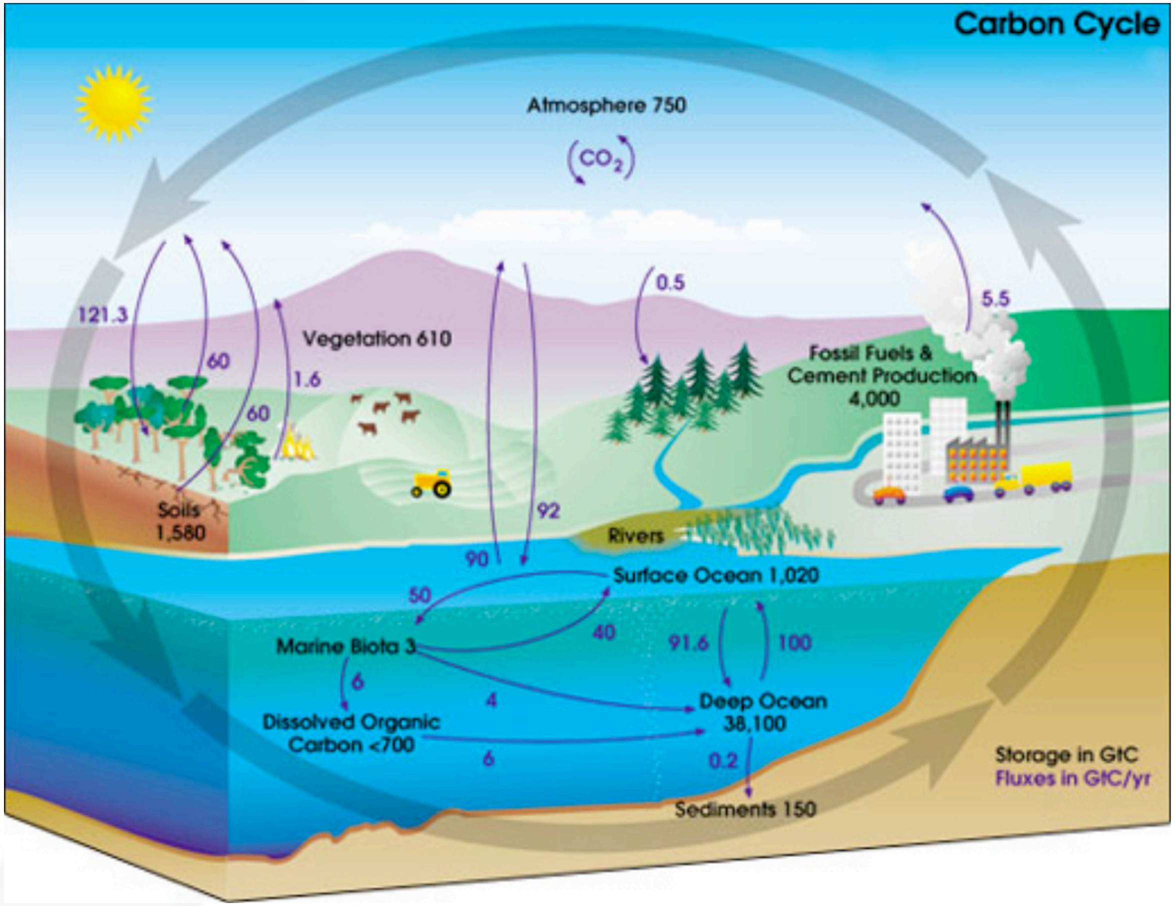
The soil carbon in ORCHIDEE

GUENET Bertrand

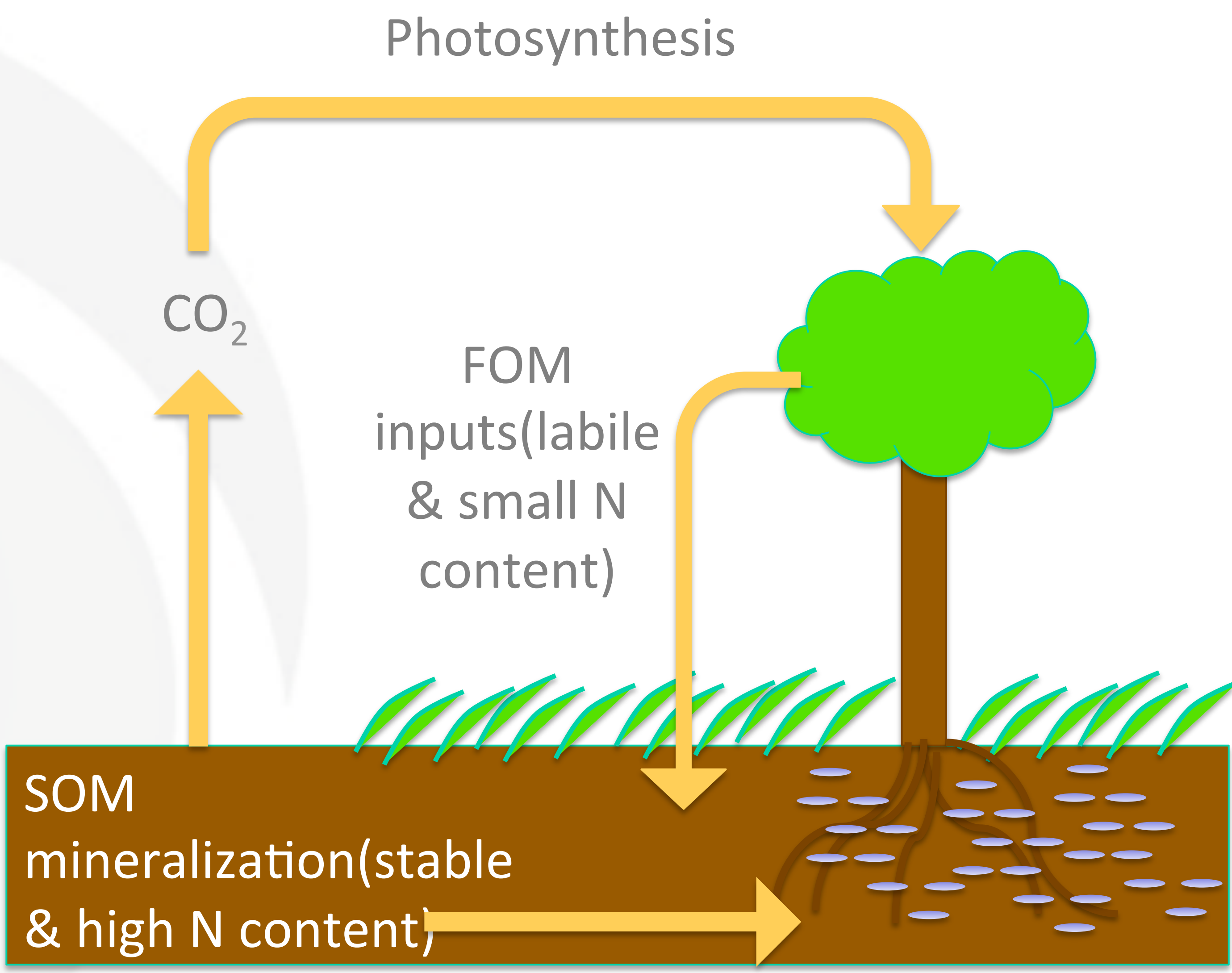
THE GLOBAL C CYCLE AND ITS SOIL COMPONENT

- The C cycle: a complex cycle composed of different pools.
- These pools interact *via* different fluxes.

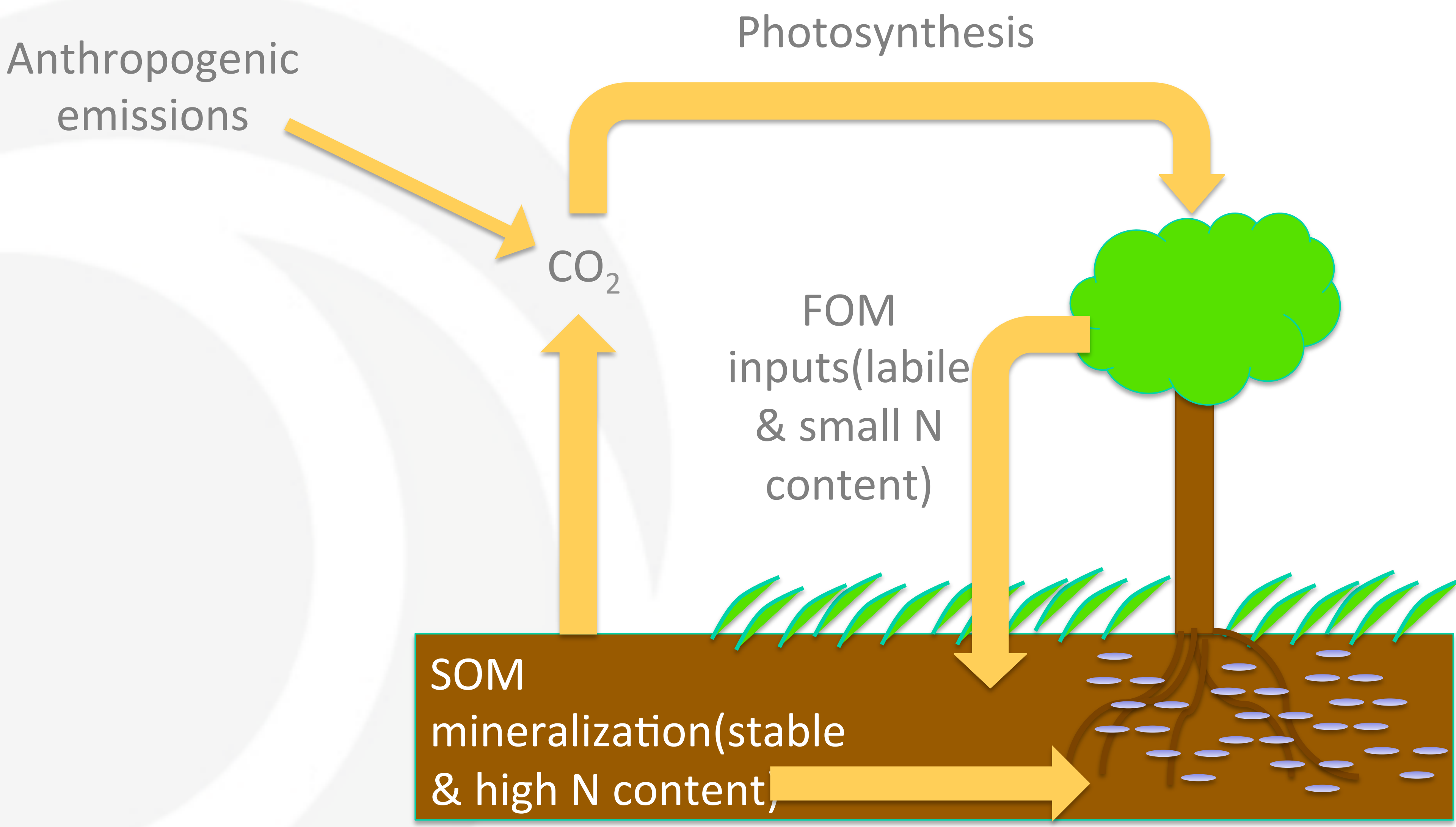


SOILS: MAJOR ACTORS OF THE C CYCLE

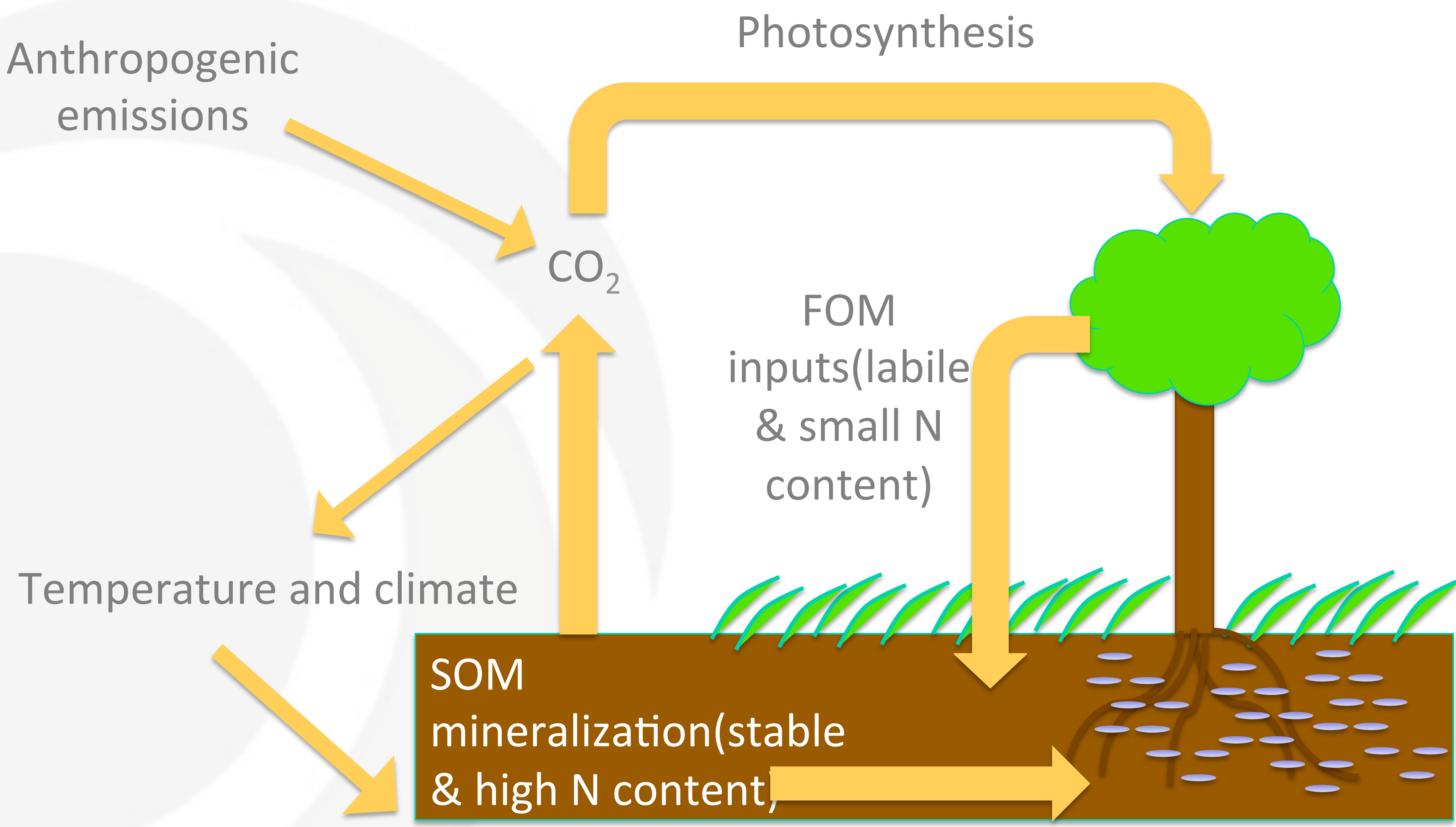
- Temperature and humidity(Reichstein et al., 2003)
- Amount and chemical composition of the Fresh Organic Matter (FOM) (Guenet et al., 2010)



