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INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Process-based modelling of the short and long-term dynamics of ^{137}Cs in Fukushima coniferous forests

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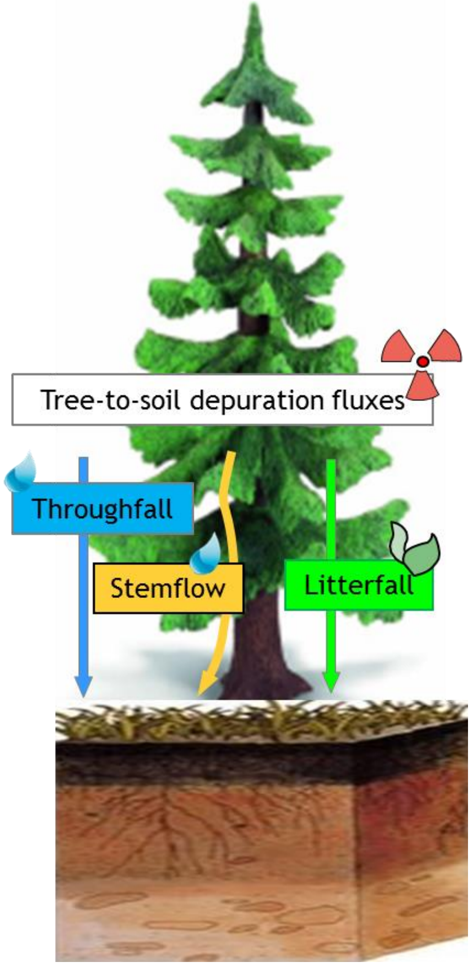
Review of literature data (2011-2017)

(*) *Cryptomeria japonica*
Chamaecyparis obtusa

- Even-aged Japanese cedar & cypress forests*
  in Fukushima & neighbouring Prefectures
- ^{137}Cs contents in tree organs & soil layers
  e.g. concentrations (Bq/kg), surface stocks (Bq/m^2),
  depuration fluxes (Bq/m^2/d) …
- Tree vegetation characteristics
  e.g. stand age, stand density, tree height, trunk diameter,
  stem volume, biomasses, leaf area indexes, litterfall …
- Organic & mineral soil characteristics
  e.g. layers' depths, mass of litter, bulk soil density,
  OM decomposition rate, exchangeable K …
- Local climatic characteristics
  e.g. precipitation, temperature …

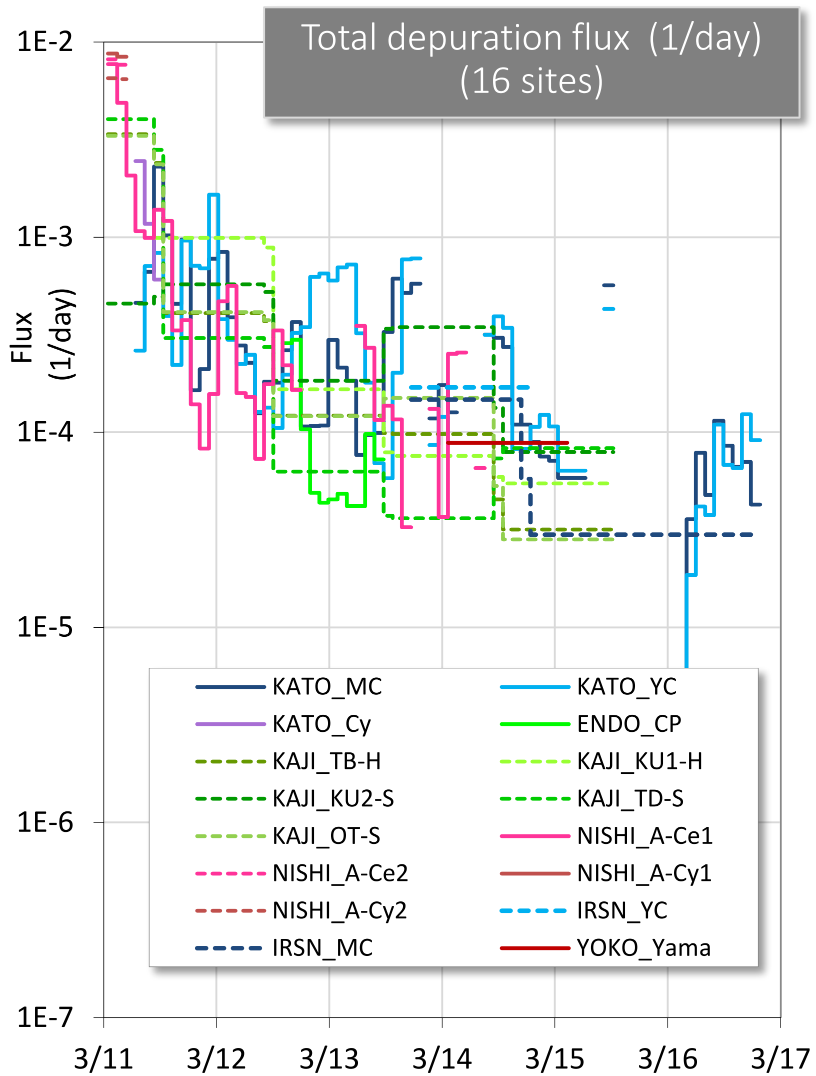


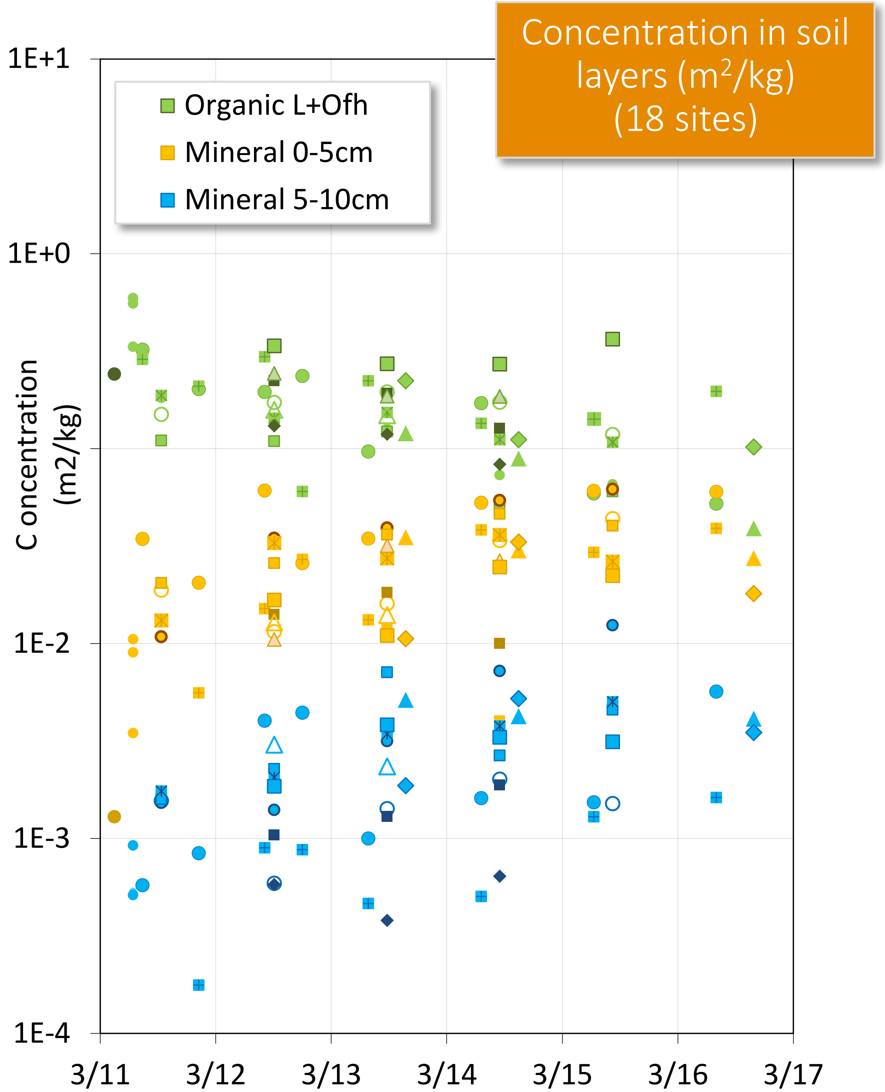
34 sites, with ^{137}Cs deposit from 10 to >1000 kBq/m^2

