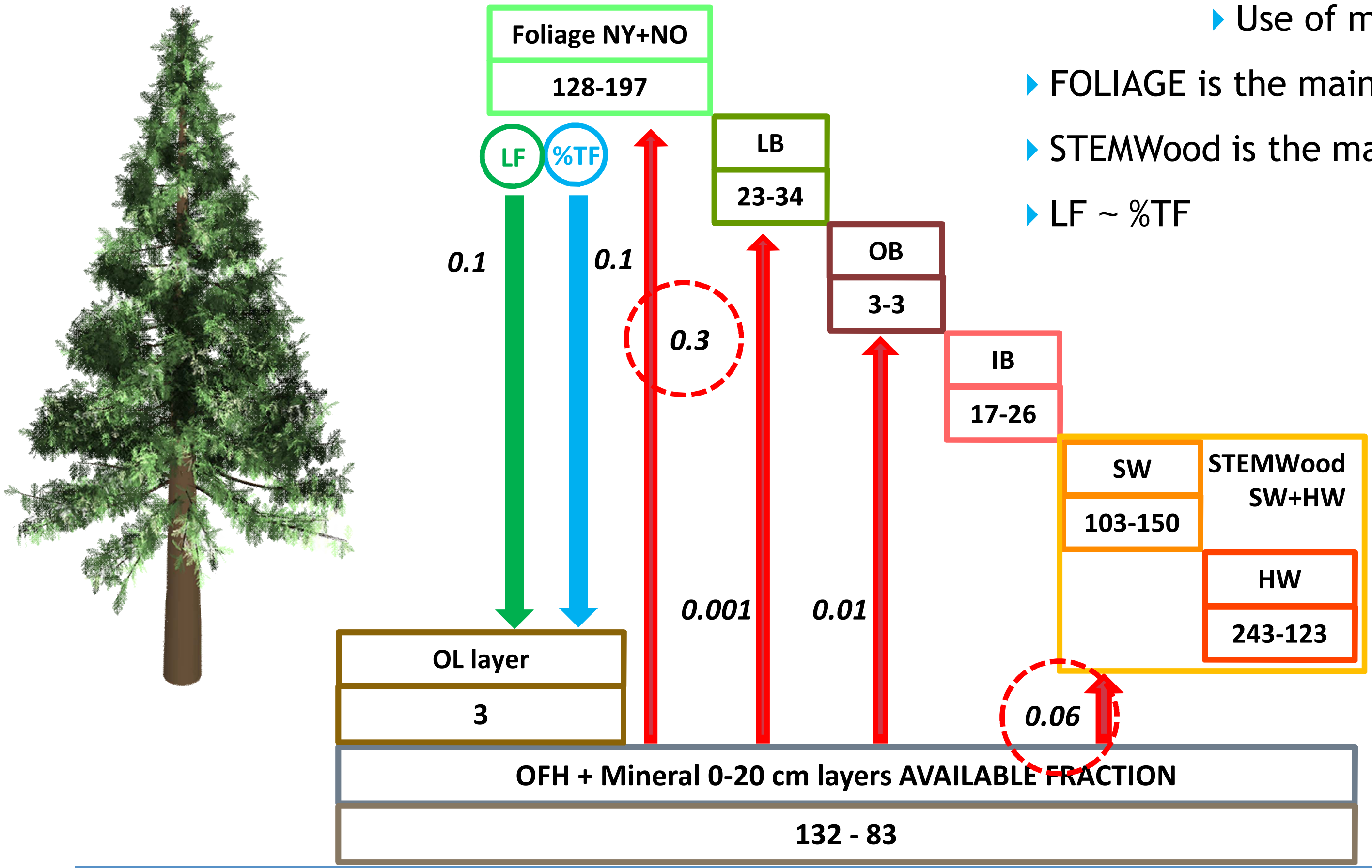
CROWN	STEM

ORGAN	K
STOCK MC-YC	

Root UPTAKE

- UPTAKE (IMMOBILIZATION & Δfoliage) rates from the soil available fraction
- COOCH3NH4 extraction (exchangeable pool)
- 2-12 % soil K budget