SOILS AND GLOBAL CHANGES



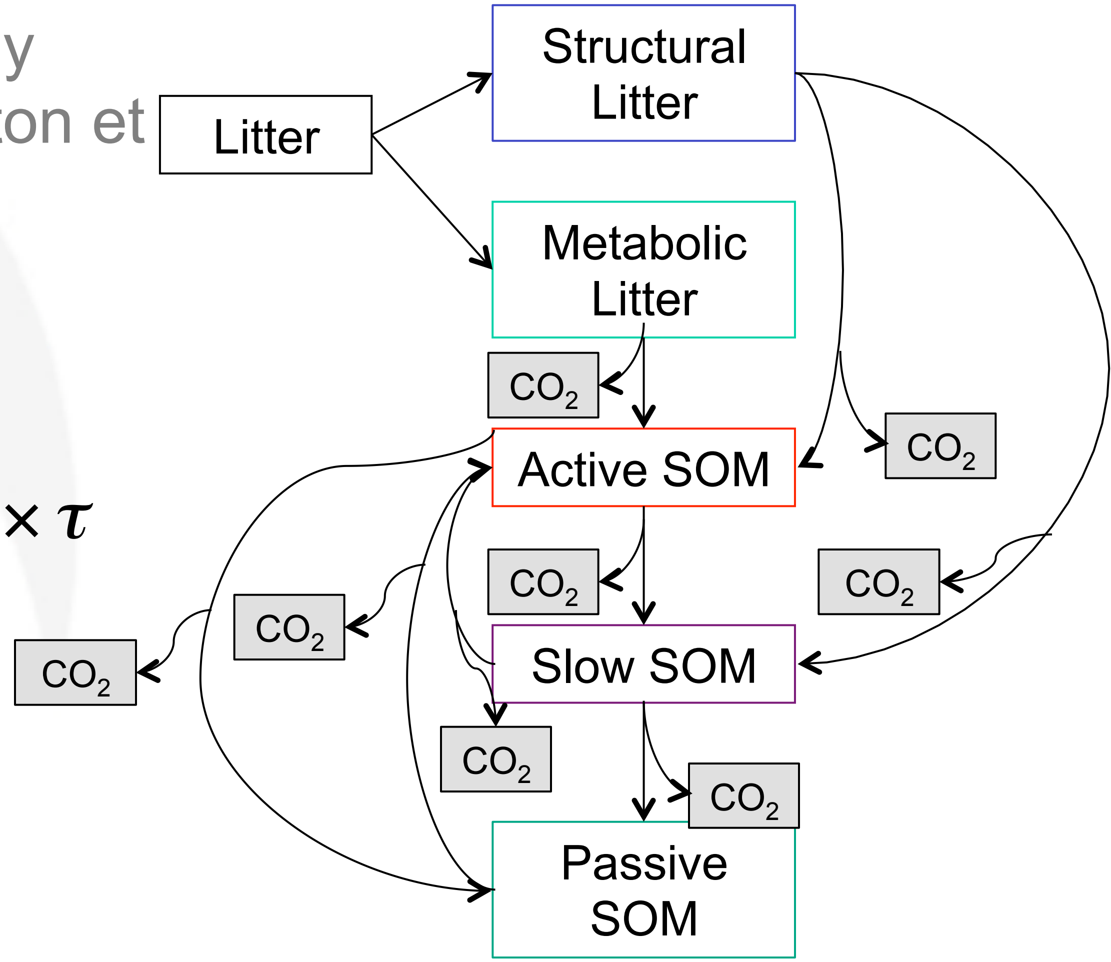
SOILS AND GLOBAL CHANGES



THE SOIL C IN ORCHIDEE

- Soil representation mainly based on CENTURY (Parton et al., 1987).

$$\frac{\partial SOC}{\partial t} = I - k \times SOC \times \theta \times \tau$$



THE SOIL C IN ORCHIDEE

- Split between stomate_litter.f90 and stomate_soilcarbon.f90
- Run at ½ hourly time-step whereas stomate runs at daily time-step.
- Moisture and temperature function calculated in stomate_litter.f90

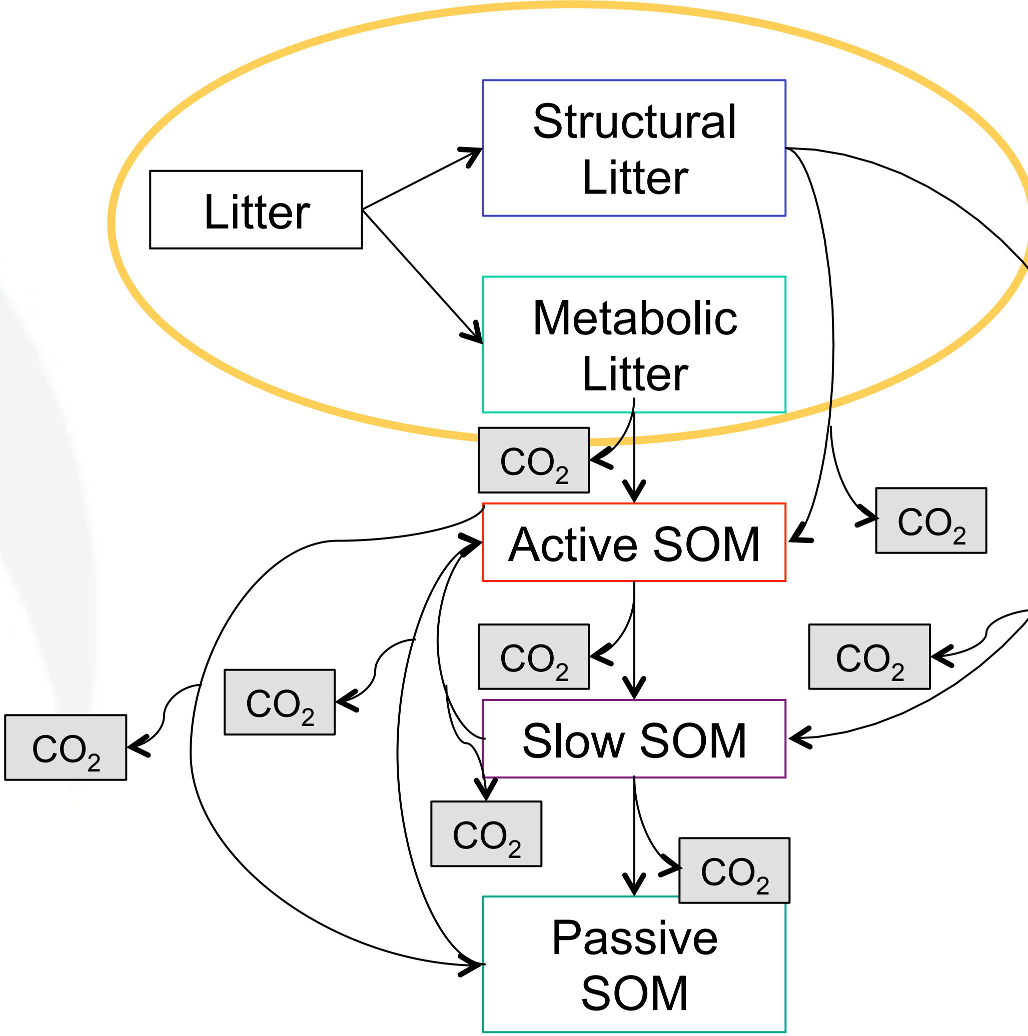
$$\tau = Q_{10}^{(T-Topt)/10}$$

$$\theta = Max(0.25, Min(1, M))$$

$$M=-1.1*SM^2+2.4*SM-0.29$$

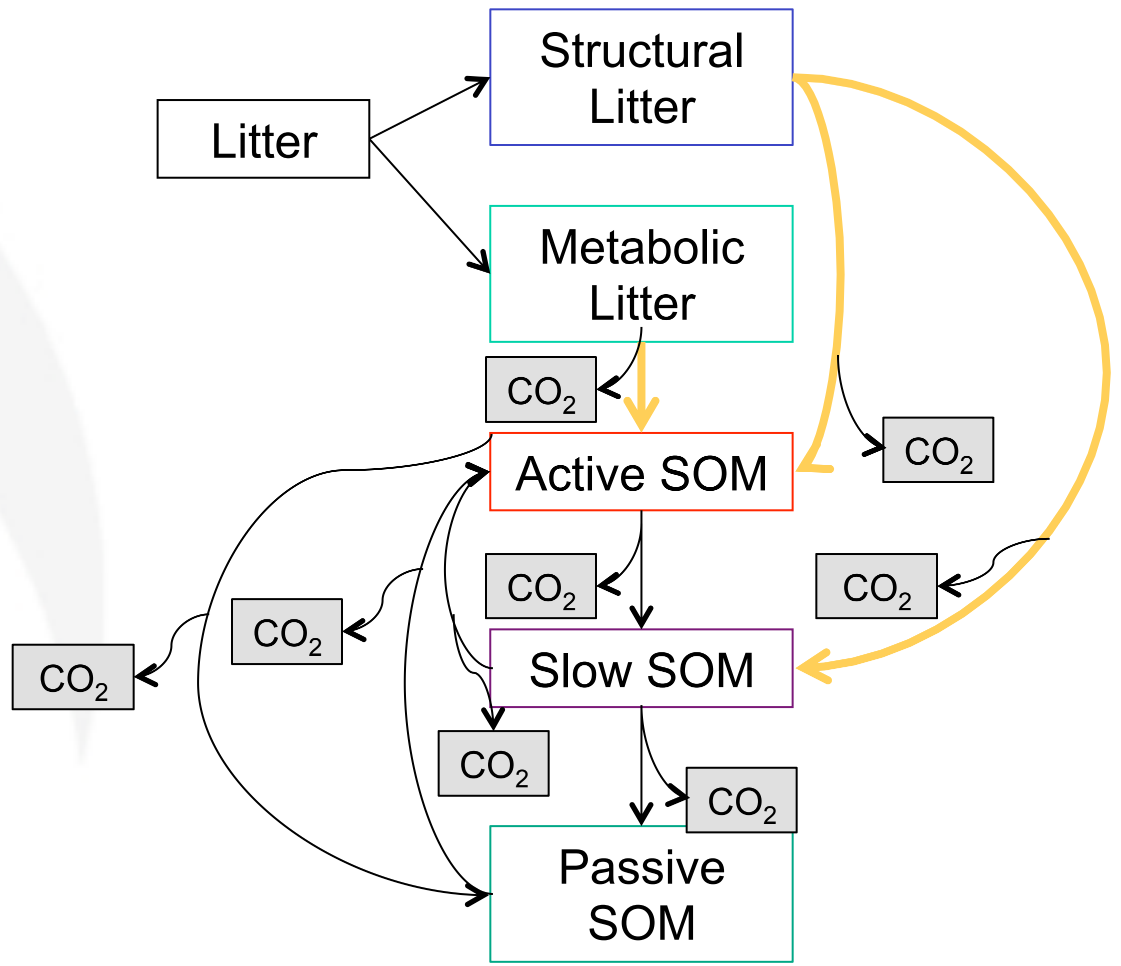
THE SOIL C IN ORCHIDEE

- Input from plants through *bm_to_litter* and *turnover*
- Split between above and below ground
- Split into two pools: metabolic/structural depending on lignin and N content of the litter.



THE SOIL C IN ORCHIDEE

- Inputs from litter decomposition in *soilcarbon_input*
- Distributed into the active and slow pools control by the lignin content.

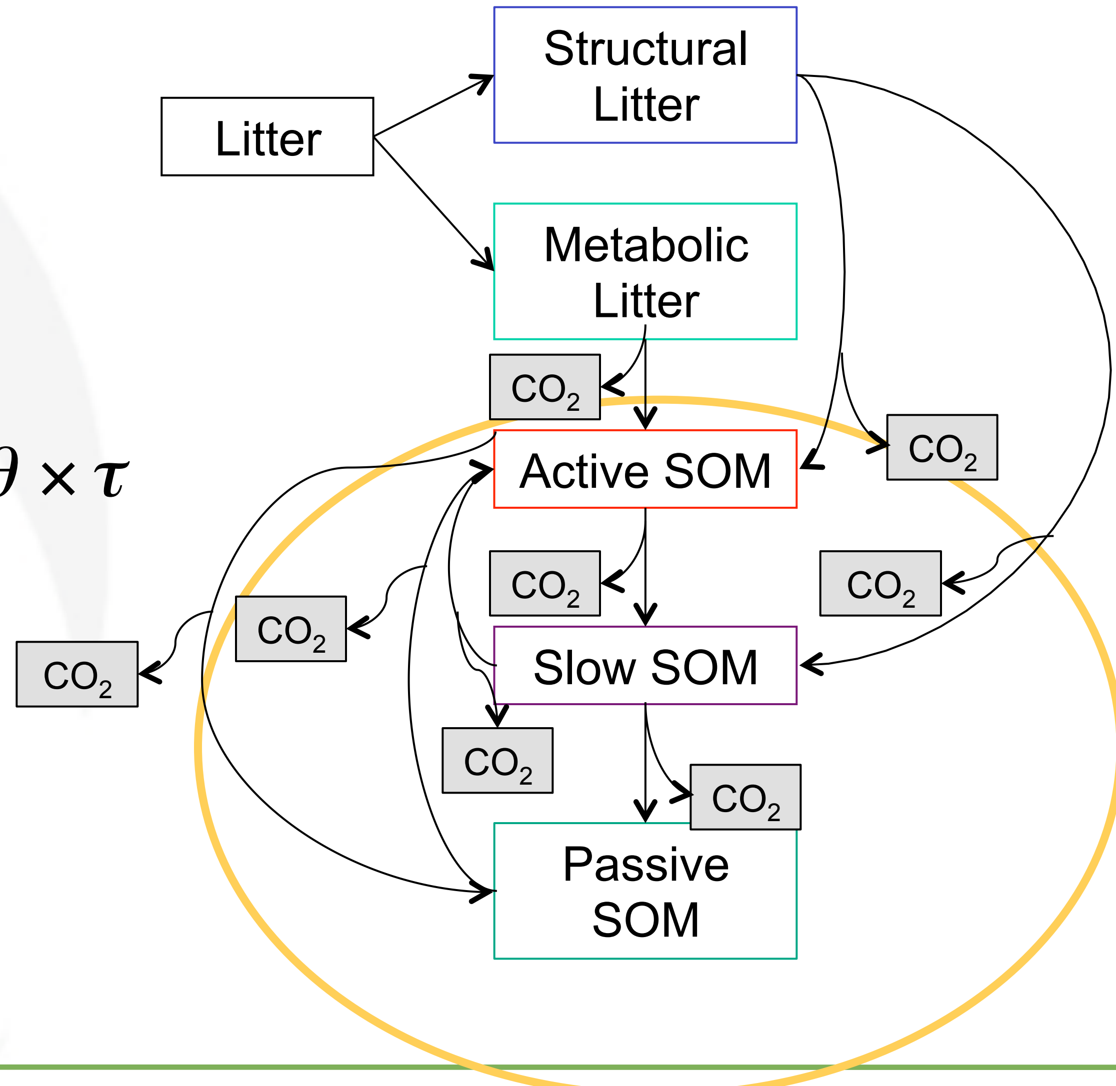


THE SOIL C IN ORCHIDEE

- Decomposition following 1st order kinetics.

$$\frac{\partial SOC}{\partial t} = I - k \times SOC \times \theta \times \tau$$

- A fraction of C decomposed is respired the 1-resp is distributed in the other pools.