RESEARCH GROUP	REFERENCES	FOREST (#Sites)	DATA (*)
Forestry and Forest Products Research Institute (Tsukuba)	Itoh et al. 2014-15	Cypress (1) Cedar (9)	DF
	Kuroda et al. 2013; Kajimoto et al. 2015; Komatsu et al. 2016; Imamura et al. 2017; Ohashi et al. 2017; Fujii et al. 2019	Cypress (2) Cedar (3)	C, S, B
Forestry and Forest Products Research Institute (Chuo-ku)	Shinomiya et al. 2014; Hiruta et al. 2016; Toriyama et al. 2018;	Cypress (1)	C, S (in soil)
University of Tsukuba & Institute of Radioprotection and Nuclear Safety (France)	Kato et al. 2012-14-17-19; Hisadome et al. 2013; Loffredo et al. 2014-15; Teramage et al. 2014-16; Takahashi et al. 2015-18; Coppin et al. 2016; Kurihara et al. 2018; Hurtevent et al. (in prep)	Cedar (3) Cypress (1)	C, S, DF, B
University of Tokyo & Chiba University	Endo et al. 2014-15; Murakami et al. 2014 ; Pumpanen et al 2016	Cedar (1)	C (in tree), DF
National Institute for Environmental Studies (Tsukuba)	Nishikiori et al. 2015-19	Cedar (2) Cypress (2)	C (in tree), DF
Japanese Atomic Energy Agency (Fukushima)	Niizato et al. 2016	Cedar (1)	DF
Japanese Atomic Energy Agency (Ibaraki)	Koarashi et al. 2012-16-19; Nakanishi et al. 2014	Cedar (2)	C, S (in soil)
Institute of Environmental Radioactivity (Fukushima)	Yoschenko et al. 2016, 18	Cedar (2)	C, S, DF, B
National Institute for Environmental Studies (Tamuragunn)	Shoko et al. 2017	Cedar (2) Cypress (1)	C, S (in soil)
Gakushuin university (Tokyo)	Ohno et al. 2012	Cedar (1)	C, S (in soil)

(*) Concentrations, Stocks, Depuration Fluxes, Biomasses

Site-specific depuration flux & concentration in soil layers
normalized by the local deposit





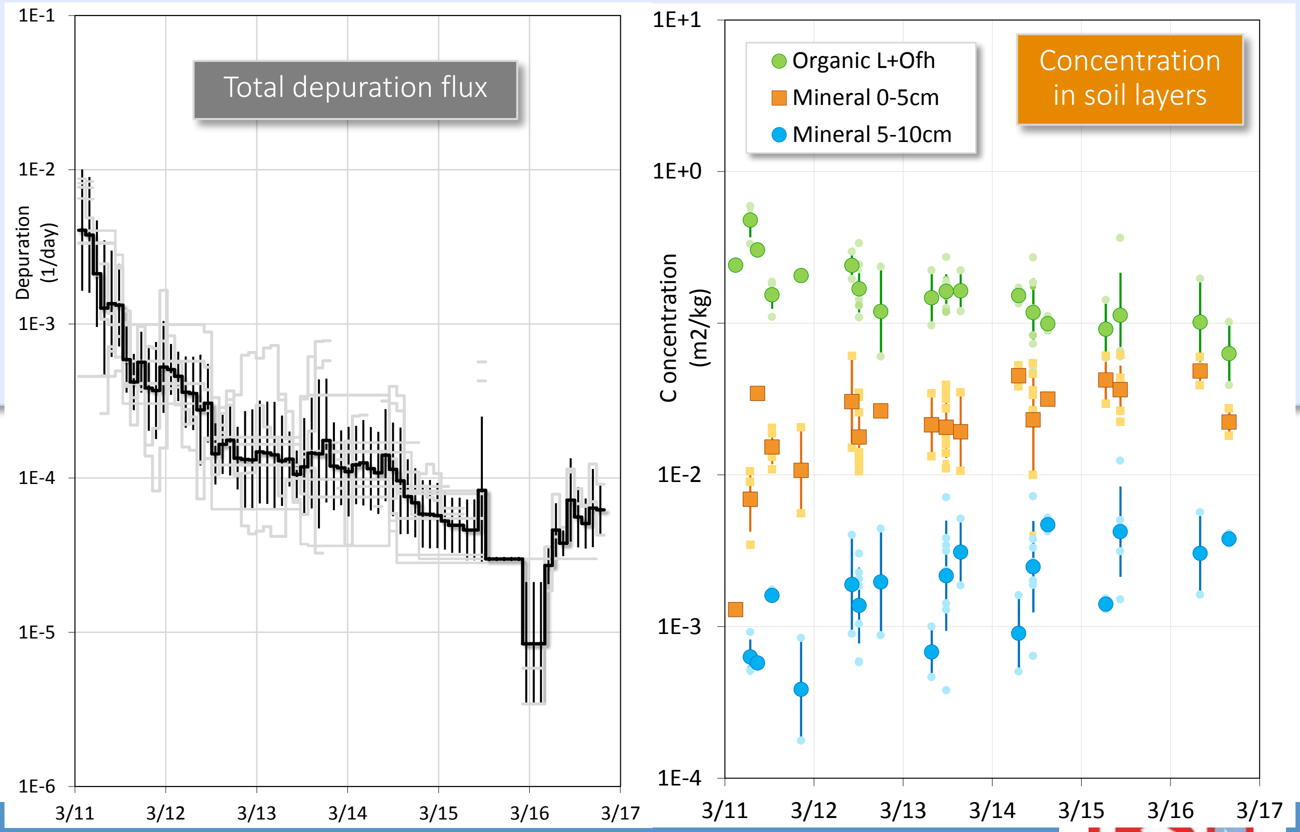
Modelling any particular site is still too challenging

- **Part of the residual variability is still poorly understood**
  ie cannot be modelled with a deterministic approach
  - Unknown atmospheric deposition conditions / interception fraction (at most sites)
  - Uncertainty in the total deposit or radiological data (at sites where too few samples)
  - Incomplete time series, especially between June 2011 (at most sites)

- **Most of the field studies were not designed for model development & testing**
  ie do not provide all the information required
  - Missing key model parameters (at most sites)
  - Missing some radiological quantities (at most sites)
  - No investigation of soil or tree vegetation (at some sites)
  - Missing forest stand characteristics (at some sites)

Our approach

- **Site-average approach** by averaging ^{137}Cs data among sites to estimate a mean (+ SD) evolution over the 6-y period