- 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



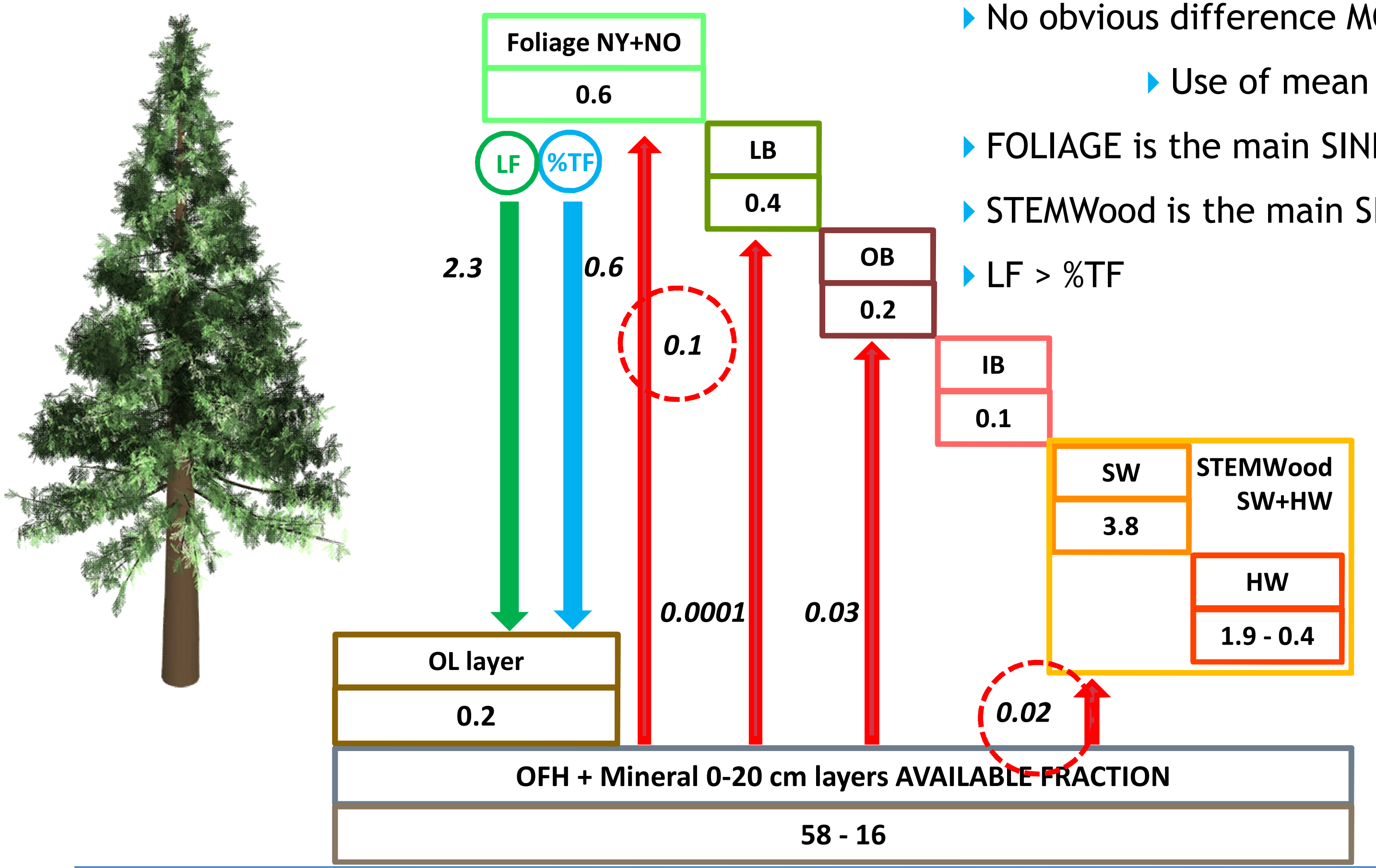
Cs transfer rates

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

CROWN | STEM

- UPTAKE (IMMOBILIZATION & Δfoliage) rates from the soil available fraction
- COOCH3NH4 extraction (exchangeable pool)
- 1-6 % soil ^{133}Cs budget

- No obvious difference MC vs YC stocks except HW
- 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



