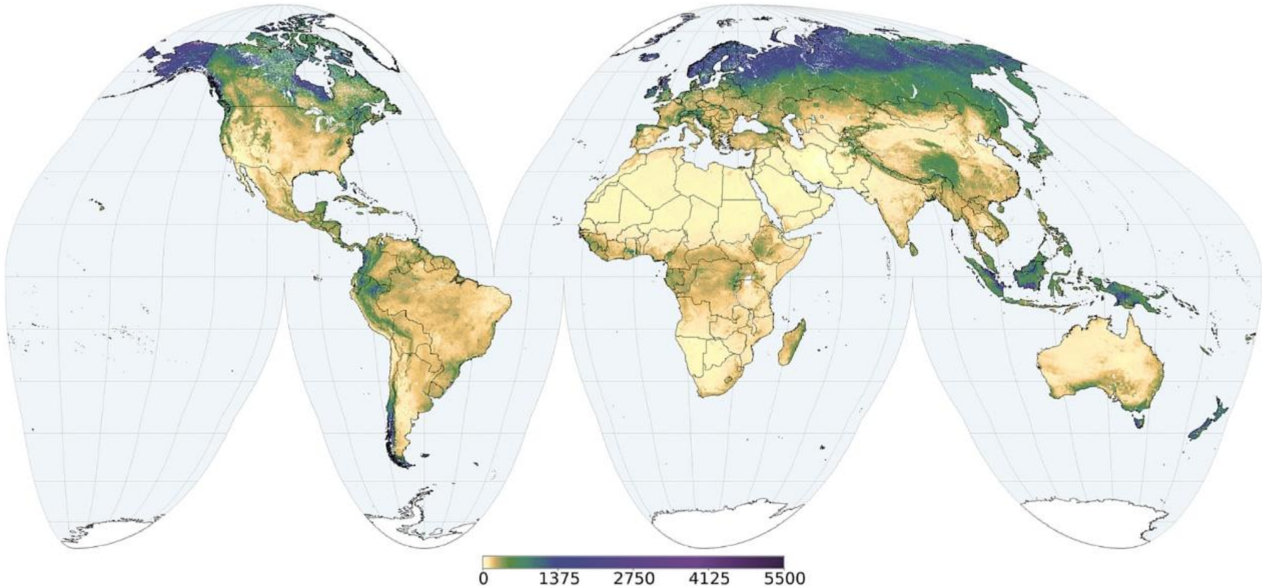
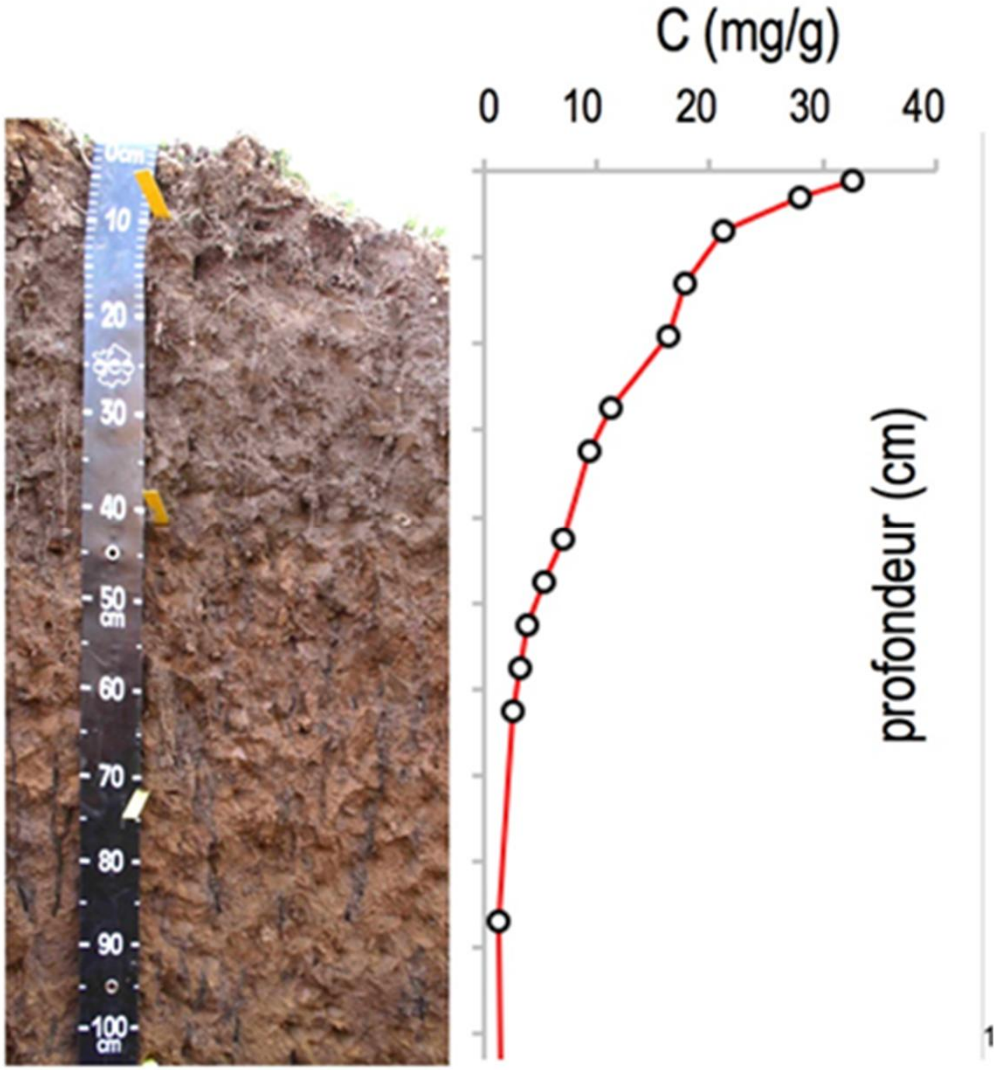


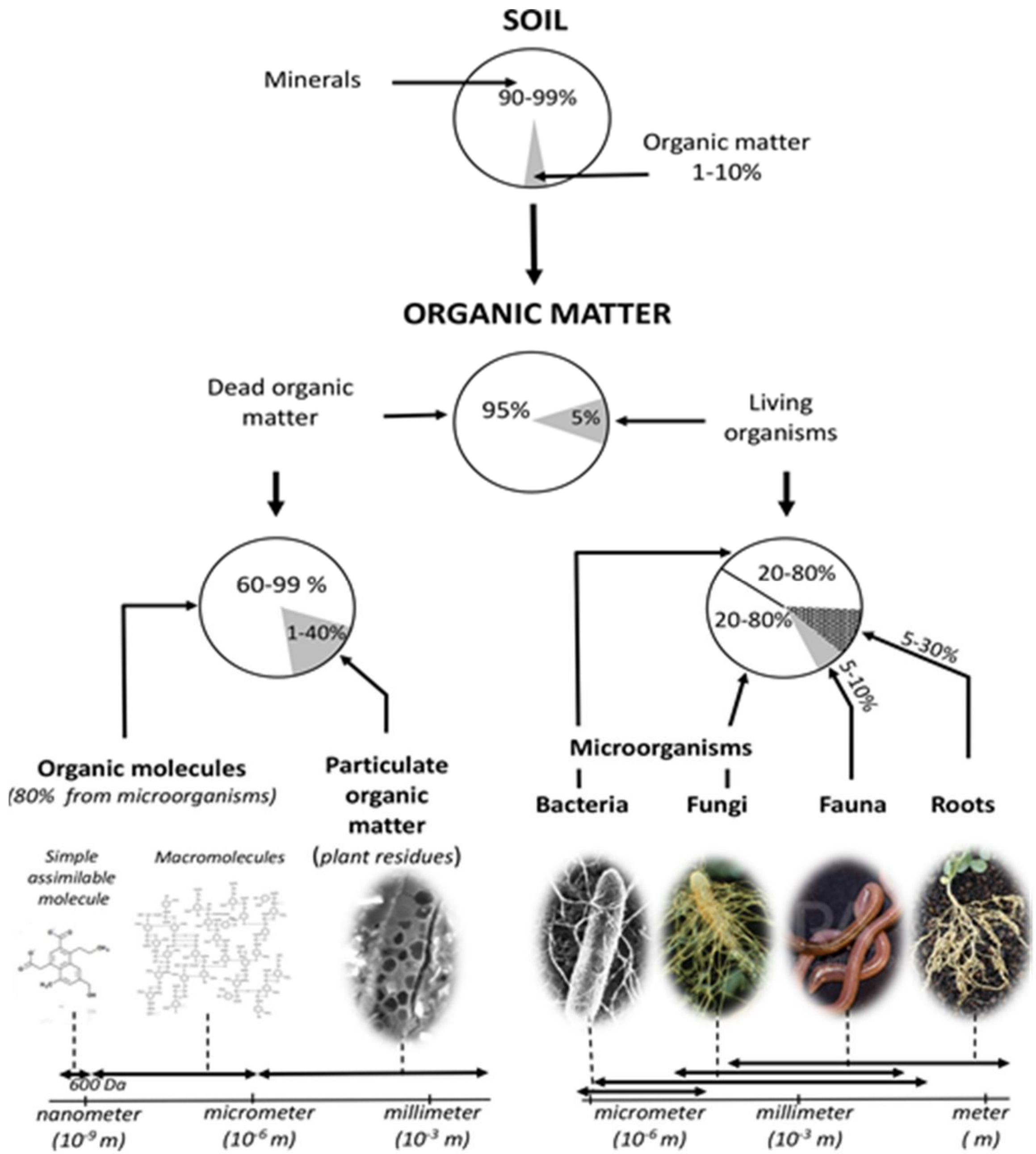
(Poggio et al., 2021)

Stocker du carbone dans les sols agricoles: une piste pour atténuer le changement climatique ?