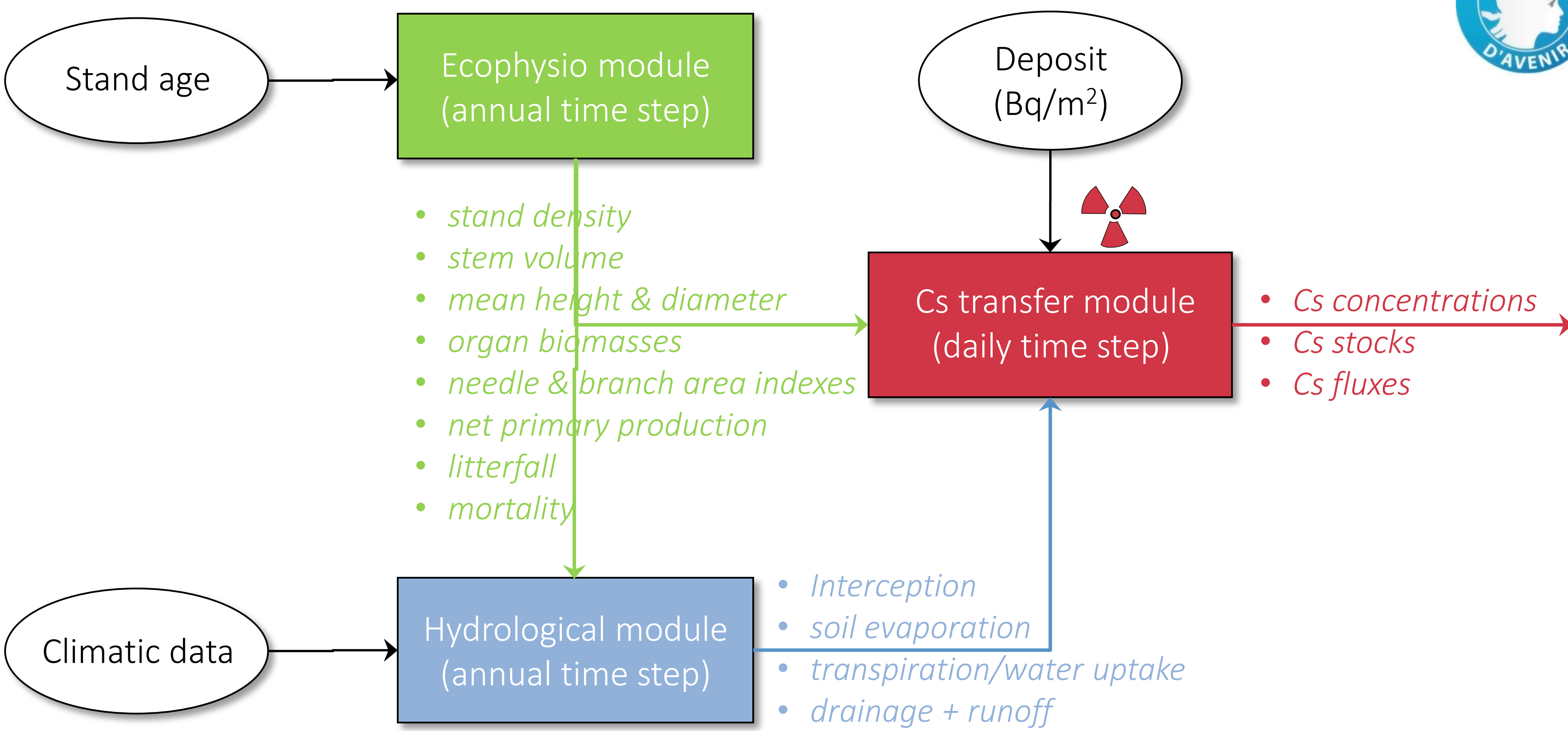
Our approach

- **Site-average approach** by averaging ^{137}Cs data among sites to estimate a mean (+ SD) evolution over the 6-y period
- Use of (empirical) **eco-physiological & hydrological submodels** to assess tree characteristics & water fluxes, at this "generic" site
- P**robabilistic approach** (*Monte-Carlo technique*) to account for variability/uncertainty associated with data and model parameters

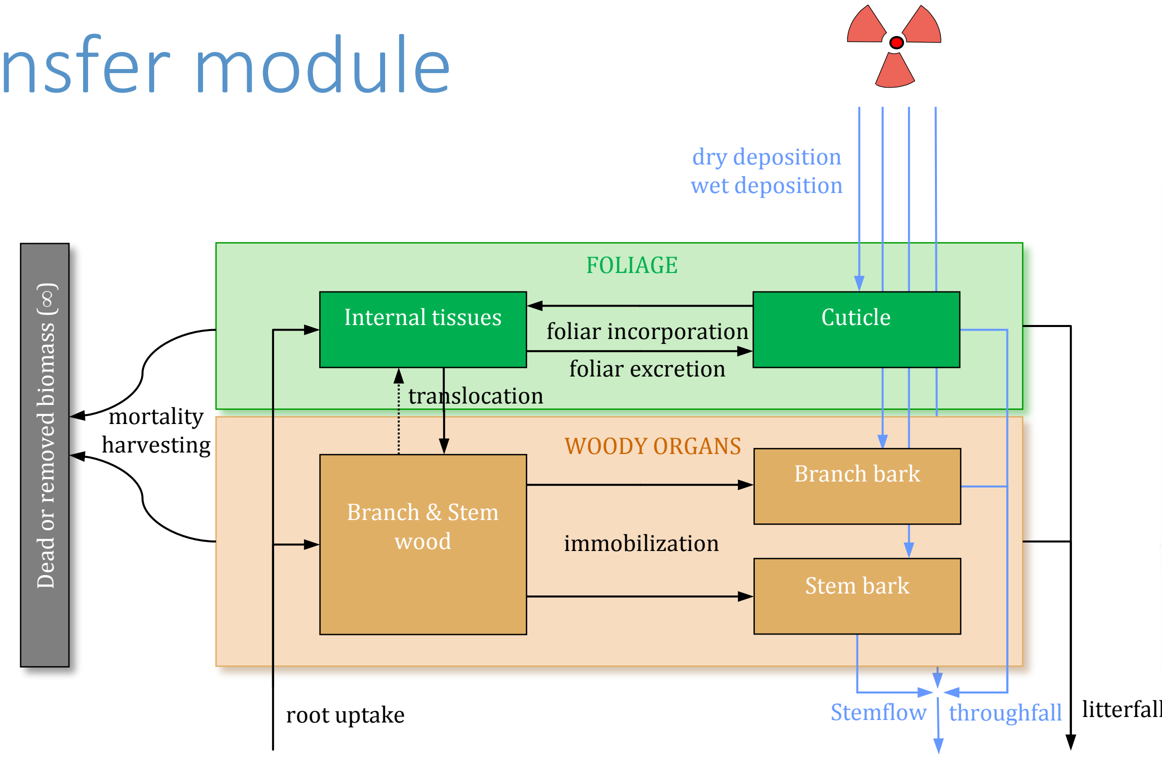
TREE4 forest model

Derived from a simplistic model developed after Chernobyl (*Calmon et al., Sci. Total Environment, 2015*)

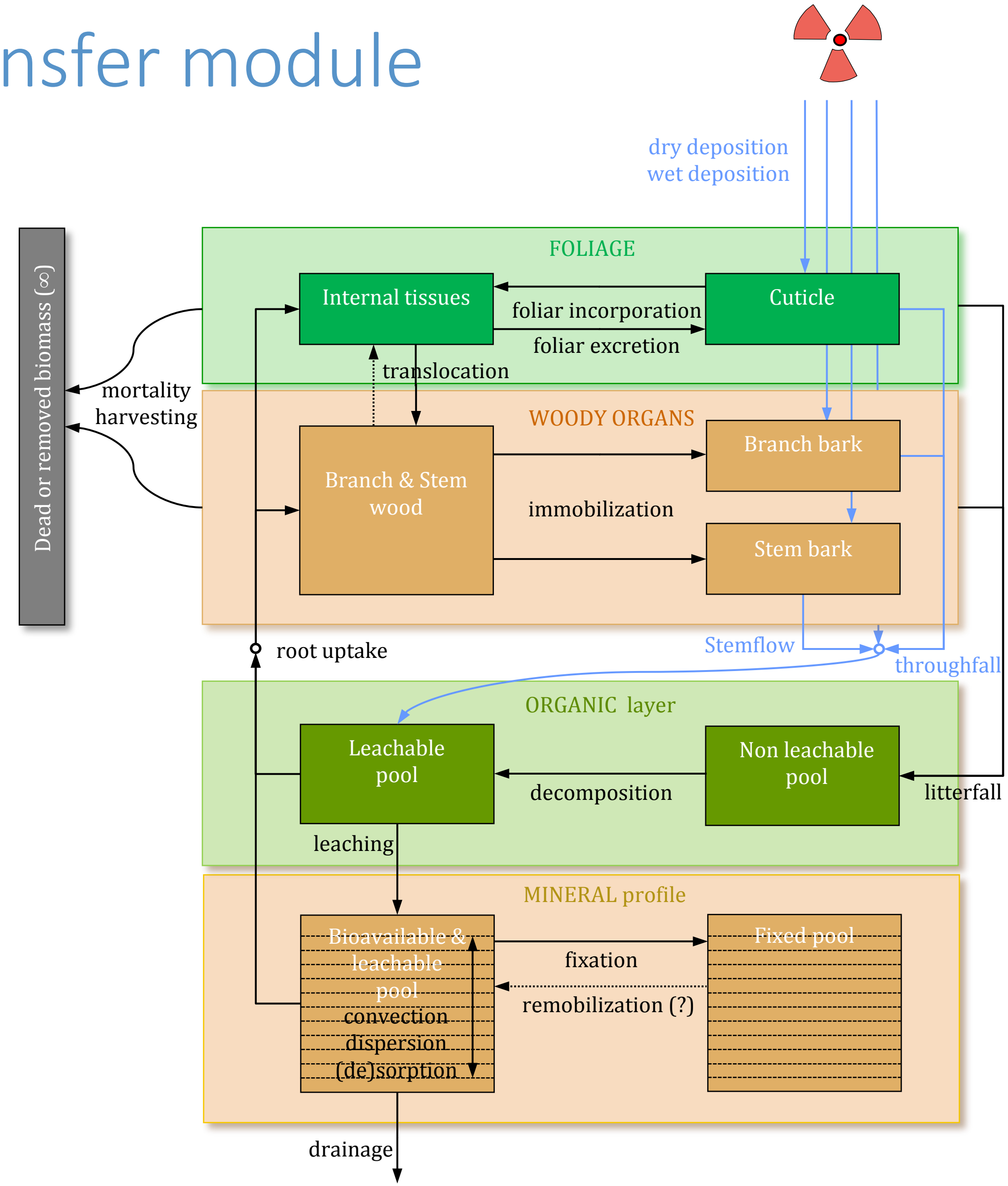
Significantly improved in AMORAD project (2013-2019)