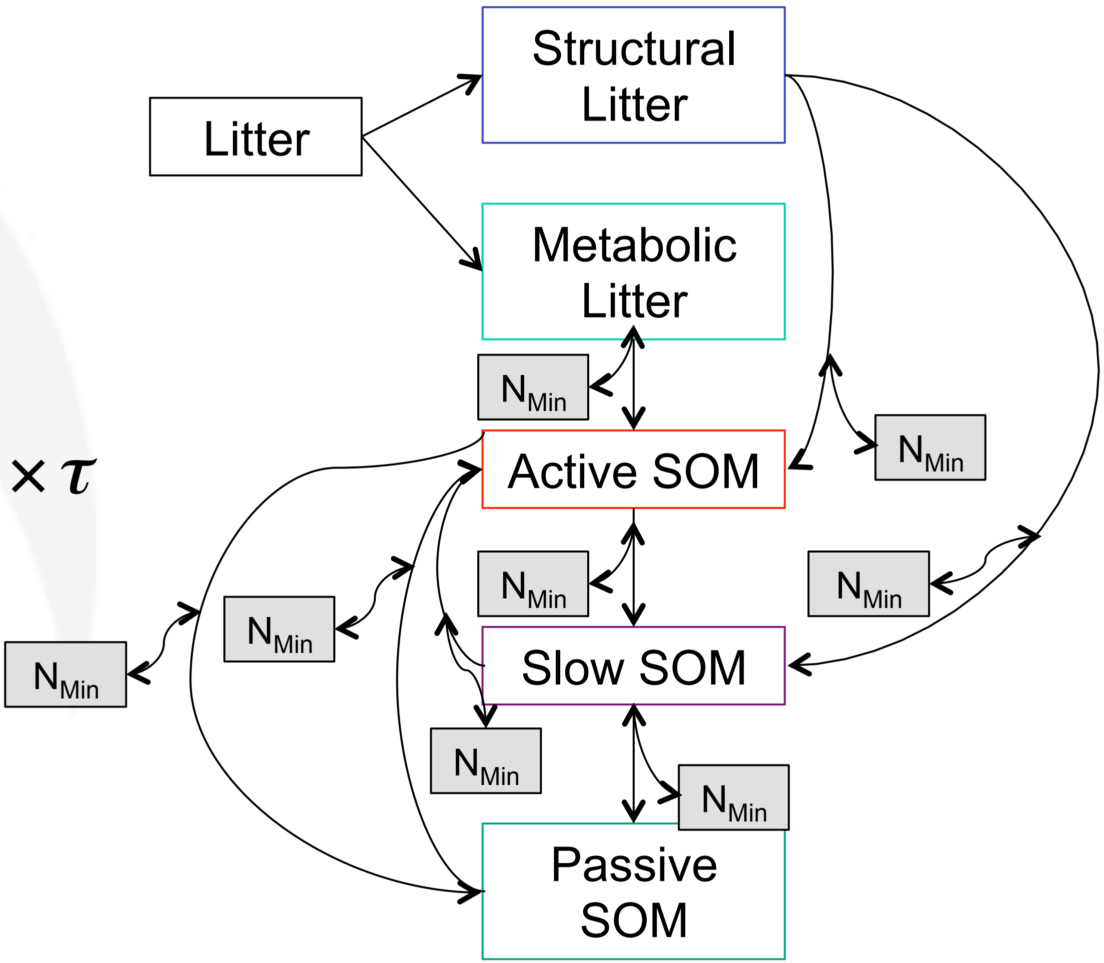


THE SOIL N IN ORCHIDEE

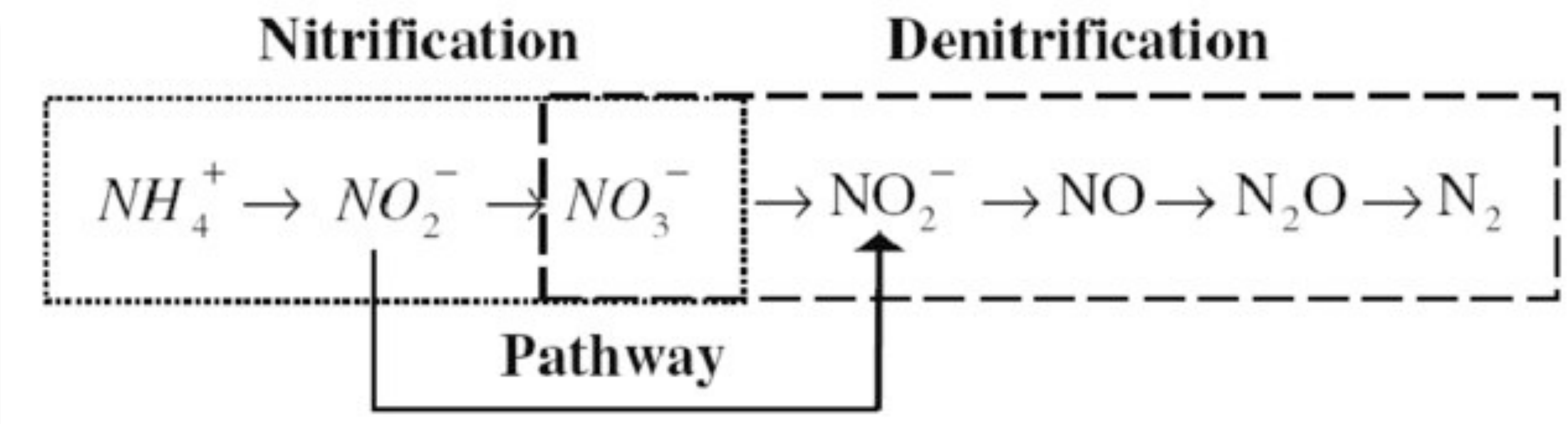
- Decomposition following 1st order kinetics.

$$\frac{\partial SON}{\partial t} = I - k \times SON \times \theta \times \tau$$

- The flux of N from one pool to another must satisfy the CN_target of the receiving pools



HOW THE NITRIFICATION/DENITRIFICATION PROCESSES ARE REPRESENTED

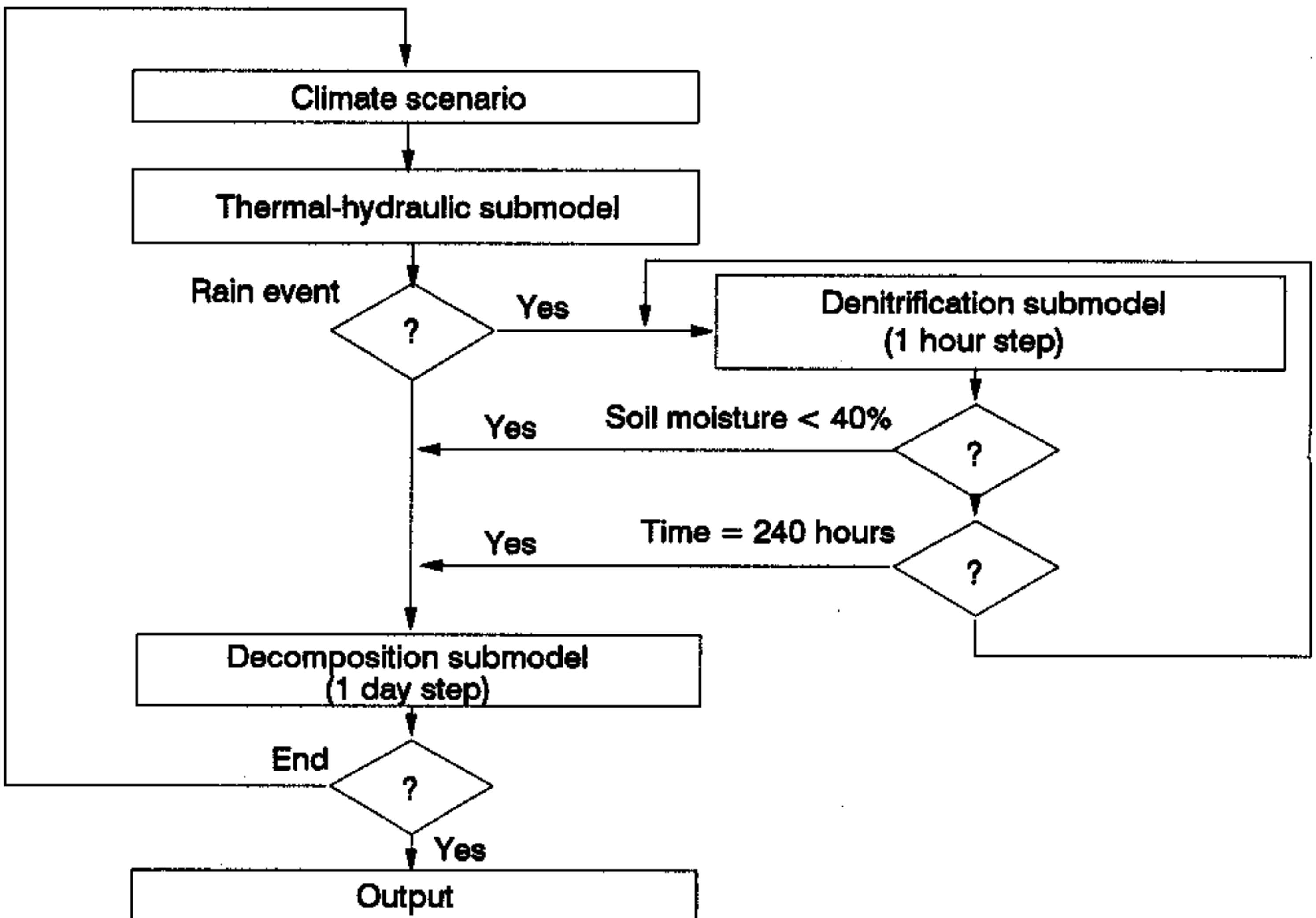


Peng and Zhu (2006)

HOW THE NITRIFICATION/DENITRIFICATION PROCESSES ARE REPRESENTED

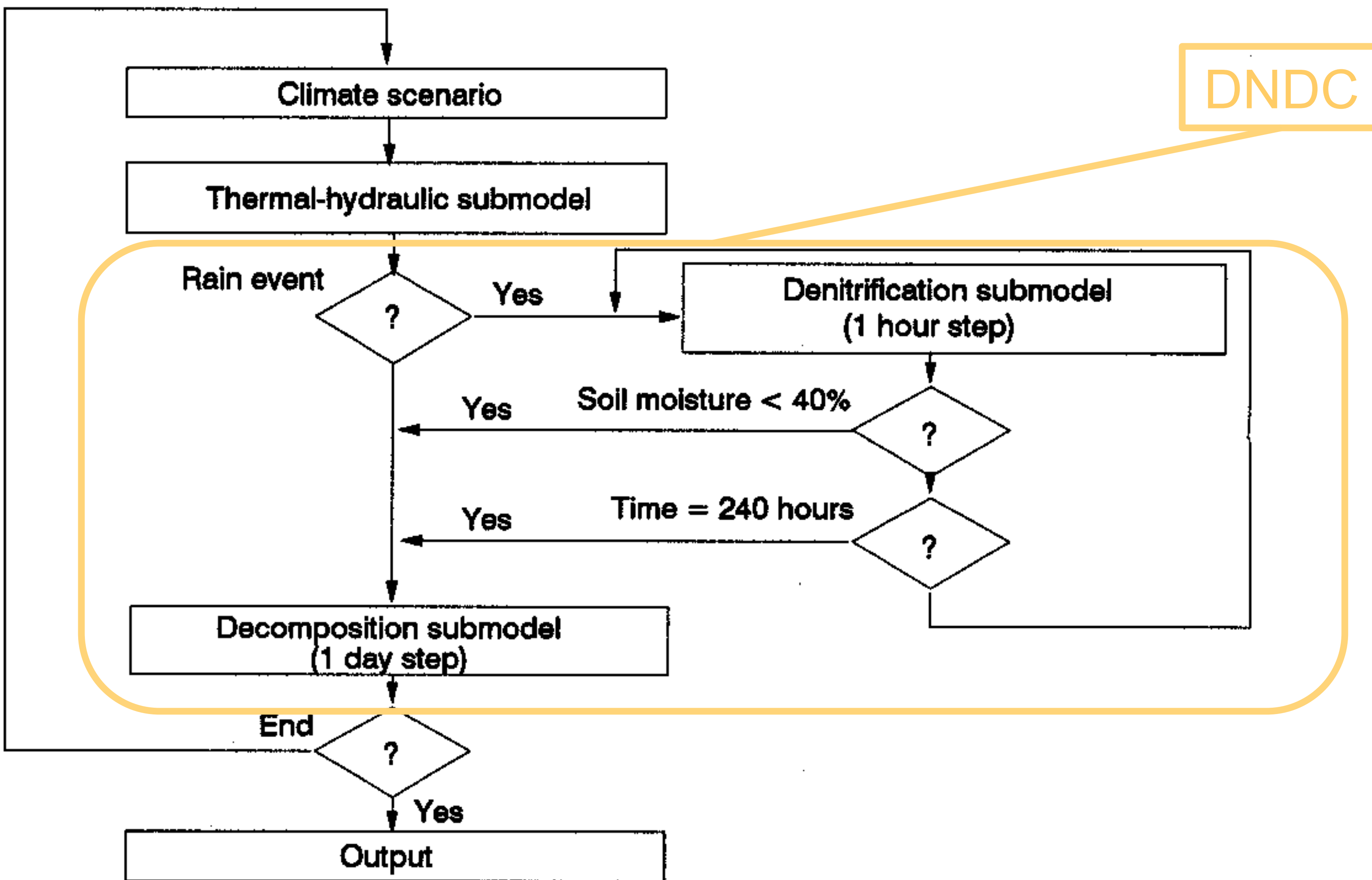
- Key point -> N outputs fluxes & GHG production
- DNDC is an old model based on Li et al. 1992.
- Design to represent denitrification *and* decomposition.
- In ORCHIDEE, only the N-related aspects are used but in a simplified way.