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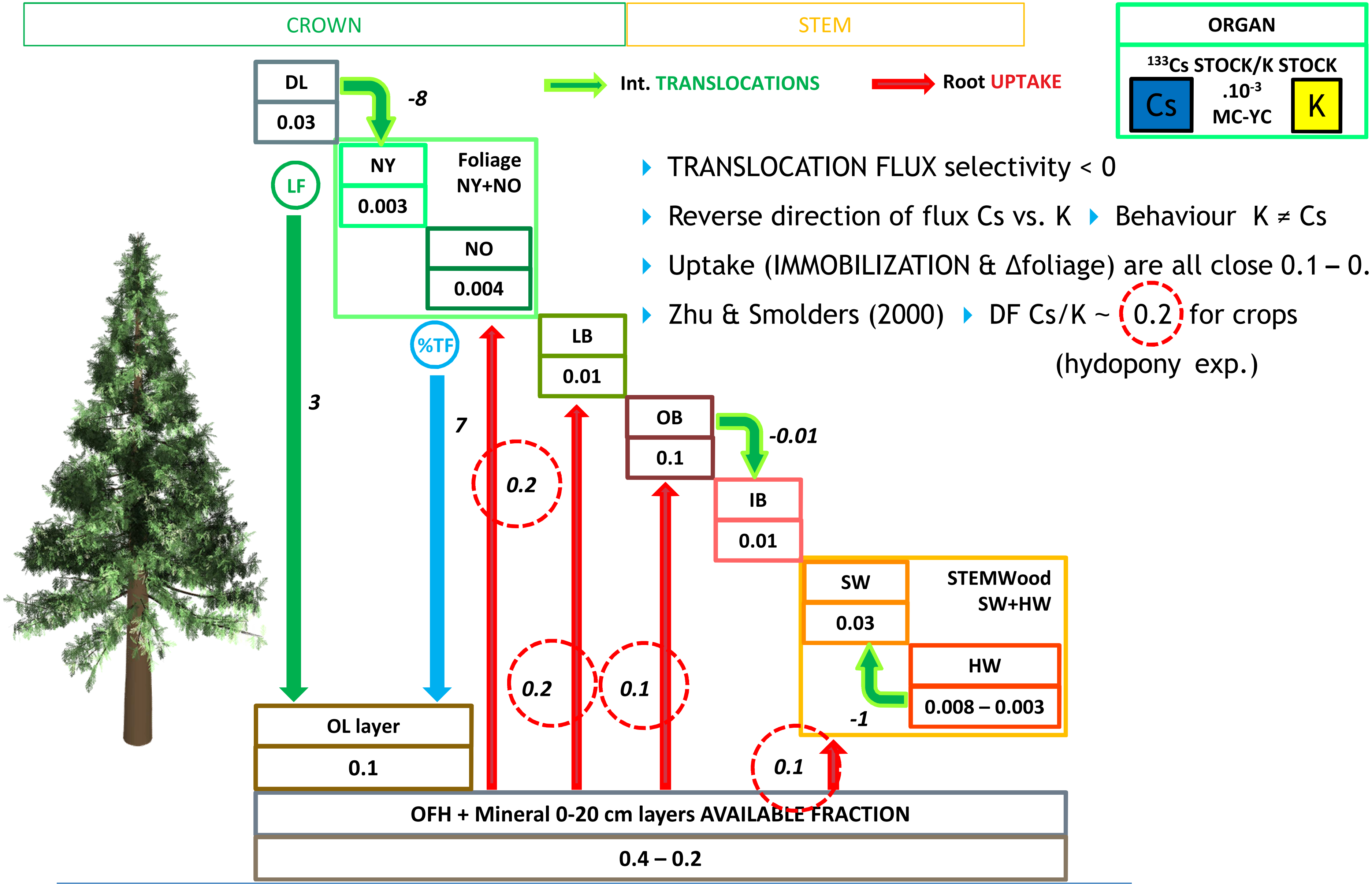
Cs selectivity vs. K

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



- TRANSLOCATION FLUX selectivity < 0
- Reverse direction of flux Cs vs. K ▸ Behaviour K ≠ Cs
- Uptake (IMMOBILIZATION & Δfoliage) are all close 0.1 – 0.2
- Zhu & Smolders (2000) ▸ DF Cs/K ~ 0.2 for crops (hydopony exp.)

Behaviour of stable analogs K & ^{133}Cs

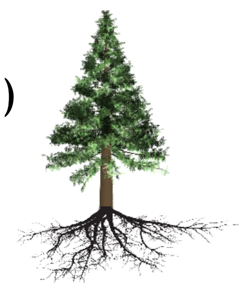
- ^{133}Cs and K exhibit different dynamics
  - K is at equilibrium $U + \Sigma T = R$
  - ^{133}Cs is recycled in excess $U + \Sigma T = 2 R$
  - Detoxification process for a non essential element?

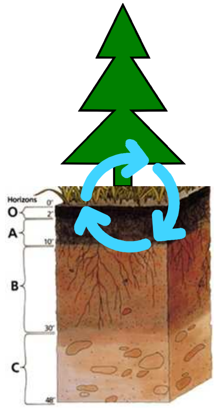
Is the ^{133}Cs a good surrogate for assessing the rCs root uptake?

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

Remaining questions & prospects

- Monitoring of ^{137}Cs still required… … in parallel with K and 133Cs 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?





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