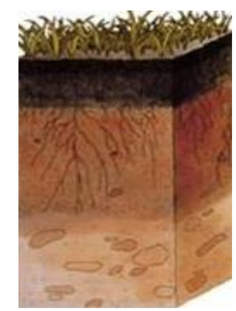


Cs transfer module



Cs transfer module





Parameterization of Cs transfer processes

PROCESS	KEY PARAMETERS			
	ECOLOGICAL	HYDROLOGICAL	PEDOLOGICAL	CHEMICAL (Cs)
Dry interception	effective tree area indexes (foliage, branch , stem)			
Wet interception	tree area indexes, free throughfall coefficient, water retention capacity	precipitation height at deposition		chemical affinity for tree surfaces
Throughfall, stemflow	free throughfall coefficient	rainfall, wet interception fraction		weathering rate
Litterfall	biomass turnover, K in living/dead foliage			Cs/K selectivity
Foliar excretion	K excretion, K in living foliage			Cs/K selectivity
In-bark immobilization	net primary production, K in bark/wood			Cs/K selectivity
Mortality	mortality rate			
Root uptake	K demand for growth, root density profile		exchangeable K in soil	Cs/K selectivity
Decompo			decomposition rate	
Lea		percolation flux		Kd organic
Conv		percolation flux		Kd mineral
Dispersion		soil water content, percolation flux	dispersivity	
Foliar incorporation				incorporation rate
Translocation (phloem)				translocation rate
Fixation				fixation rate
~~Translocation (xylem)~~	NEGLECTED			
~~Remobilisation~~	NEGLECTED			

$$UpCs = \int_0^{h_{root}} \underbrace{sel^{up} \frac{UpK}{[K]_{ex}}}_{kinetic\ rate(z)} \rho_{root}(z)\ [Cs]_{available}(z)\ dz$$

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In-bark immobilization	net primary production, K in bark/wood			Cs/K selectivity ★
Mortality	mortality rate			
Root uptake	K demand for growth, root density profile		exchangeable K in soil	Cs/K selectivity
Decomposition (OM)			decomposition rate	
Leaching		percolation flux		Kd organic ★
Convection		percolation flux		Kd mineral ★
Dispersion		soil water content, percolation flux	dispersivity	
Foliar incorporation				incorporation rate ★
Translocation (phloem)				translocation rate
Fixation				fixation rate ★
~~Translocation (xylem)~~	NEGLECTED			
~~Remobilisation~~	NEGLECTED			

★ unknown parameters

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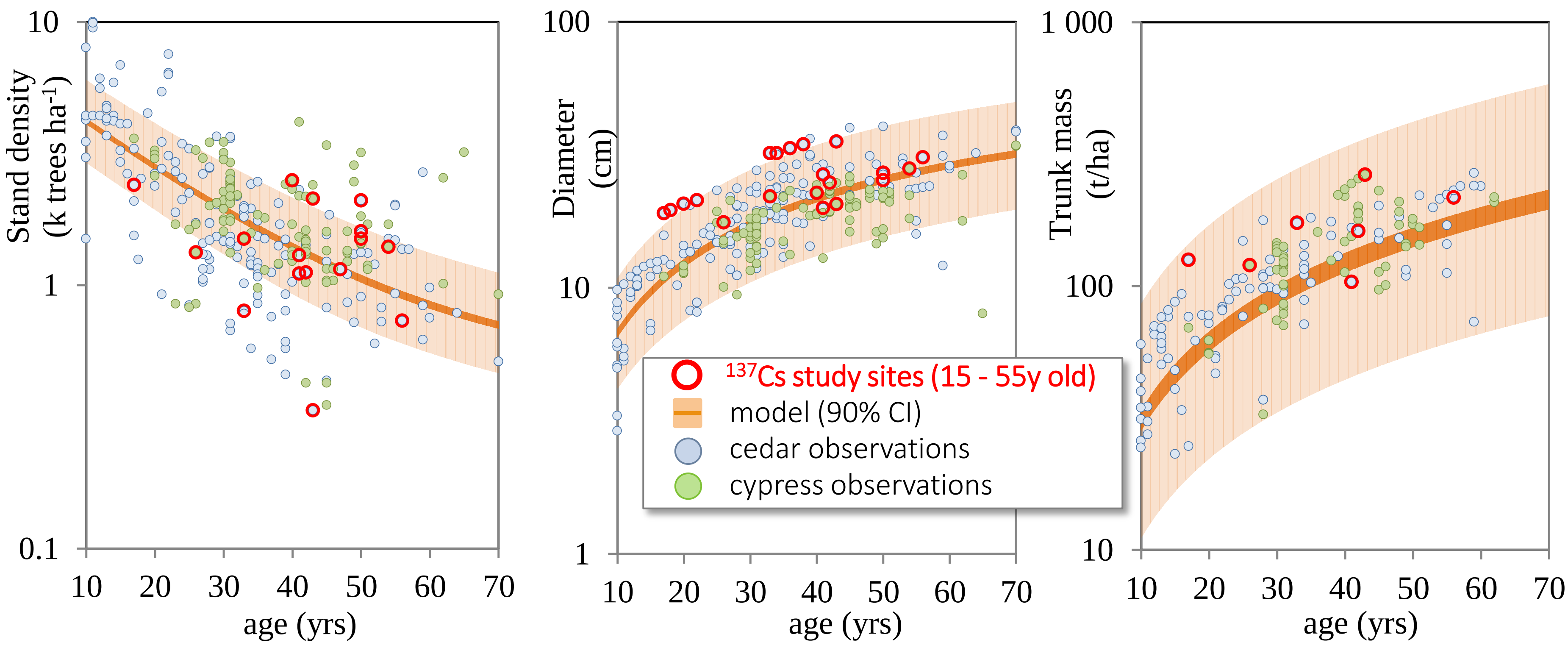
Modeling methodology

1. Estimate **hydrolo & ecophysio modules parameters** (pdfs + correlations) by calibrating outputs against literature data for Japanese forests (*Bayesian approach*)



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1. Estimate **hydrolo & ecophysio modules parameters** (pdfs + correlations) by calibrating outputs against literature data for Japanese forests (*Bayesian approach*)

2. Estimate **available Cs module parameters** (pdfs + correlations) based on literature data for Japanese forests + expert judgement