ORIGINAL DNDC



Li et al., (1992)

ORIGINAL DNDC



Li et al., (1992)

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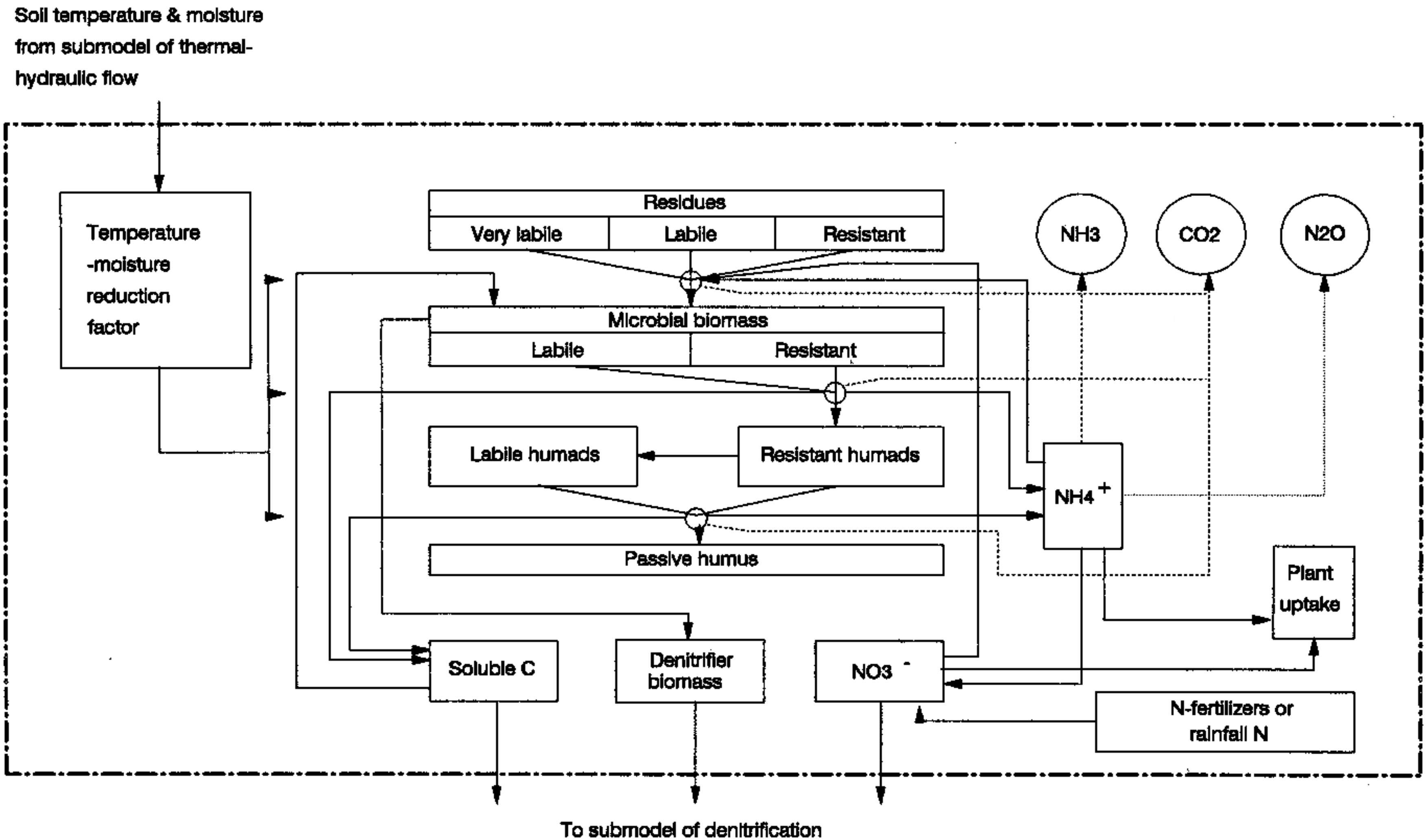
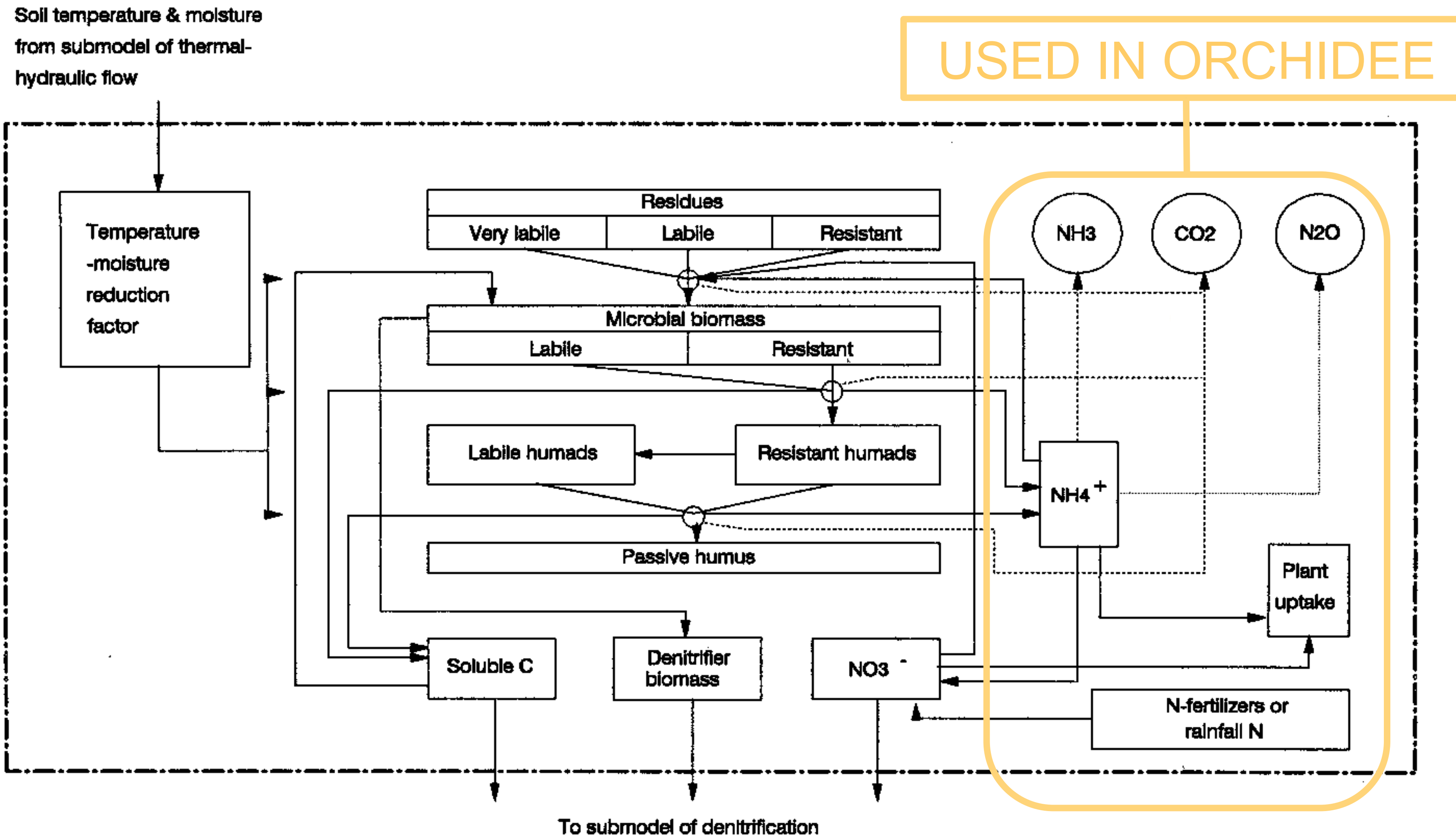


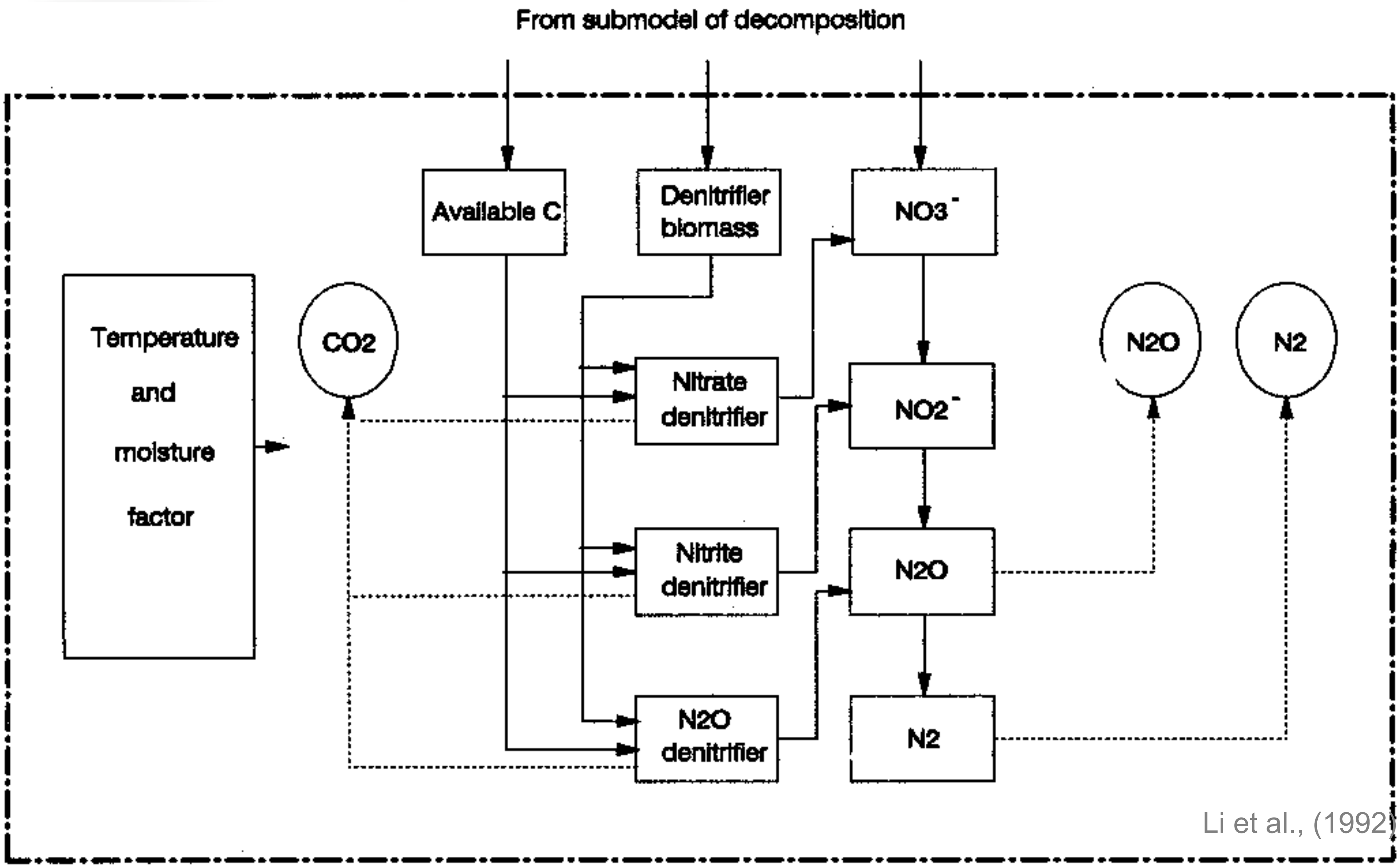
Li et al., (1992)

ORIGINAL DNDC

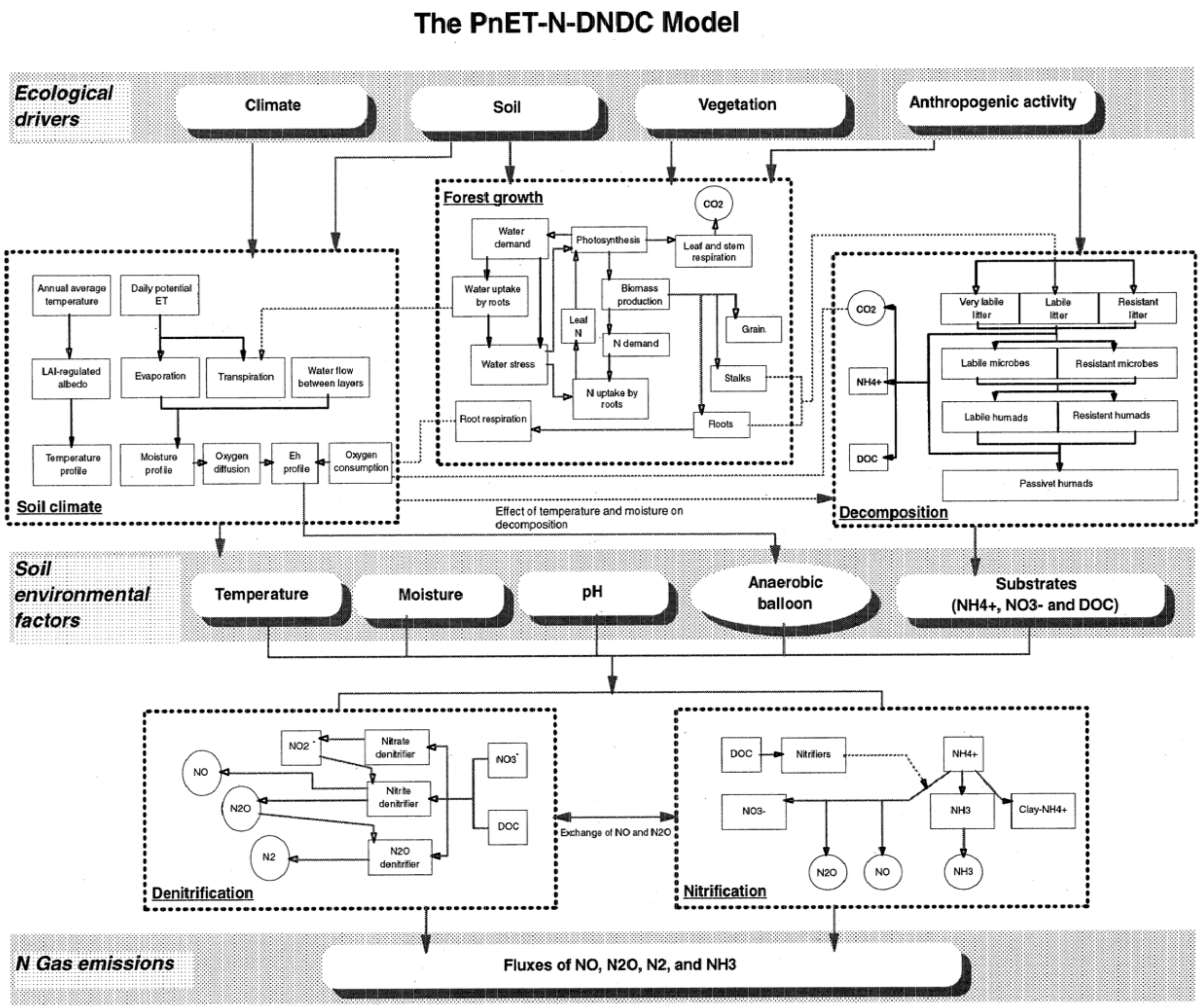


Li et al., (1992)

ORIGINAL DNDC



IMPROVED DNDC



Li et al., (2000)