PARAMETER	UNIT	PDF (*)	REFERENCES
...			
Wood density	kg m^{-3}	$\mathcal{N}$(320, 35)	Ugawa et al 2012, Koniyama 2011, Fukuda et al 2003, Fujiwara et al 2004, Hurtevent et al (in prep)
Foliage turnover	yr	$\mathcal{N}$(5, 1.4)	Miyaura & Hozumi 1993, Kiyono & Akama 2016, Watanabe et al. 2004, Saito & Tamai 1989, Hurtevent et al (in prep)
Branch turnover	yr	$\mathcal{N}$(27.5, 5)	Miyaura & Hozumi 1993, Hurtevent et al (in prep)
Specific foliage area index	m^2 kg^{-1}	$\mathcal{N}$(4.7, 2.5)	Tadaki et al 1964, Landsberg & Sands 201, Yamashina & Yoshitake 1963, Kawanabe & Shidei 1968, Hashimoto & Suzaki 1979, Nishina 1987, Katsuno & Hozumi 1990, Miyamoto et al 2013, Cannell 1982, Yuruki 1964, Tadaki et al 1965
Plant area index	m^2 m^{-2}	$\mathcal{LN}$(6.0, 3.0)	Komatsu et al 2008, Murakami et al 2000, Katsuno & Hozumi 1990, Sumida 2013, Tsuruta et al 2016, Takanashi et al 2003, Shinohara et al 2015, Loffredo et al. 2014; Kumagai et al 2014, Saito et al 2013, Shimizu et al 2003
Water storage	mm	$\mathcal{N}$(1.95, 0.55)	Murai et al 1993, Komatsu et al 2008, Saito 2013, Suzuki et al 1979, Shimizu et al 2003, Sun et al 2014, Shinohara et al 2015
K content in foliage	g kg^{-1}	$\mathcal{LN}$(4.5, 1.5)	Wang et al 2016, Hurtevent et al (in prep)
K content in wood	g kg^{-1}	$\mathcal{LN}$(1.5, 1)	Wang et al 2016, Iizuka et al. 2018, Hurtevent et al (in prep)
Bulk soil density	kg m^{-3}	$\mathcal{LN}$(500, 200)	Imamura et al 2017, Takahashi et al 2015, 2018, Nakanishi et al 2014, Fujii et al 2014, Koarashi et al 2012, 2017, Matsunaga et al 2013, Ohno et al 2012, Shoko et al 2017, Coppin et al. 2016, Toriyama et al 2018
Mass of litter	kg m^{-2}	$\mathcal{LN}$(1.6, 3.0)	Takahashi et al 2018, Kaneko et al 2013, Ohno et al 2012, Shoko et al 2017, Teramage 2017, Imamura et al 2017, Tori 2018, Coppin et al. 2016
Decomposition rate	yr^{-1}	$\mathcal{LN}$(0.25, 1.0)	Kurihara et al 2018, Shutou et al 2004, Aerts et al 1997, Joo et al. 2006, Osono et al 2007, Shutou & Nakane 2004, Nakane et al 1995, Tori 2018
Exch. K in soil	g kg^{-1}	$\mathcal{N}$(0.14, 0.06)	Fujii et 2014, Koarashi et al 2017, Matsunaga et al 2013, Nagakura et al 2016, Komatsu et al 2017, Wang et al 2016, Coppin et al. 2016
...			

(*) $\mathcal{U}$niform (min, max), $\mathcal{N}$ormal (mean, sd), $\mathcal{L}$og$\mathcal{N}$ormal (mean, sd)

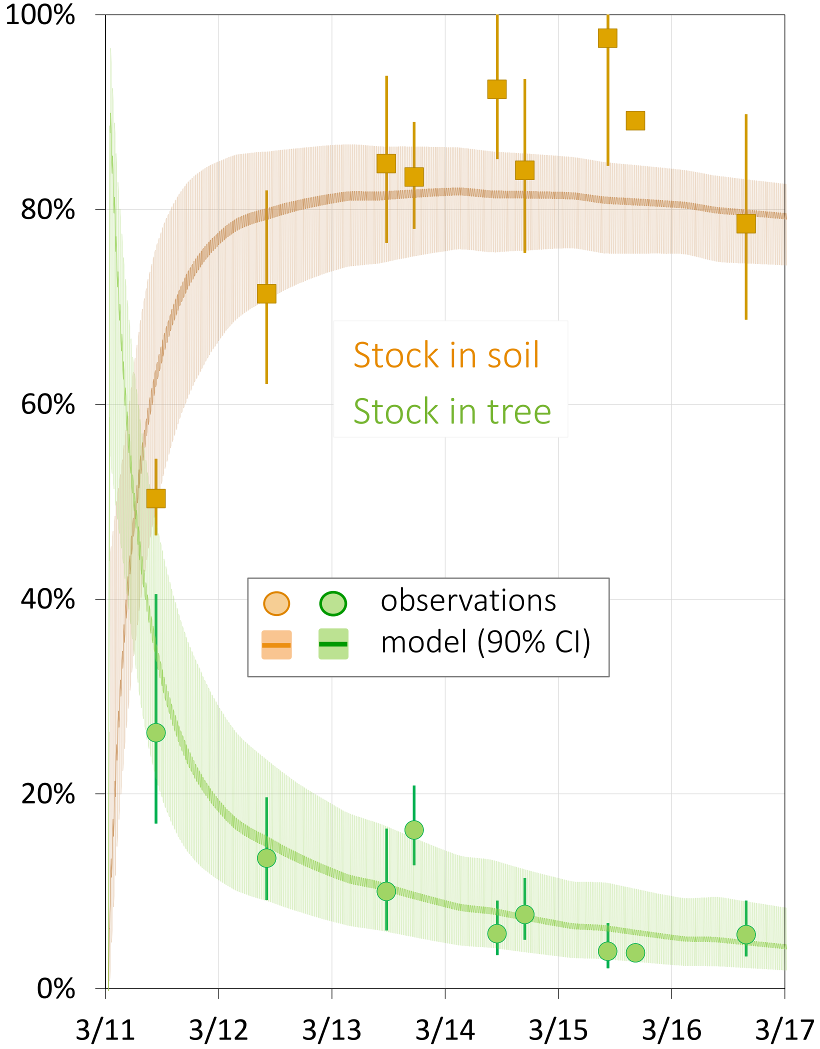
Modeling methodology

1. Estimate **hydrolo & ecophysio modules parameters** (pdfs + correlations) by calibrating outputs against literature data for Japanese forests (*Bayesian approach*)
2. Estimate **available Cs module parameters** (pdfs + correlations) based on literature data for Japanese forests + expert judgement
3. Estimate **unknown Cs module parameters** (pdfs + correlations) by calibrating outputs against Cs data over the 6-y period (*Bayesian approach*)
4. Perform **probabilistic simulations** on the sh
for a variety of scenario assumptions

Focus on:

- managed plantation
- stand age: 15 to 55 yr
- wet deposit (2mm rainfall)

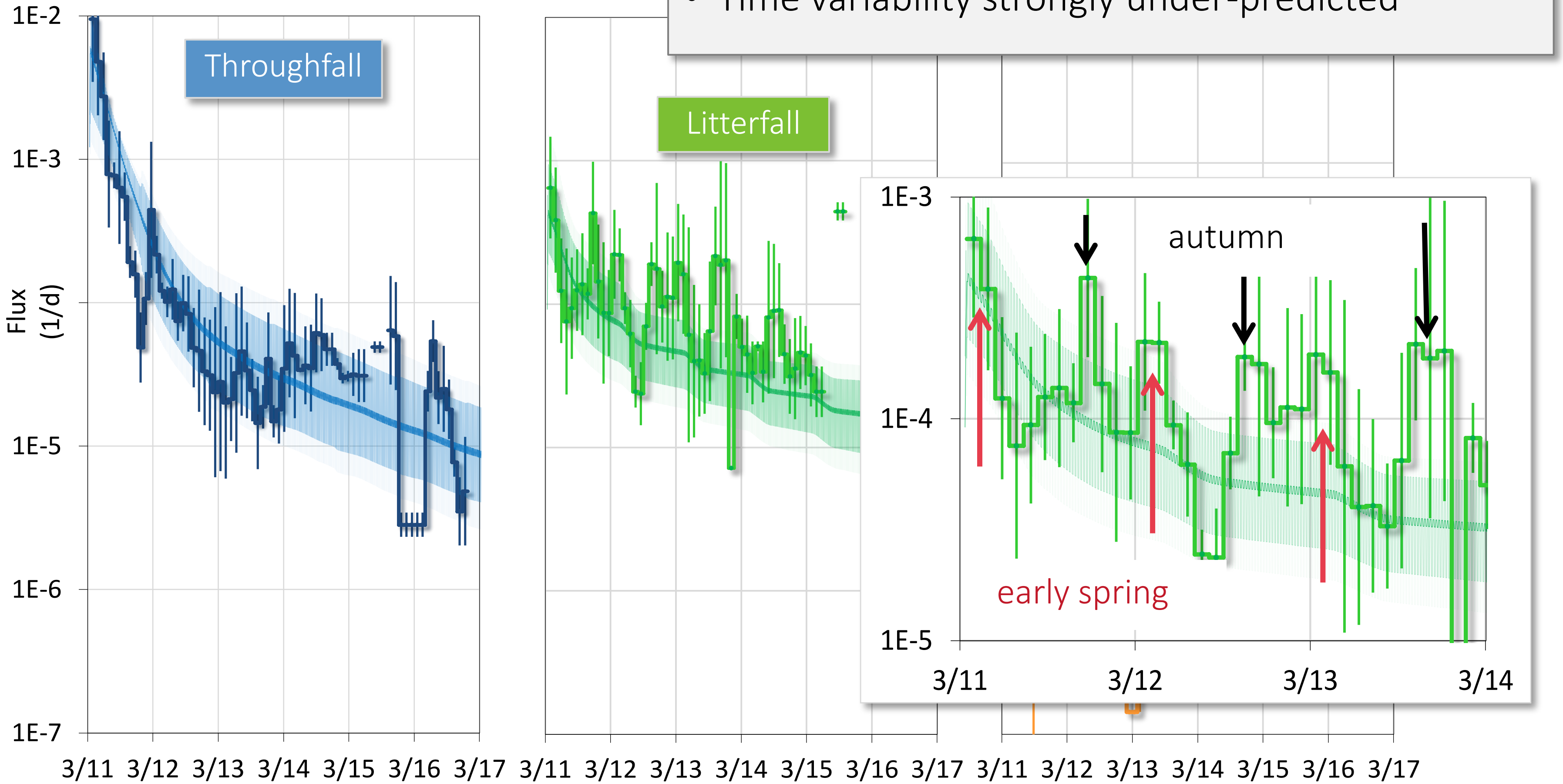
Predicted vs observed ^{137}Cs stocks (%) in soil & tree normalized by the deposit



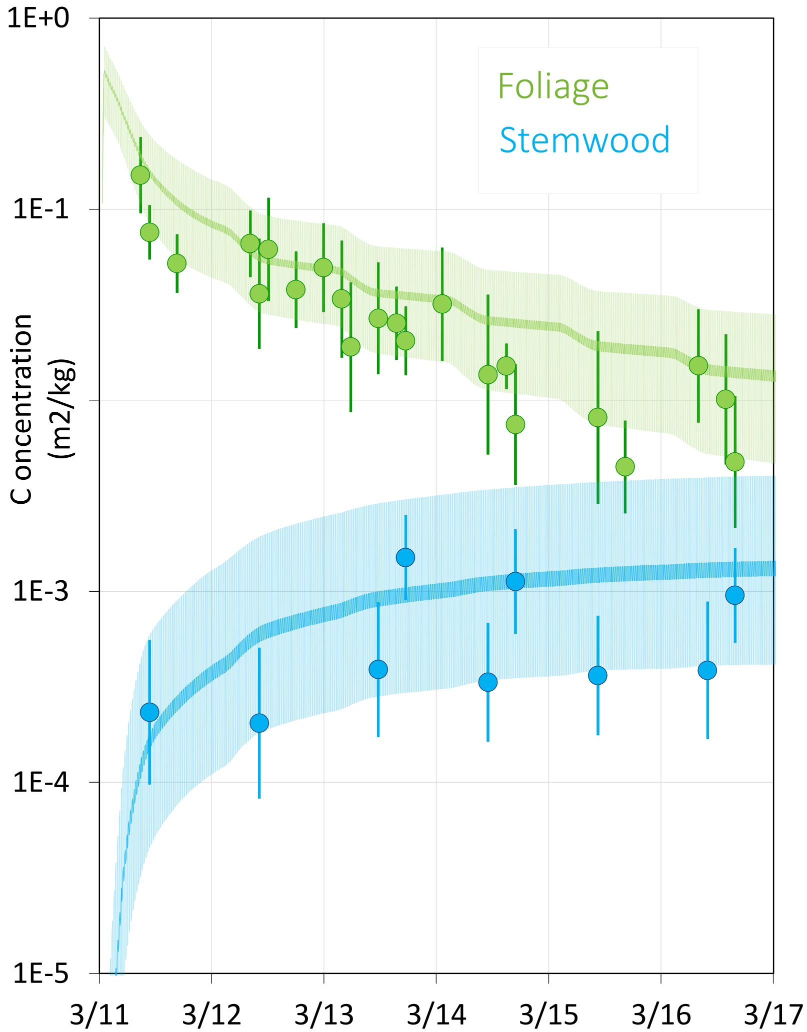
- Initial interception by tree vegetation from 60% to 95% (most likely 90%)
- Interception fraction drastically decreases with rainfall height (>4 mm)
- Rapid decrease in tree vegetation (mainly canopy depuration)
- After 6 years:
  - ~5% in tree
  - ~80% in soil
  - ~13% lost by physical decay
  - ~2% lost by tree mortality/thinning

^{137}Cs depuration fluxes (day^{-1})
normalized by the deposit

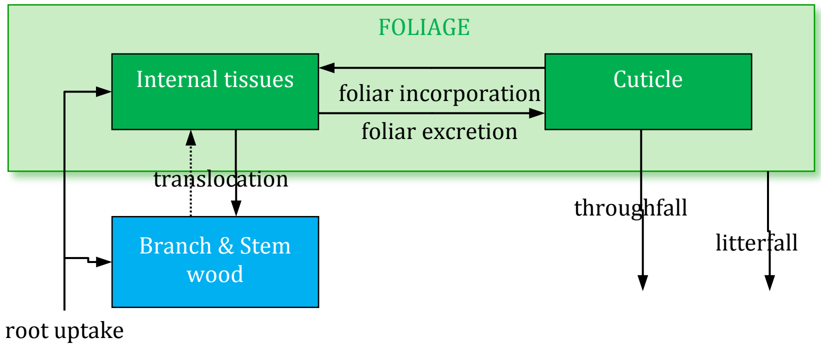
- Depuration mainly driven by throughfall in 2011
- Time variability strongly under-predicted



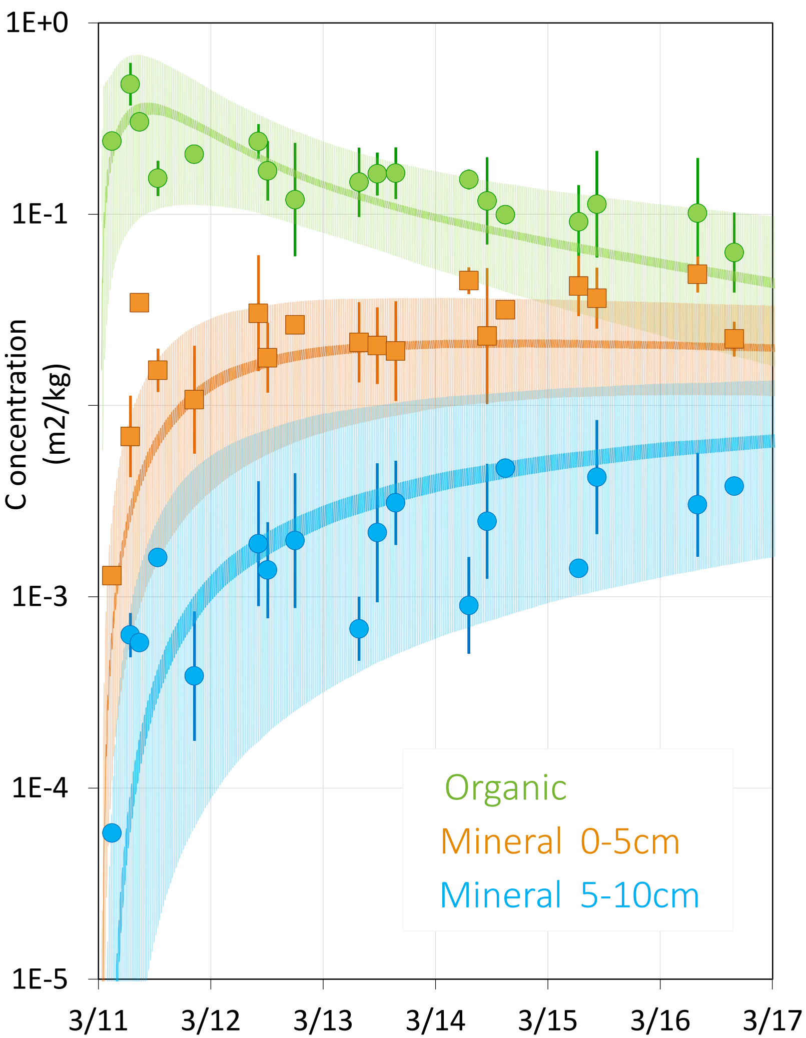
^{137}Cs concentrations (m^2/kg) in foliage & stemwood normalized by the deposit