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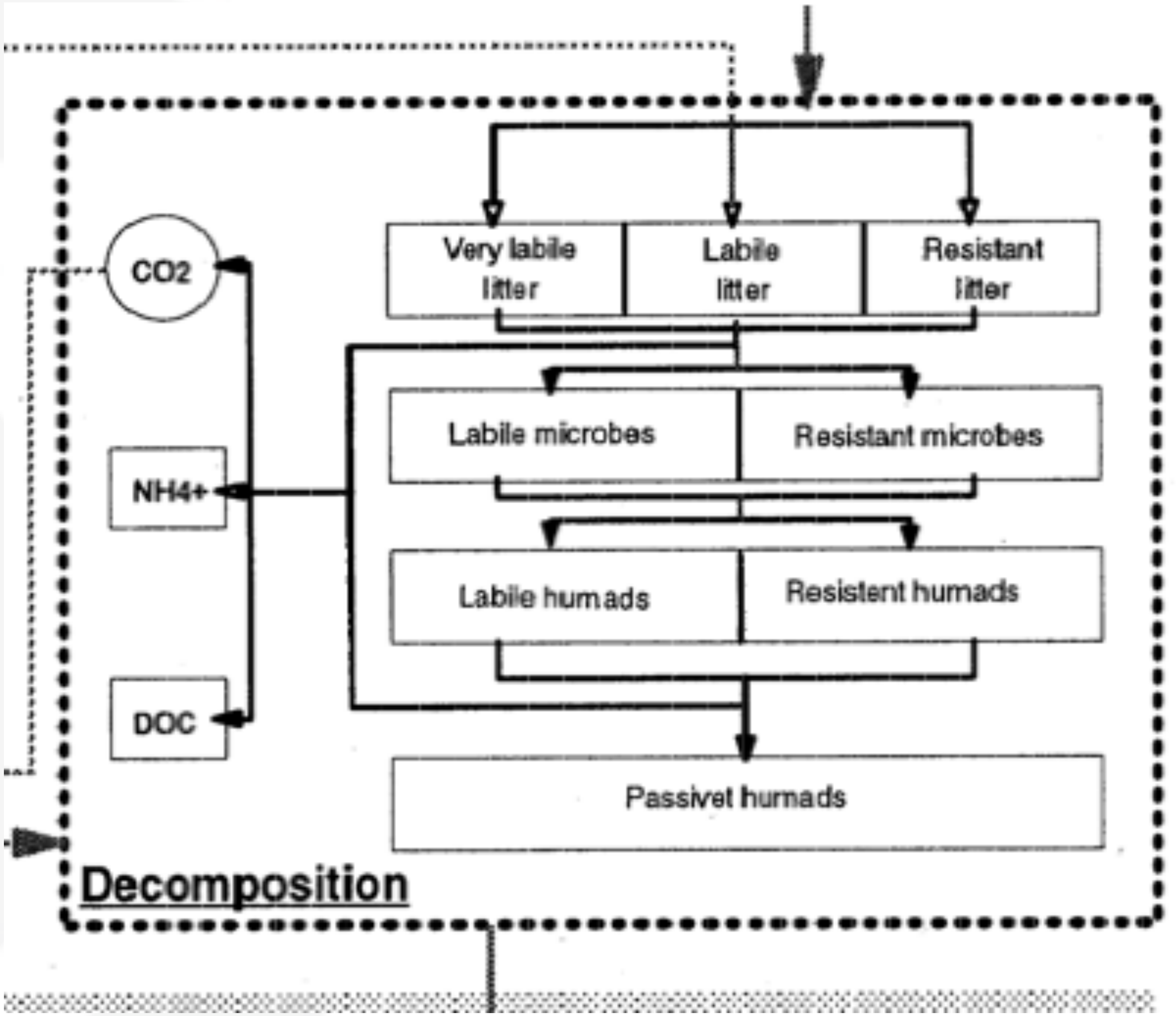

Li et al., (2000)

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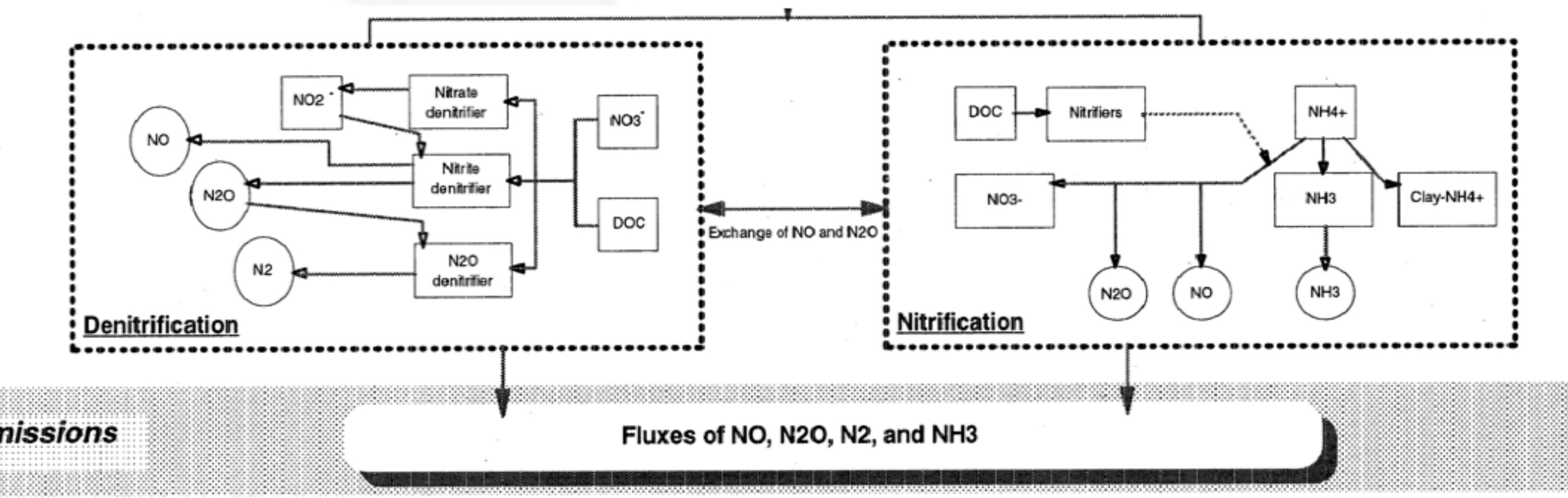
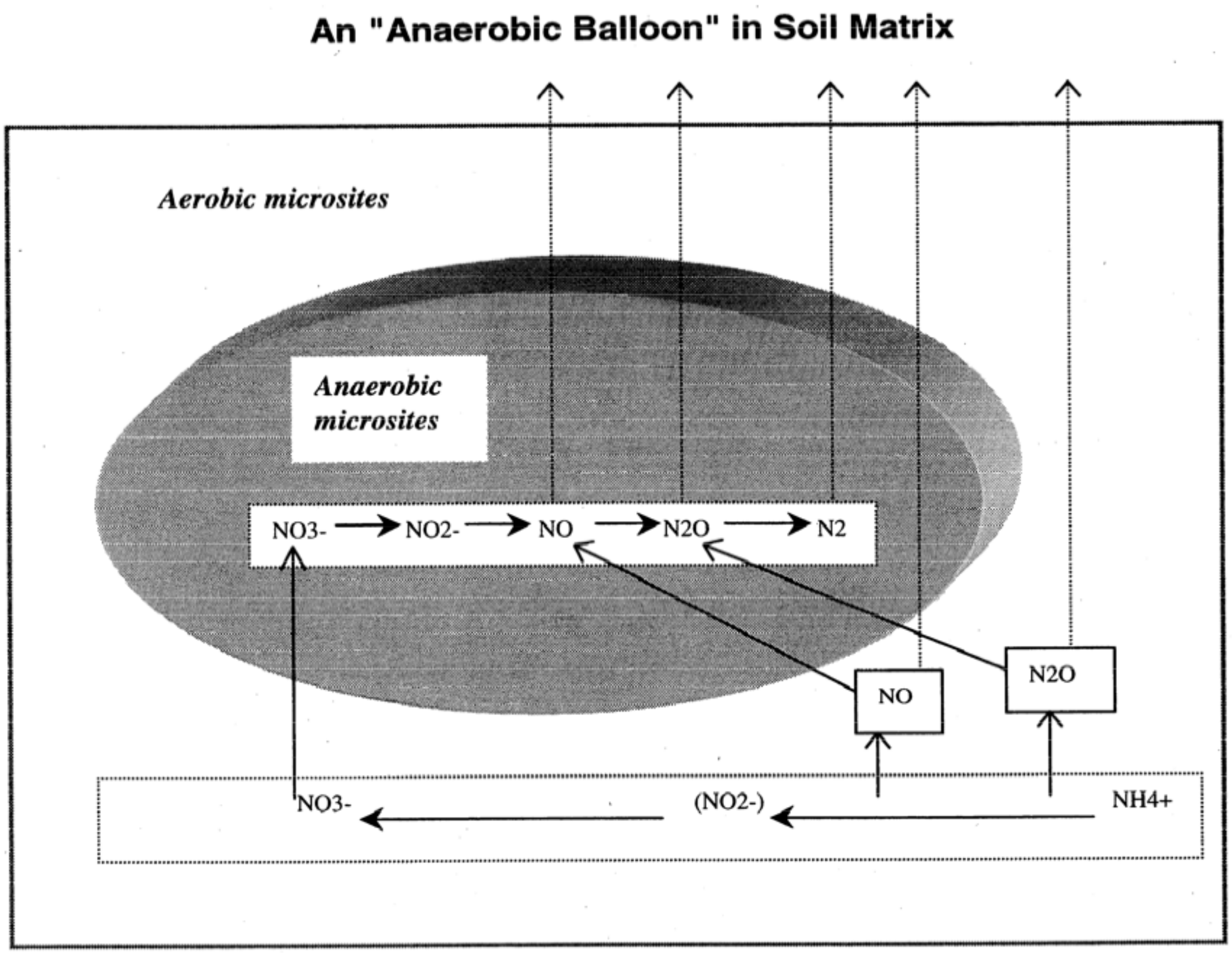


Li et al., (2000)

THE ANAEROBIC BALLOON CONCEPT



Li et al., (2000)

THE ANAEROBIC BALLOON CONCEPT

Table 2. Functions and Parameters for O_2 Diffusion and Volumetric Fraction of Anaerobic Microsites (ANVF)

Equation No.	Function	Equation
1	oxygen diffusion coefficient in soil	$D_{s[L]} = D_{air}\ afps_{[L]}^{3.33} / afps_{max[L]}^{2.0}$;
2	oxygen diffusion rate affected by frost	$D_{s[L]} = D_{s[L]}\ F\_frost$; $0 < D_{s[L]} < 1$
		if $T > 0$ °C, $F\_frost = 1.2$;
		if $T <= 0$ °C, $F\_frost = 0.8$;
		$D_{s[L]} = D_{s[L]}\ F\_frost$; $0 < D_{s[L]} < 1$
		if $T > 0$ °C, $F\_frost = 1.2$;
		if $T <= 0$ °C, $F\_frost = 0.8$;
3	oxygen partial pressure	$d(pO_{2[L]})/dt = (d(D_{s[L]}\ d(pO2_{[L]})/dz)/dz - R)/afps$;
4	Volumetric fraction of anaerobic microsites	$anvf_{[L]} = a\,(1-(b\ \ pO_{2[L]}/\ pO_{2air}))$;

a, b, constant coefficients; afps, air-filled porosity; $afps_{max}$, porosity; anvf, volumetric fraction of anaerobic microsites; D_{air}, oxygen diffusion rate in the air, 0.07236 m^2/h [*Beisecker*, 1994]; D_s, oxygen diffusion coefficient in soil; F_frost, frost factor; L, layer number; pO_2, oxygen partial pressure; R, oxygen consumption rate (kg C $ha^{-1}h^{-1}$); t, time (h); z, soil depth (m).

Li et al., (2000)

THE EQUATIONS

Table 3. Functions and Parameters for Nitrification

Equation No.	Function	Equation
1	relative growth rate of nitrifiers	$\mu_g = \mu_{MAX} (([DOC] / (1 + [DOC]) + F_m / (1 + F_m));$
2	relative death rate of nitrifiers	$\mu_d = a_{MAX} B_n / (5 + [DOC]) / (1 + F_m);$
3	net increase in nitrifiers biomass	$\mu_b = (\mu_g - \mu_d) B_n F_t F_m;$
4	nitrification rate	$R_n = R_{max} [NH4] B_n pH;$
5	temperature factor	$F_t = ((60-T)/ 25.78)^{3.503} e^{(3.503 (T-34.22)/ 25.78)};$
6	moisture factor	if wfps > 0.05 $F_m = 1.01 - 0.21$ wfps; if wfps <= 0.05 $F_m = 0;$
7	NO production from nitrification	$NO = .0025 R_n F_t;$
8	N_2O production from nitrification	$N_2O = 0.0006 R_n F_t$ wfps;

a_{MAX}, maximum death rate for nitrifiers (1.44 1/d [from *Blagodatsky and Richter*, 1998]); B_n, biomass of nitrifiers (kg C/ha); [DOC], concentration of dissolved organic C (kg C/ha); F_m, moisture factor; F_t, temperature factor; [NH4], concentration of ammonium (kg N/ha); NO, NO production from nitrification; N_2O, N_2O production from nitrification [*Ingwersen et al.*, 1999]; pH, soil pH; R_n, nitrification rate; R_{max}, maximum nitrification rate (1/h); T, soil temperature (°C); wfps, water-filled porosity; μ_{MAX}, maximum growth rate for nitrifiers (4.87 1/d [from *Blagodatsky and Richter*, 1998]); μ_b, net increase in nitrifiers biomass; μ_d, relative death rate of nitrifiers; μ_g, relative growth rate of nitrifiers.

Li et al., (2000)

THE EQUATIONS

Table 4. Functions and Parameters for Denitrification

Equation No.	Function	Equation
1	relative growth rate of Nox denitrifiers	$\mu_{NOx} = \mu_{NOx(max)}$ [DOC]/(Kc+[DOC]) $[No_x]/(Kn+[NO_x])$;
2	relative growth rate of total denitrifiers	$\mu_g = F_t\,(\mu_{NO3}\,F_{PH1} + \mu_{NO2}\,F_{PH2} + \mu_{NO}\,F_{PH2} + \mu_{N2O}\,F_{PH3}$; $F_t = 2^{((T-22.5)/10)}$; $F_{PH1} = 1 - 1 / (1 + e^{(pH-4.25/0.5)})$; $F_{PH2} = 1 - 1 / (1 + e^{(pH-5.25/1.0)})$; $F_{PH3} = 1 - 1 / (1 + e^{(pH-6.25/1.5)})$;
3	denitrifier growth rate, death rate, and consumption rate of soluble carbon	$R_g = \mu_g\,B_d$; $R_d = M_c\,Y_c\,B_d$; $R_C = (\mu_g / Y_c + M_c)\,B_d$;
4	consumption rates of N oxides	$R_{NOx} = (\mu_{NOx}/Y_{NOx} + M_{NOx}\,[No_x]/[N])\,B_d$;
5	nitrogen assimiliation rate	$q_N = R_g\,/CN$;
6	gas diffusion factor	$v = D_{max}$ afps (1 - anvf) $F_{clay}\,2^{T/20}$; $F_{clay} = 0.13 - 0.079$ clay;

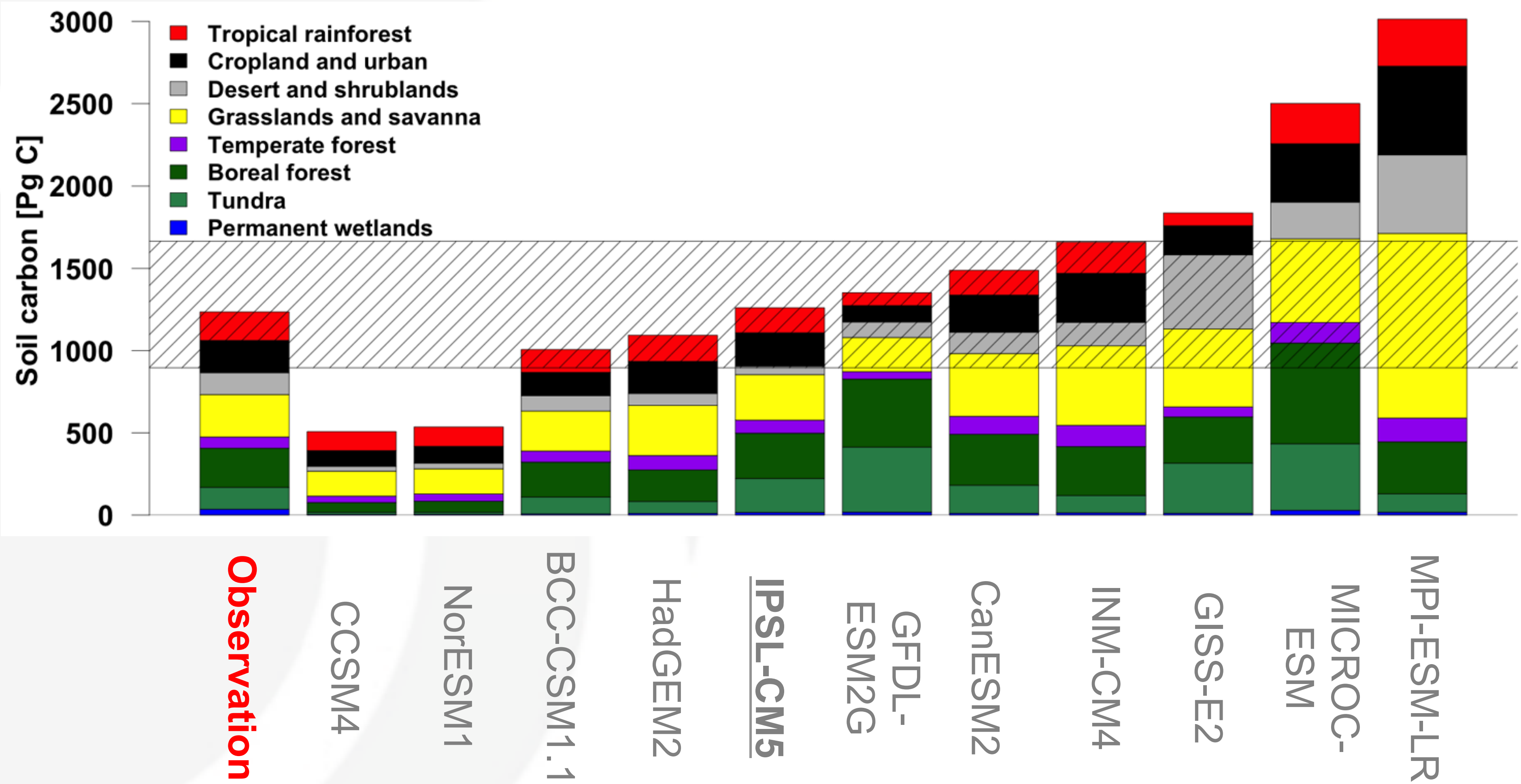
afps, air-filled porosity; anvf, volumetric fraction of anaerobic microsites; B_d, denitrifier biomass (kg C/m^3); clay, clay fraction in the soil; CN, C/N ratio in denitrifiers (3.45 [*Van Verseveld and Stouthamer* 1978]); D_c, consumption rate of soluble carbon by denitrifiers (kg C m^{-3}h^{-1}); D_{max}, maximum diffusion rate in air (m^2/h); D_{NOx}, consumption rate of N oxides by denitrifiers (kg C m^{-3}h^{-1}); [DOC], soluble C concentration (kg C/m^3); F_{clay}, clay factor; F_t, temperature factor; F_{PH1}, pH factors for NO_3^- denitrifiers; F_{PH2}, pH factors for NO_2^- and NO denitrifiers; F_{PH3}, pH factors for N_2O denitrifiers; Kc, half-saturation value of soluble carbon (0.017 kg C/m^3 [*Shan and Coulman*, 1978]); Kn, half-saturation value of N oxides (0.083 kg N/m^3 [*Shan and Coulman*, 1978]); M_c, maintenance coefficient on carbon (0.0076 kg N kg^{-1}h^{-1} [*Van Verseveld et al.*, 1977]); [N], concentration of all NO_x (kg N/ m^3); $[No_x]$, concentration of for NO_3^-, NO_2^-, NO and N_2O (kg N/m^3); pH, soil pH; q_n, nitrogen assimilaion rate (kg N ha^{-1}h^{-1}); T, soil temperature (°C); v, gas diffusion factor (%); Y_c, maximum growth rate of denitrifiers on soluble carbon (0.503 kg C/kg C [*Van Verseveld et al.*, 1977]); M_{NOx}, maintainance coefficient on N oxides (0.09, 0.035 and 0.079 kg N/kg/ for NO_3^-, NO_2^- (+NO*) and N_2O, respectively, based on *Van Verseveld et al.* [1977]); R_d, denitrifier death rate; R_g, denitrifier growth rate; Y_{NOx}, maximum growth rate on N oxides (0.401, 0.428 and 0.151 kg C/kg N for NO_3^-, NO_2^- (+NO*) and N_2O, respectively, based on *Van Verseveld et al.* [1977]); μ_g, relative growth rate of total denitrifiers (1/h); μ_{NO3}, μ_{NO2}, μ_{NO}, μ_{N2O}, relative growth rate of NO_3^--, NO_2^--, NO-, and N_2O denitrifiers; μNOx, relative growth rate of NO_x denitrifiers (1/h); $\mu_{NOx(max)}$, maximum growth rates (0.67 1/h for NO_3^-, NO_2^- denitrifiers, and 0.34 1/h for NO and N_2O denitrifiers, based on *Hartel and Alexander* [1987]). The parameters are shared by NO_2^- and NO due to the lack of data for NO.

Li et al., (2000)

WHAT IS DONE IN ORCHIDEE

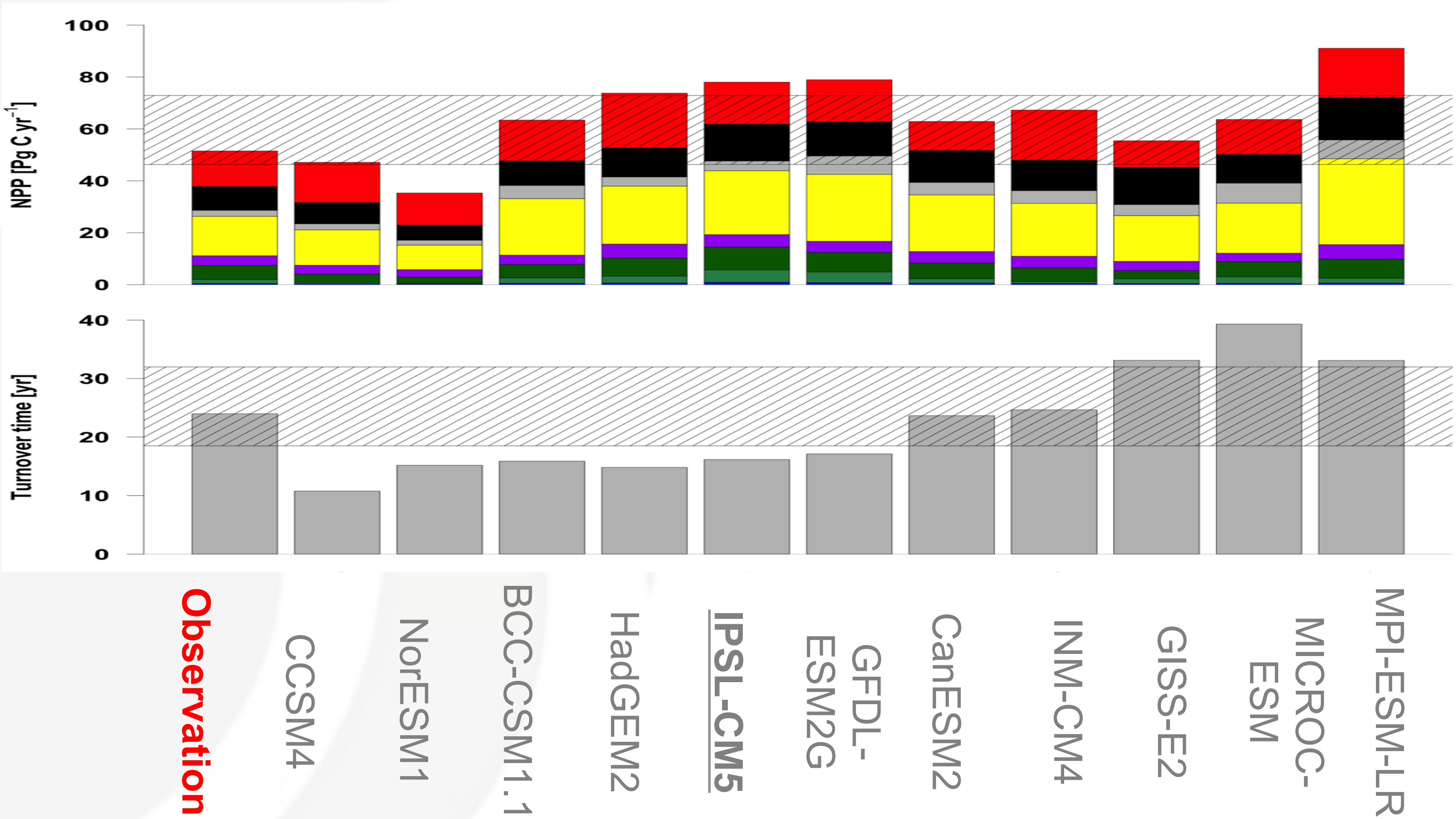
- Implemented by Zaehle et al., (2010)
- At that time, no DOC and no soil C discretization.
- Active C pools used instead of DOC.
- Gas diffusion is calculated using a fixed soil depth value of 20cm.
- Several parameters tuned.
- With Nicolas, we decided to let the original parameter values.

HOW GOOD ARE EARTH SYSTEM MODELS TO REPRESENT SOIL C STOCK



Todd-Brown et al. (2013)

HOW GOOD ARE EARTH SYSTEM MODELS TO REPRESENT SOIL C STOCK



Todd-Brown et al. (2013)

MEAN RESIDENCE TIME

- Based on 14C data, ESM MRT are overestimated by ~40%

Table 1. Global soil carbon stocks and carbon uptake for CMIP5 models that experienced a quadrupling of atmospheric CO_2 from a preindustrial value of 285 ppm over a period of 140 years.

ESM	Initial SOC (Pg C)	% change in SOC	% change in SOC after ^{14}C con-straint	^{14}C-imposed sink reduction (%)	τ_{slow} (year)*	$\tau_{passive}$ (year)	r_f	r_s	^{14}C-imposed correction factors†			
									τ_{slow}	$\tau_{passive}$	r_f	r_s
CESM1 (BGC)	571	6.3	5.1	19	56 ± 16	1310 ± 241	0.06 ± 0.05	0.33 ± 0.05	–	3.7 ± 1.5	–	0.34 ± 0.75
GFDL-ESM2M	1344	26	3.3	87	231 ± 196	–	0.17 ± 0.07	–	16 ± 18	–	0.06 ± 0.14	–
HadGEM2-ES	1028	63	33	46	208 ± 84	–	0.12 ± 0.07	–	17 ± 12	–	0.07 ± 0.32	–
IPSL-CM5A-LR	1340	27	25	5.9	218 ± 82	1181 ± 347	0.06 ± 0.03	0.29 ± 0.07	–	14 ± 8.3	–	0.07 ± 0.14
MRI-ESM1‡	1403	36	22	40	347 ± 117	1065 ± 257	0.17 ± 0.09	0.10 ± 0.06	–	13 ± 7.2	0.46 ± 0.79	0.34 ± 0.74
Mean§	1137 ± 312	32 ± 18	18 ± 12	40 ± 27	212 ± 104	1185 ± 123	0.12 ± 0.06	0.24 ± 0.12	16.5 ± 0.5	10.2 ± 4.6	–	–

*τ_{slow}, $\tau_{passive}$ denote the turnover time, and r_f, r_s denote the transfer coefficient from the fast to the slow pool and from the slow to the passive pool, respectively. Reported values were estimated as an area-weighted mean and standard deviation of all model grid cells. †The mean and standard deviation of the ^{14}C-imposed correction factors were derived from using the ^{14}C observations at each site in a single optimization and then averaging these scalar adjustments across the set of 157 optimizations. ‡The ^{14}C-constrained sink reduction and correction factor for MRI were based on an inverse analysis that changed the pool size of both slow and passive pools. The reported percentage change in SOC and sink reduction were derived from transient simulations starting at steady state with the reduced complexity model. See methods in the supporting materials. §The multimodel mean and standard deviation were estimated using the mean value from each of the five ESMs.

He et al., 2016

A NEW SOIL SCHEME FROM THE MICT BRANCH

- For CMIP6, some LSMs will have permafrost C, explicit N cycle and perhaps both
- All the necessary piece of code exist within the « orchidee environment »
- Opportunity to benefit from the huge effort done in the MICT branch by many colleagues (Dan Zhu, Philippe Ciais, Matthieu Guimberteau, Charlie Koven, …)

Only an option in the trunk controlled by OK_SOIL_CARBON_DISCRETIZATION

WHAT DO WE TOOK FROM MICT?