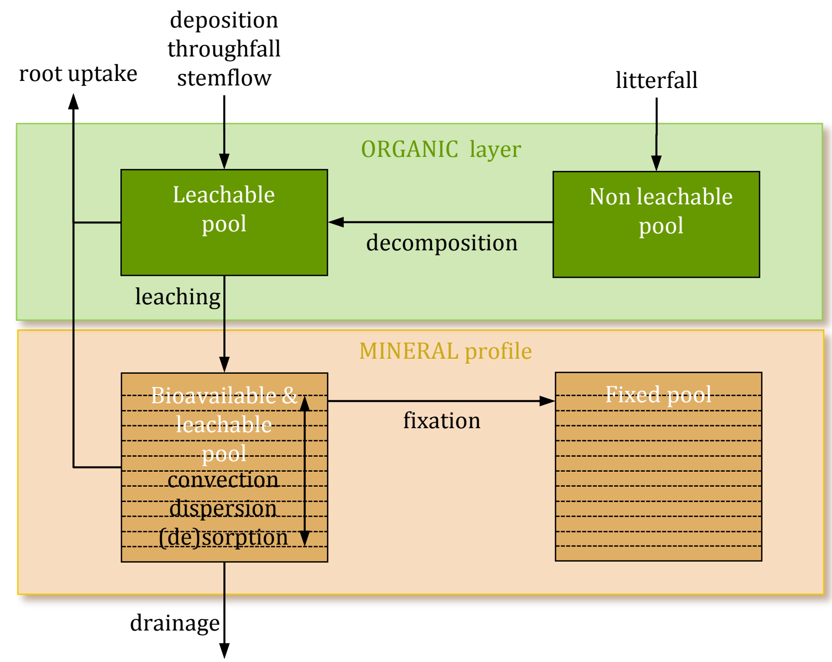
- Strong decrease in foliage (depuration & biomass turnover)
- Rapid increase in wood (translocation from living foliage)
- Root uptake contribution to stemwood < 30%



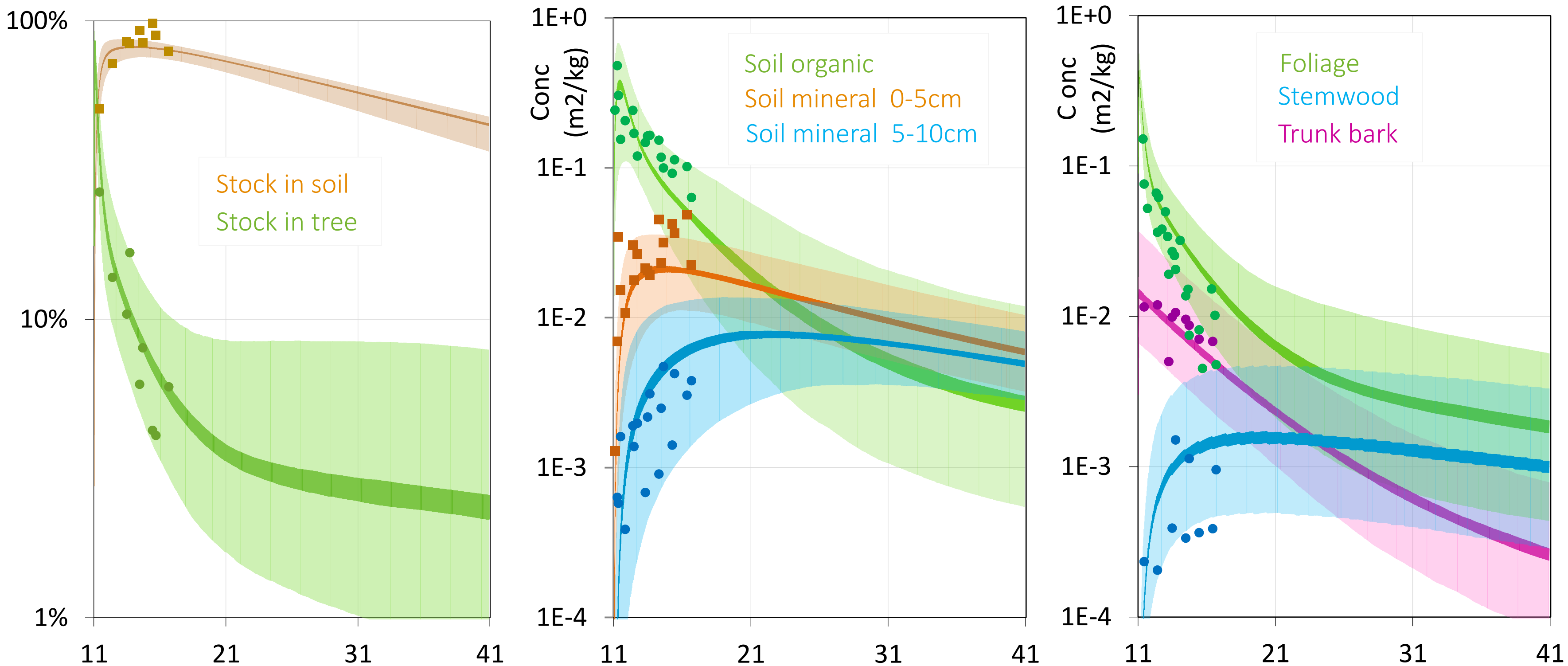
^{137}Cs concentrations in organic & top mineral layers normalized by the deposit



- Peak in organic layer in early autumn 2011
- Rapid migration down the mineral profile
- High sensitivity to Kds, especially in organic



Long-term 30-yr forecast



- **Quasi-equilibrium state** after ~2035, ie constant concentration ratios

  Mineral 0-10cm ≈ 2 x (Organic ≈ Foliage) ≈ 2 x Stemwood

- **But much uncertainty,** because long-term processes hardly identifiable or neglected, e.g. immobilization in heartwood, long-term ageing in soil, …

To conclude

1. Comprehensive analysis of short-term (6-y) observations with the help of a process-based dynamic model
2. Overall consistency between observations & predictions if relevant values for the few unknown parameters
3. Short-term dynamics dominated by foliar pathway processes, although root pathway contribution is not negligible (>3y)
4. Long-term forecasts remain uncertain ⇒ **long-term field monitoring** & **research on long-term processes are needed**
5. Future modelling efforts also put on **mixed/DBL Japanese forests,** far less investigated than coniferous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SUPPLEMENTARY INFORMATION