- Several options are available in MICT but not in the trunk (fire, grassland management, permafrost C)
- Focus on permafrost C
- Not only adding « frozen C »
- Soil C is discretized
- Diffusion is added (including bioturbation and cryoturbation)
- Temperature effect on SOC mineralization
- When frozen, nroot is set to -> impact on water stress and on transpiration.
- Optional
    - Zimov effect
    - Insolation effect (thermal conductivity affected by SOC)

WHAT IS NEW

- Soil organic N is also discretized
- Mineral N is not
- No effect on N plant uptake

ONGOING DEVELLOPEMENT

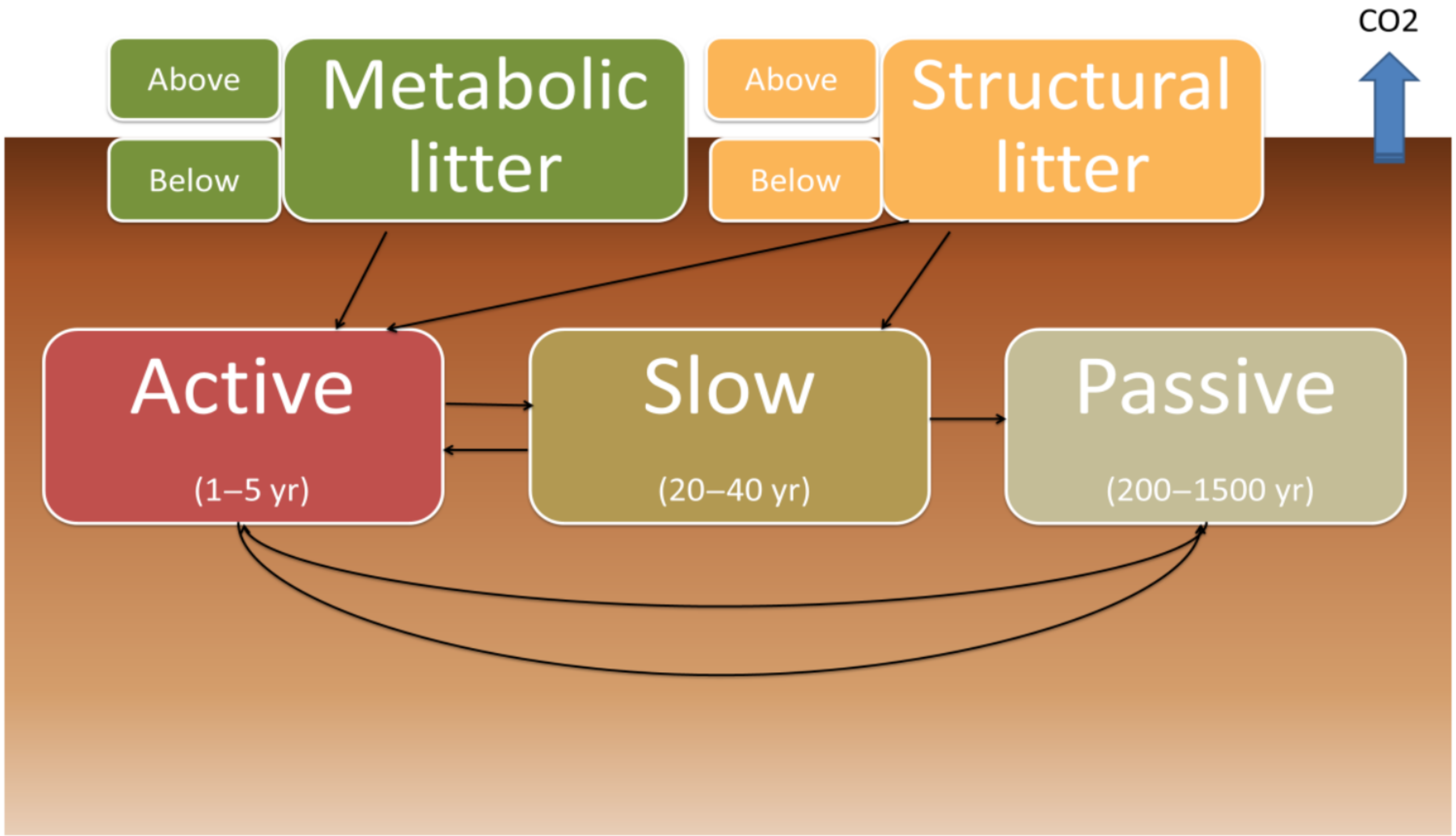
- Representation of the soil C/N profile
- Lateral outputs of C (DOC, Erosion)
- Representation of Priming effect.
- Carbon isotopes (^{14}C and ^{13}C)
- Peatlands

Soil Carbon discretization

- Any models used for CMIP5 represent the soil C profiles.
- A substantial part of the soil C stored in deep layers (Jobbagy and Jackson, 2000)
- Deep C dynamic different from surface C (Fontaine et al., 2007)
- In ORCHIDEE any C is lost by drainage or runoff instead of the importance of allochtonous C in the aquatic ecosystems functionning (Cole et al., 2007, Bianchi et al., 2011)

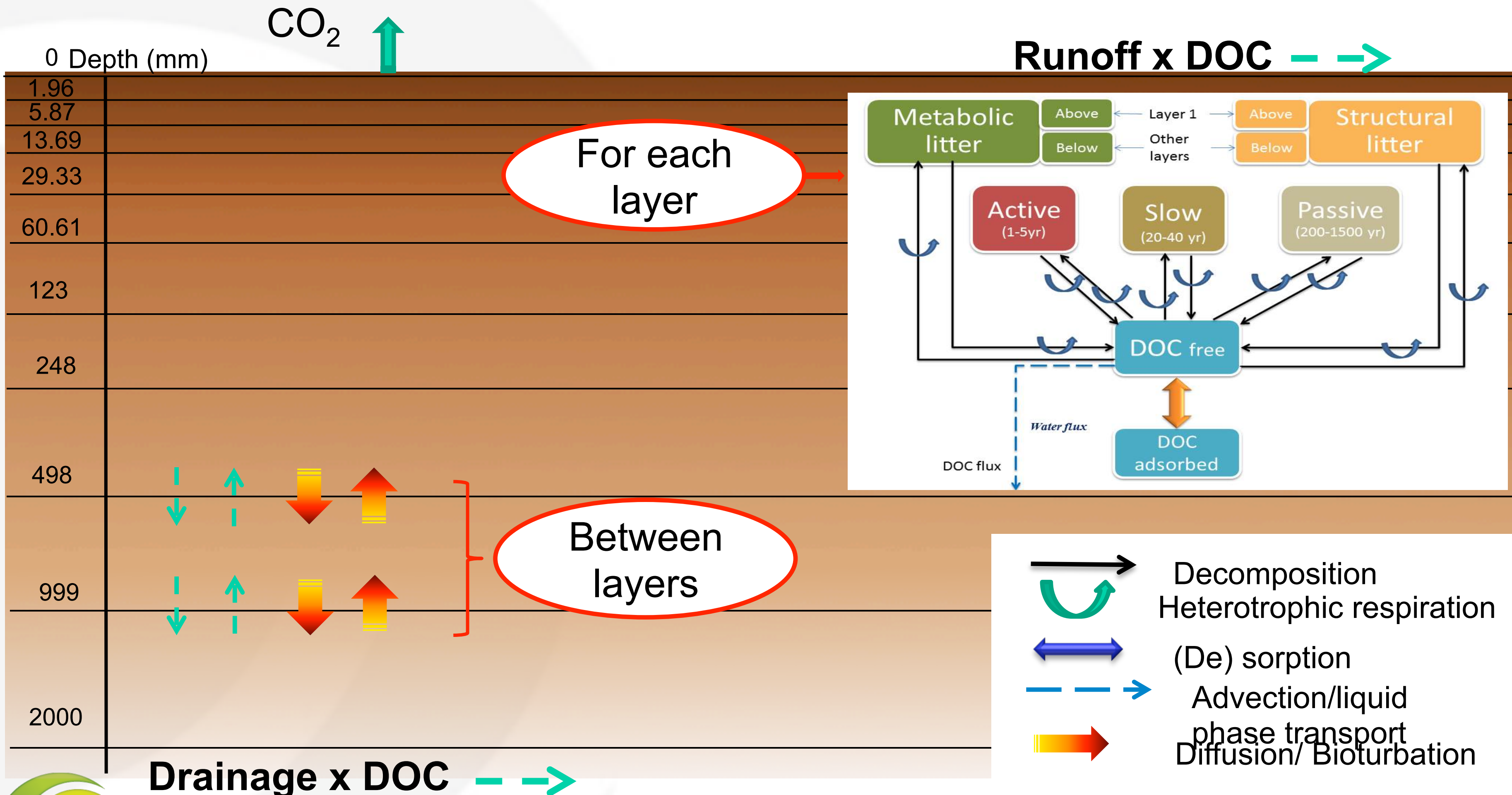
Soil Carbon discretization

ORCHIDEE SVN r3340



Soil Carbon discretization

Soil C discretized using the same layers than hydrology scheme (11 layers). A new pool introduced (DOC)



Soil Carbon discretization

- Adsorption of DOC following initial mass isotherms

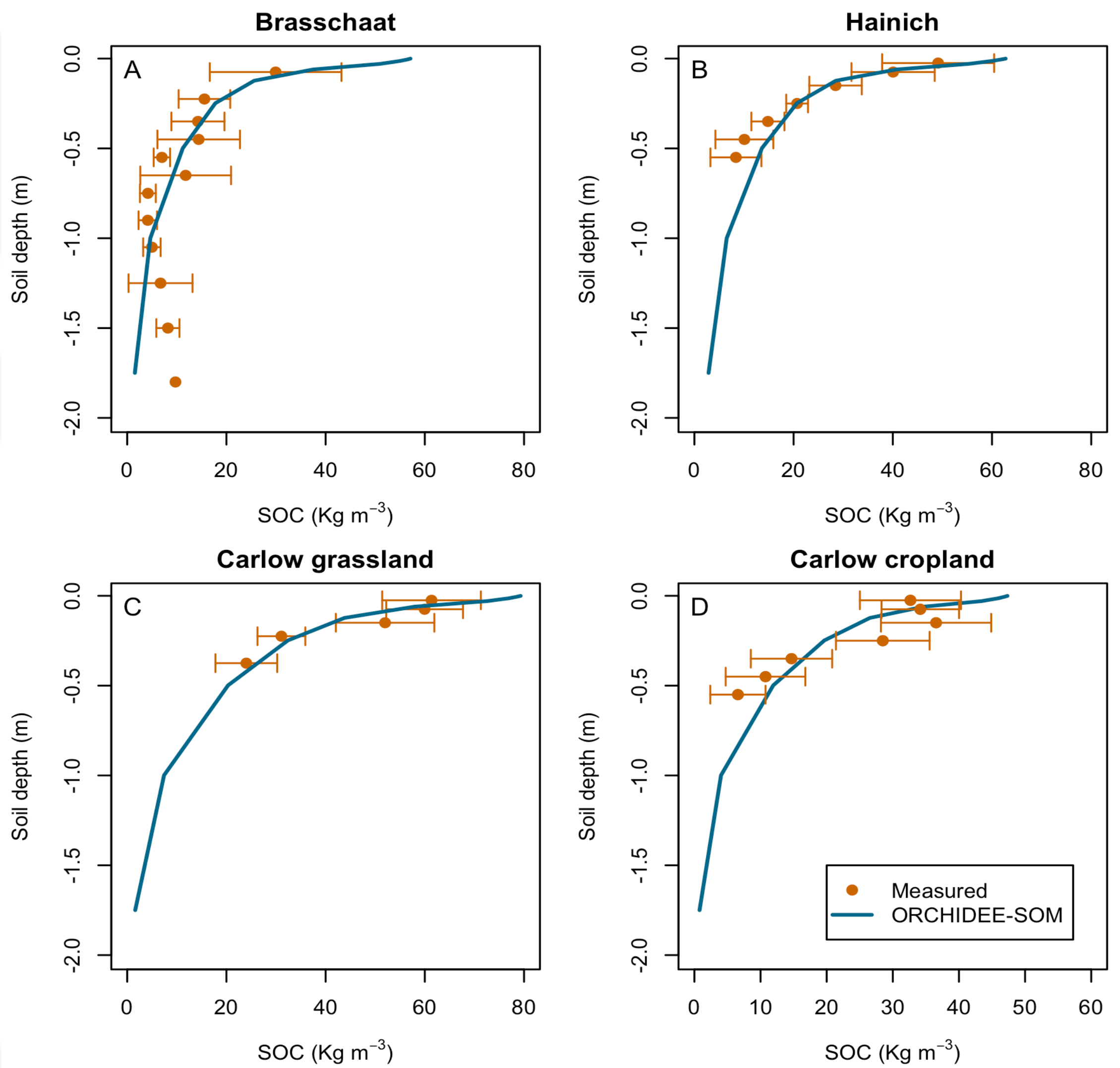
$$DOC_{ads} = Kd \times DOC_{free}$$

- DOC transported within the profile following the water movements (Futter et al., 2007) and exported following the runoff and the drainage fluxes

- POC and DOC transported using the second Fick's law

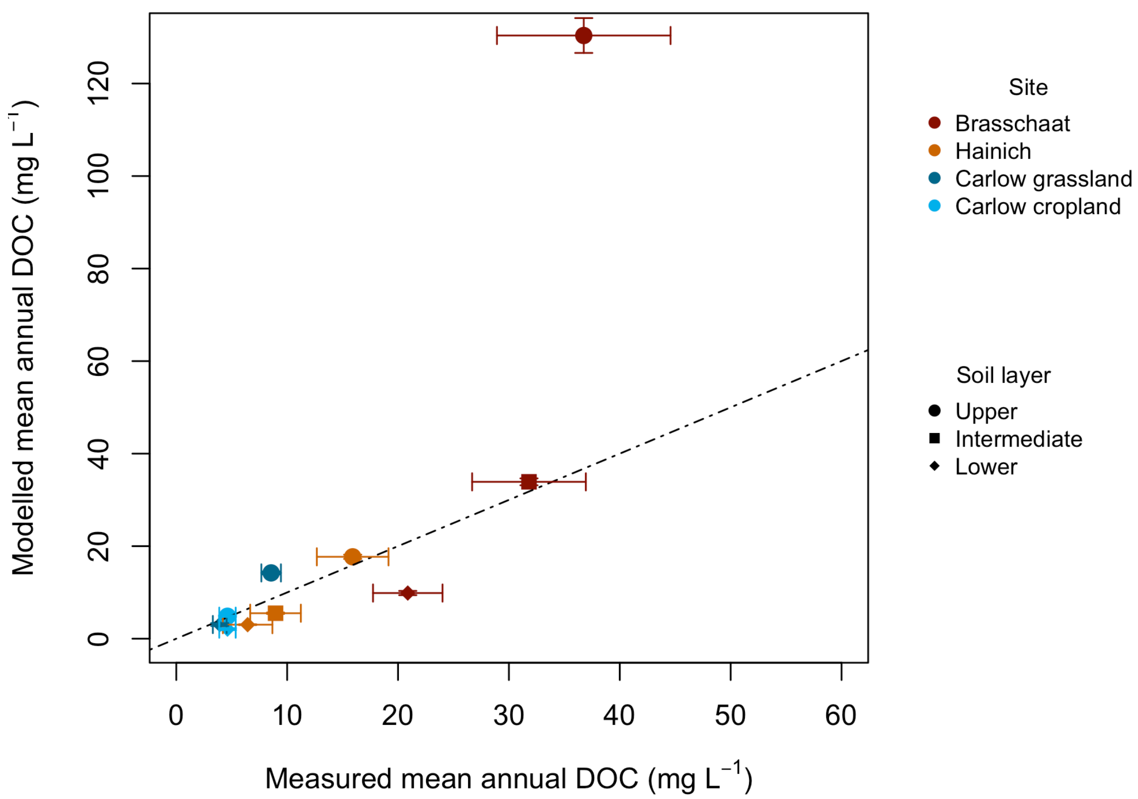
$$F_D = -D \times \frac{\partial^2 C}{\partial z^2}$$