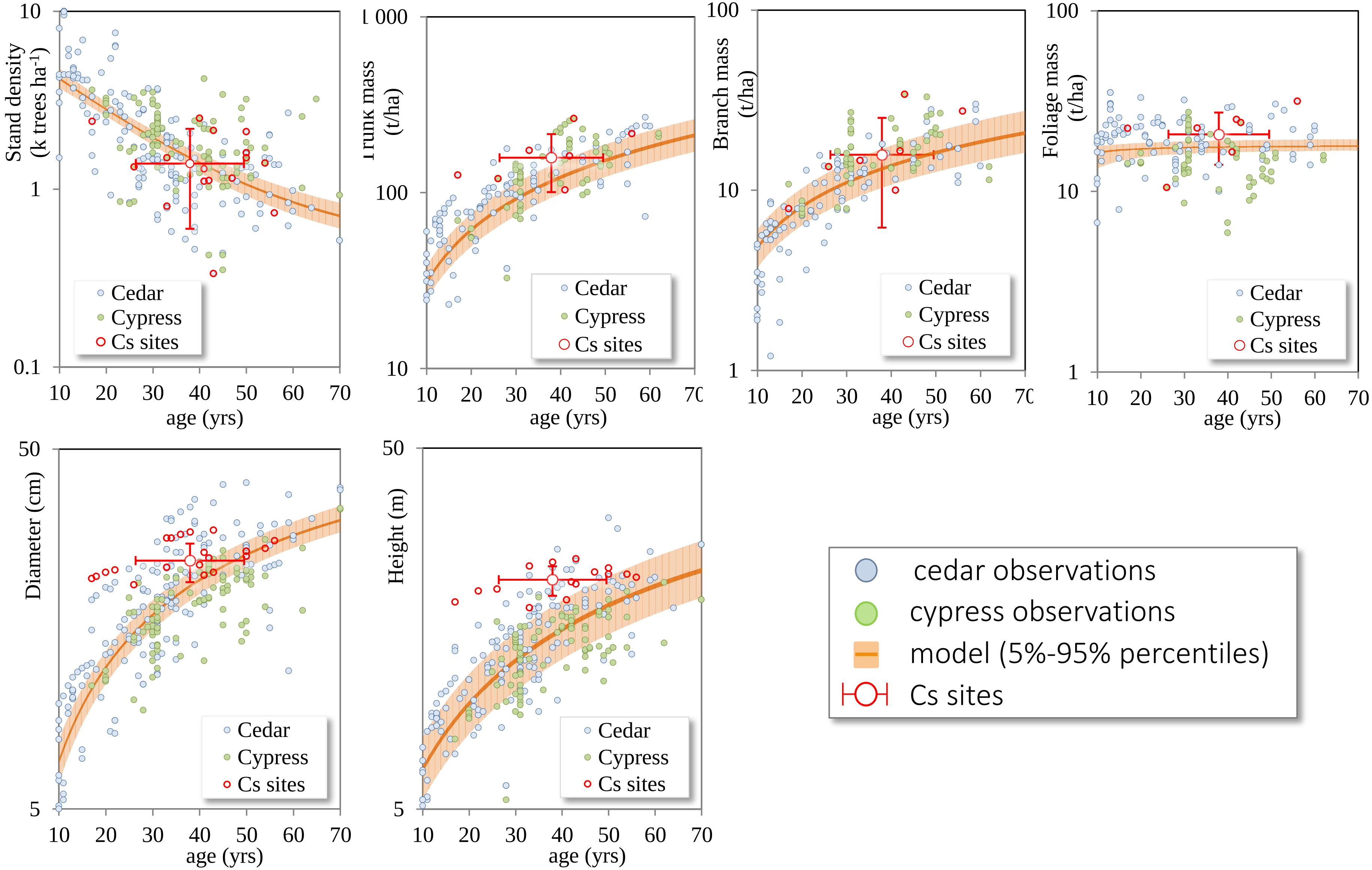
Eco-physiological module

- Mostly Relies on the use of empirical relationships
- Age-dependent stand density, DBH, H & stem volume: Mitscherlich laws (in case of a managed plantation)
- Biomasses : allometric relationships
- Mortality : stand density(t)
- Litterfall : half-life time
- NPP : deduced from mortality, biomass growth & litterfall through mass balance
- Tree area indexes: specific area coefficients

Hydrological module

- Mostly relies on the use of empirical relationships
- Canopy interception, soil evaporation & tree transpiration: depends on annual temperature and precipitation through empirical relationships (established from field observations for a variety of forested watersheds throughout Middle Japan).
- Drainage: estimated from previous contributions by mass balance (water storage & runoff are neglected).
- Percolation flux(z): deduced from tree transpiration and an idealized root density profile.

Some ecophysiological module outputs (managed plantations)



PARAMETER	UNIT	REFERENCES		LAW(*) [min-max]
t^g	Julian day	Yamashita et al 2004, Inagaki et al 2010		$\mathcal{N}$(120, 8) [90-150]
τ^g	day	Yamashita et al 2004, Inagaki et al 2010		$\mathcal{N}$(100, 12) [60-140]
ρ_T	kg m^{-3}	Ugawa et al 2012, Koniyama 2011, Fukuda et al 2003, Fujiwara et al 2004, Hurtevent et al 2019		$\mathcal{N}$(320, 35) [200-440]
τ_F	yr	Miyaura & Hozumi 1993, Kiyono & Akama 2016, Watanabe et al. 2004, Saito & Tamai 1989, Hurtevent et al 2019		$\mathcal{N}$(5, 1.4) [1-9]
τ_{Br}	yr	Miyaura & Hozumi 1993, Hurtevent et al 2019		$\mathcal{N}$(27.5, 5) [5-50]
τ_{TBk}	yr	-		$\mathcal{U}$(25, 50)
p	s.d.	Sun et al 2014, 2017, Saito et al 2013, Loffredo et al 2016		$\mathcal{LN}$(0.2, 0.4) [0-0.5]
SLA	m^2 kg^{-1}	Tadaki et al 1964, Landsberg & Sands 201, Yamashina & Yoshitake 1963, Kawanabe & Shidei 1968, Hashimoto & Suzaki 1979, Nishina 1987, Katsuno & Hozumi 1990, Miyamoto et al 2013, Cannell 1982, Yuruki 1964, Tadaki et al 1965, Tadaki & Kawasaki 1966, Tadaki et al 1967, Tanimoto 1975		$\mathcal{N}$(4.7, 2.5) [1-8]
d_{min}	cm	-		$\mathcal{U}$(0.15, 0.25)
η	-	Katsuno & Hozumi 1998, 1990		$\mathcal{U}$(0.1, 0.15)
L	mm	*defined as S/pai*		$\mathcal{LN}$(0.37, 0.2) [0.05-1.2]
S	mm	Murai et al 1993, Komatsu et al 2008, Saito 2013, Hattori et al 1982, Suzuki et al 1979, Shimizu et al 2003, Sun et al 2014, Shinohara et al2015		$\mathcal{N}$(1.95, 0.55) [0.5-3.5]
pai	m^2 m^{-2}	Komatsu et al 2008, Murakami et al 2000, Katsuno & Hozumi 1990, Sumida 2013, Tsuruta et al 2016, Takanashi et al 2003, Shinohara et al 2015, Loffredo et al., 2014, 2015; Yukuri 1964, Kumagai et al 2014, Saito et al 2013, Shimizu et al 2003, Hattori & Chikaarashi 1988, Miyamoto et al 2013		$\mathcal{LN}$(6.0, 3.0) [3-18]
W_L	kg m^{-2}	Takahashi et al 2018, Kaneko et al 2013, Ohno et al 2012, Shoko et al 2017, Teramage 2014, 2017, Imamura et al 2017, Toriyama et al 2018		$\mathcal{LN}$(1.6, 3.0) [0.5-10]
λ^{dec}	yr^{-1}	Kurihara et al 2018, Shutou et al 2004, Aerts et al 1997, Joo et al. 2006, Osono et al 2007, Shutou & Nakane 2004, Nakane et al 1984, 1995, Toriyama et al 2018		$\mathcal{LN}$(0.25, 1.0) [0.14-1.5]
ρ_S	kg m^{-3}	Imamura et al 2017, Takahashi et al 2015, 2018, Nakanishi et al 2014, Fujii et al 2014, Koarashi et al 2012, 2017, Matsunaga et al 2013, Ohno et al 2012, Shoko et al 2017, Toriyama et al 2018		$\mathcal{LN}$(500, 200) [250-1200]
h_R	m	Fujimaki et al 2007, Noguchi et al 2005, Jackson et al 1996, Schenk & Jackson 2002, Teramage et al 2014, 2016		$\mathcal{U}$(0.15, 0.30)
d	m	Ota et al 2016		$\mathcal{LN}$(0.05, 0.03) [0-0.2]
θ	m^3 m^{-3}	Tsuruta et al 2016, Nakane et al 1995, Kaneko et al 2013, Hurtevent et al 2019		$\mathcal{U}$(0.05, 0.5)
$[K]_{F\text{-}alive}$	g kg^{-1}	Wang et al 2016, Hurtevent et al 2019		$\mathcal{LN}$(4.5, 1.5) [0.5-15]
$[K]_{F\text{-}dead}$	g kg^{-1}	Hurtevent et al 2019		$\mathcal{LN}$(2.25, 1.5) [0.25-8]
$[K]_{Bk}$	g kg^{-1}	Wang et al 2016, Hurtevent et al 2019		$\mathcal{LN}$(0.35, 0.2) [0.025-1.5]
$[K]_W$	g kg^{-1}	Wang et al 2016, Iizuka et al. 2018, Hurtevent et al 2019		$\mathcal{LN}$(1.5, 1) [0.15-4]
$ExcK$	kg ha^{-1} yr^{-1}	Hurtevent et al 2019, Cole & Rapp 1981, Sase et al 2008, DeSchrijver et al 2007		$\mathcal{N}$(15, 5) [0-30]
$[K]_{S0}$	g kg^{-1}	Hurtevent et al 2019, Fujii et 2014, Koarashi et al 2012, 2017, Matsunaga et al 2013, Nagakura et al 2016, Komatsu et al 2017, Wang et al 2016		$\mathcal{N}$(0.14, 0.06) [0.05-0.3]
P	mm	Laceby et 2016, Ugawa et 2012		$\mathcal{N}$(1420, 160)
T	°C	Laceby et 2016, Ugawa et 2012		$\mathcal{N}$(11.3, 1.0)

(*) Uniform: $\mathcal{U}$(min, max), Normal: $\mathcal{N}$(mean, sd), Log-normal: $\mathcal{LN}$(mean, sd)