SITE SIMULATIONS



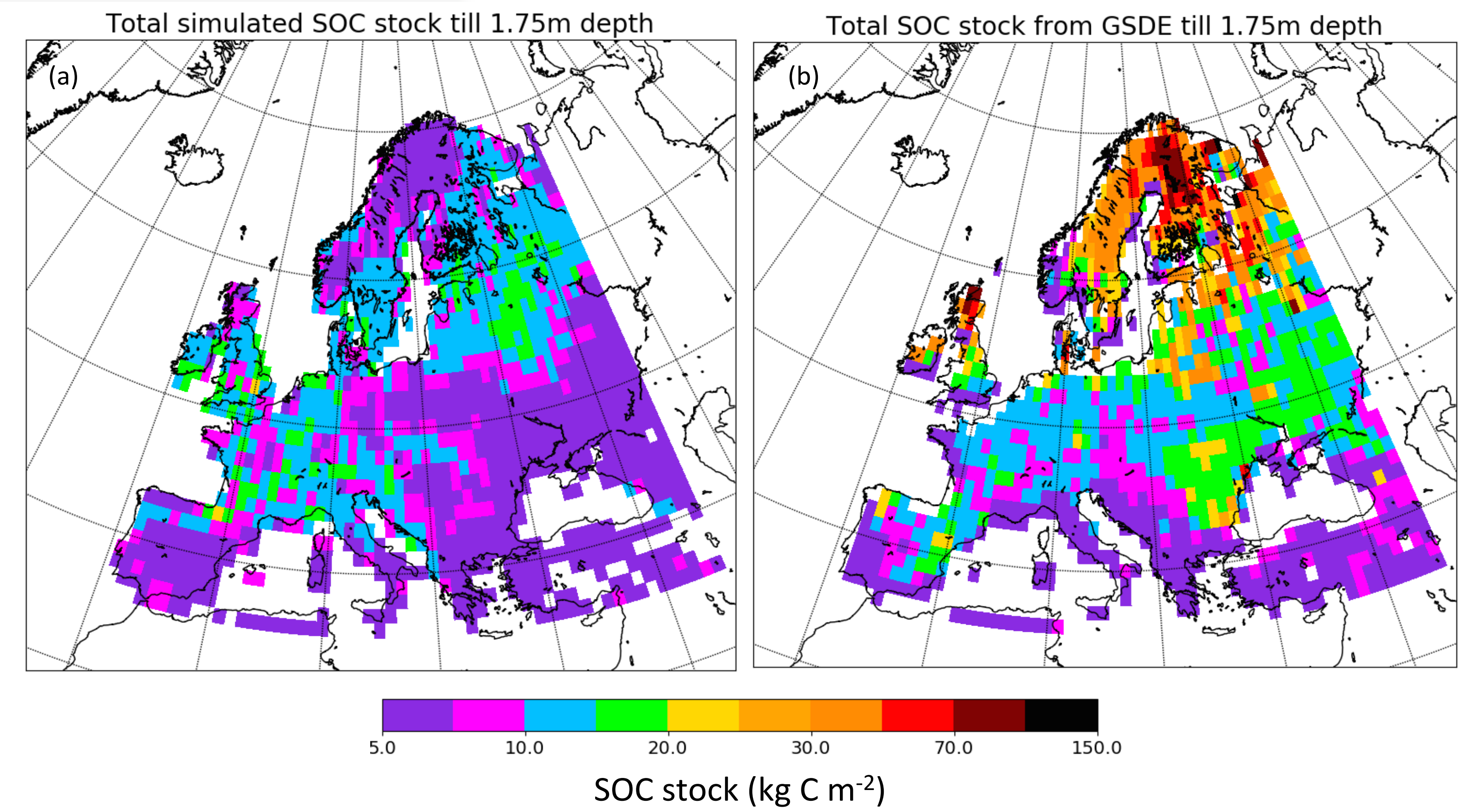
Camino-Serrano et al., (2018)

SITE SIMULATIONS



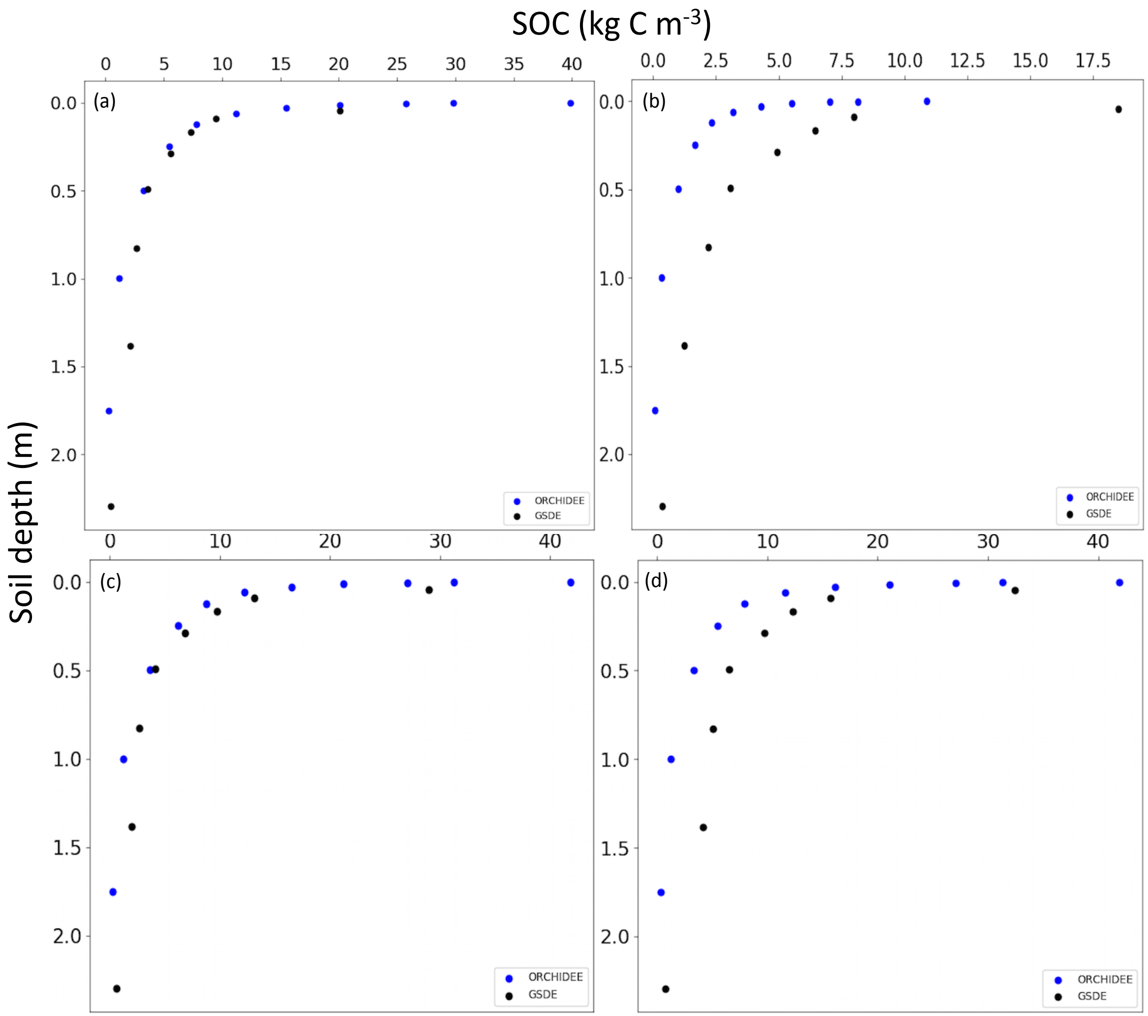
Camino-Serrano et al., (2018)

OVER EUROPE



Guenet et al., (*In prep*)

OVER EUROPE



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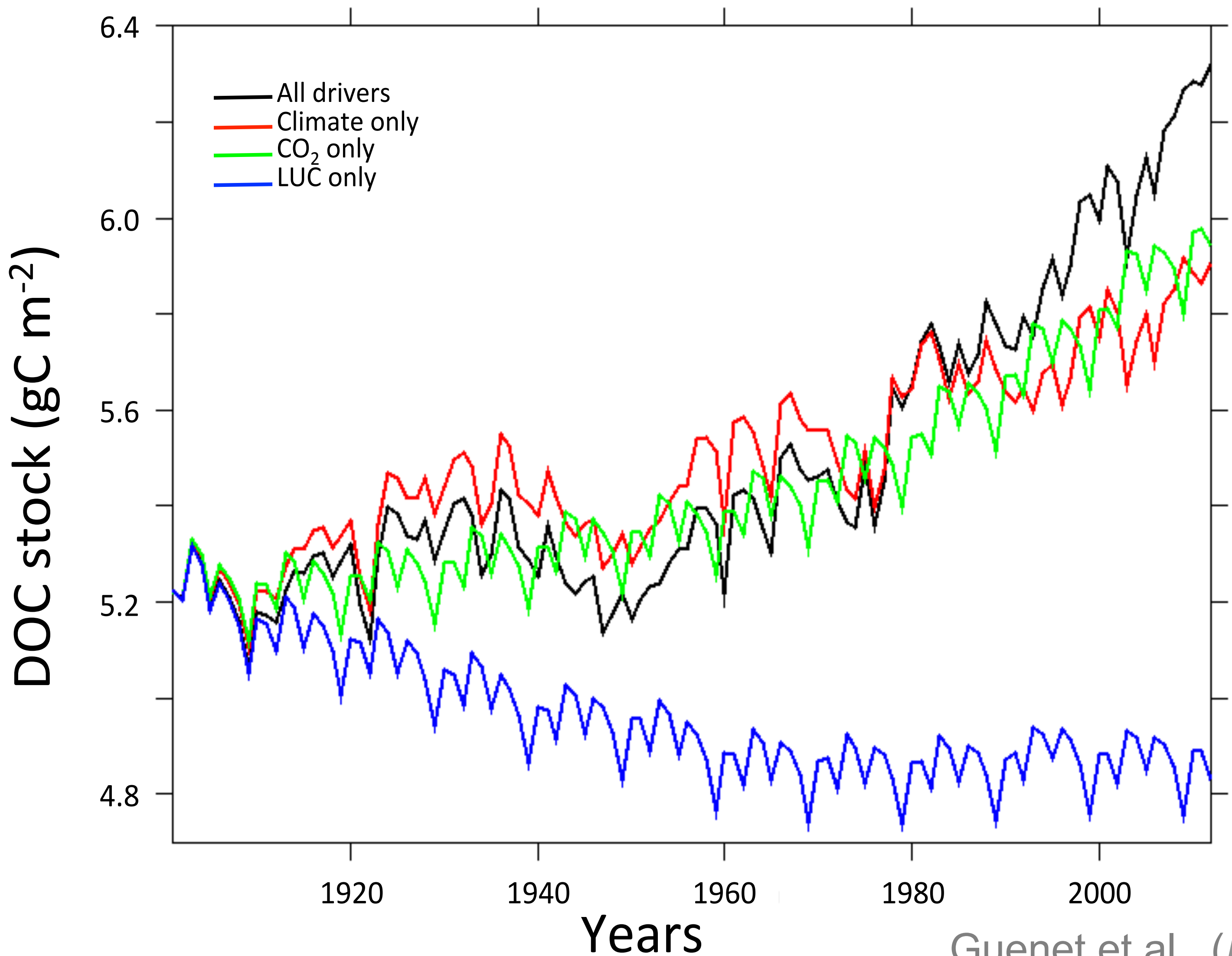

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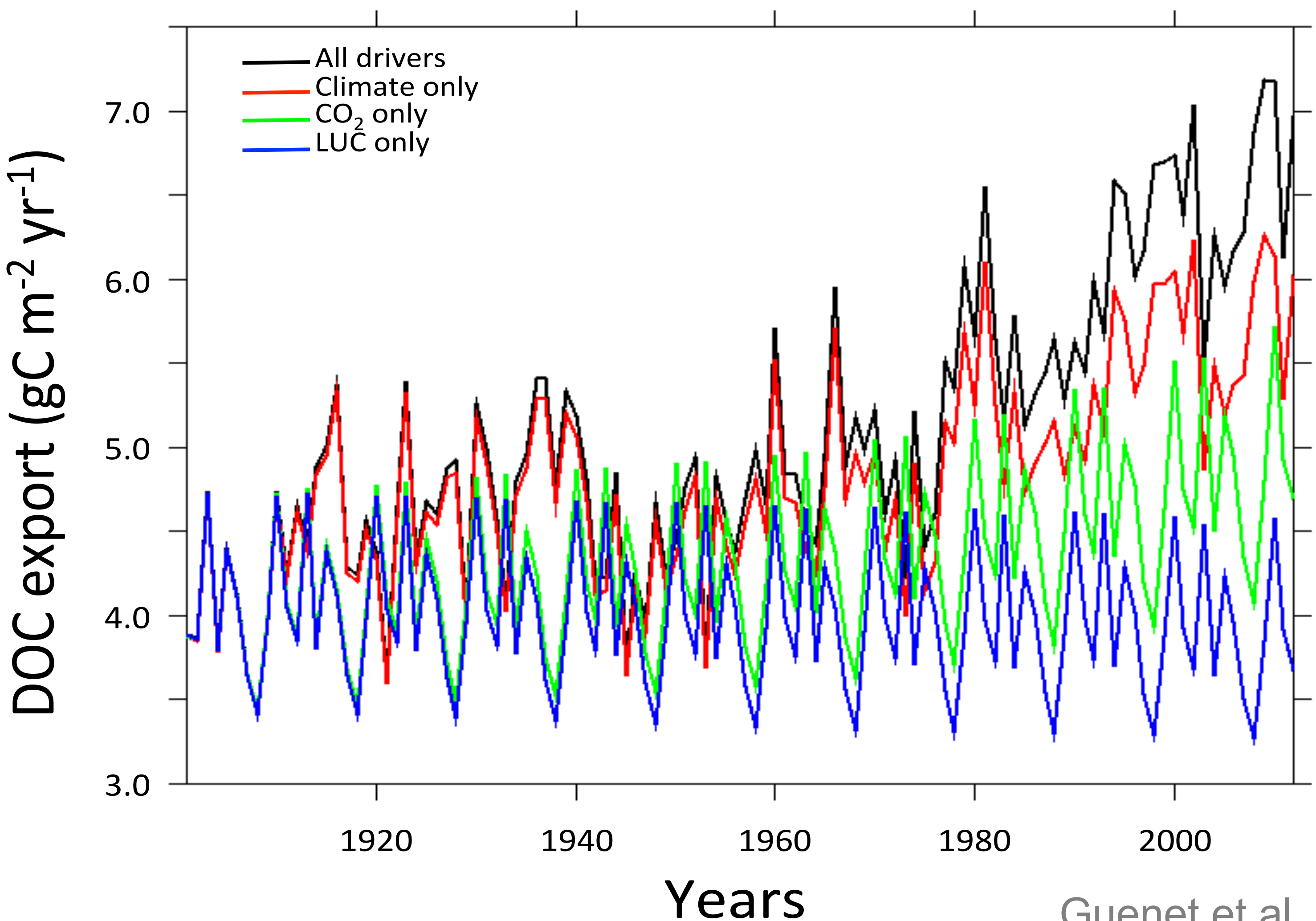

Guenet et al., (*In prep*)

THANK YOU FOR YOUR ATTENTION!