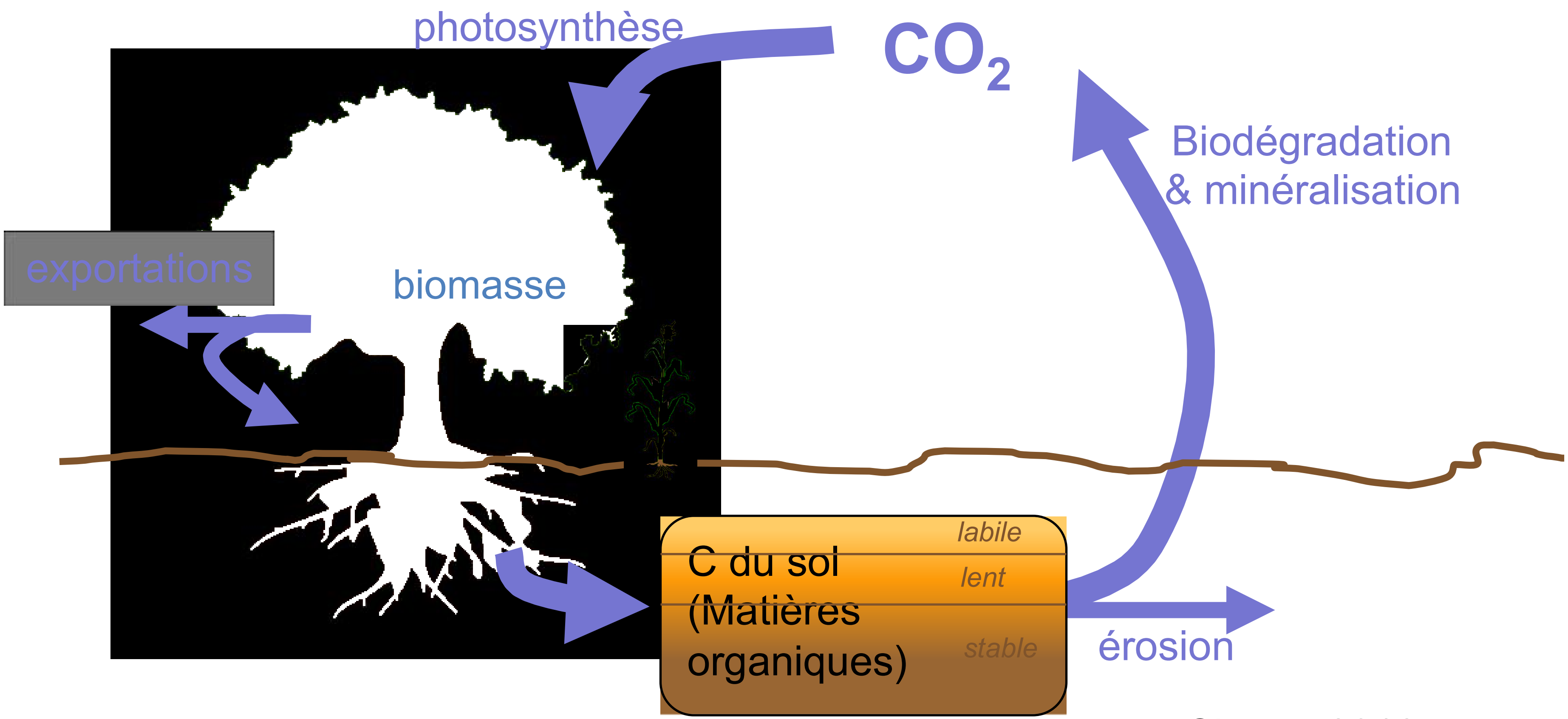
Sylvain PELLERIN

- ✓ Les « Matières organiques du sol » (MOS) représentent entre 1 et 10% de la masse du sol
- ✓ La concentration en MOS est généralement décroissante avec la profondeur
- ✓ Les MOS sont composées à 55% de carbone (C) → Carbone Organique du Sol (COS) ≠ Carbone Inorganique (ex $CaCO_3$)



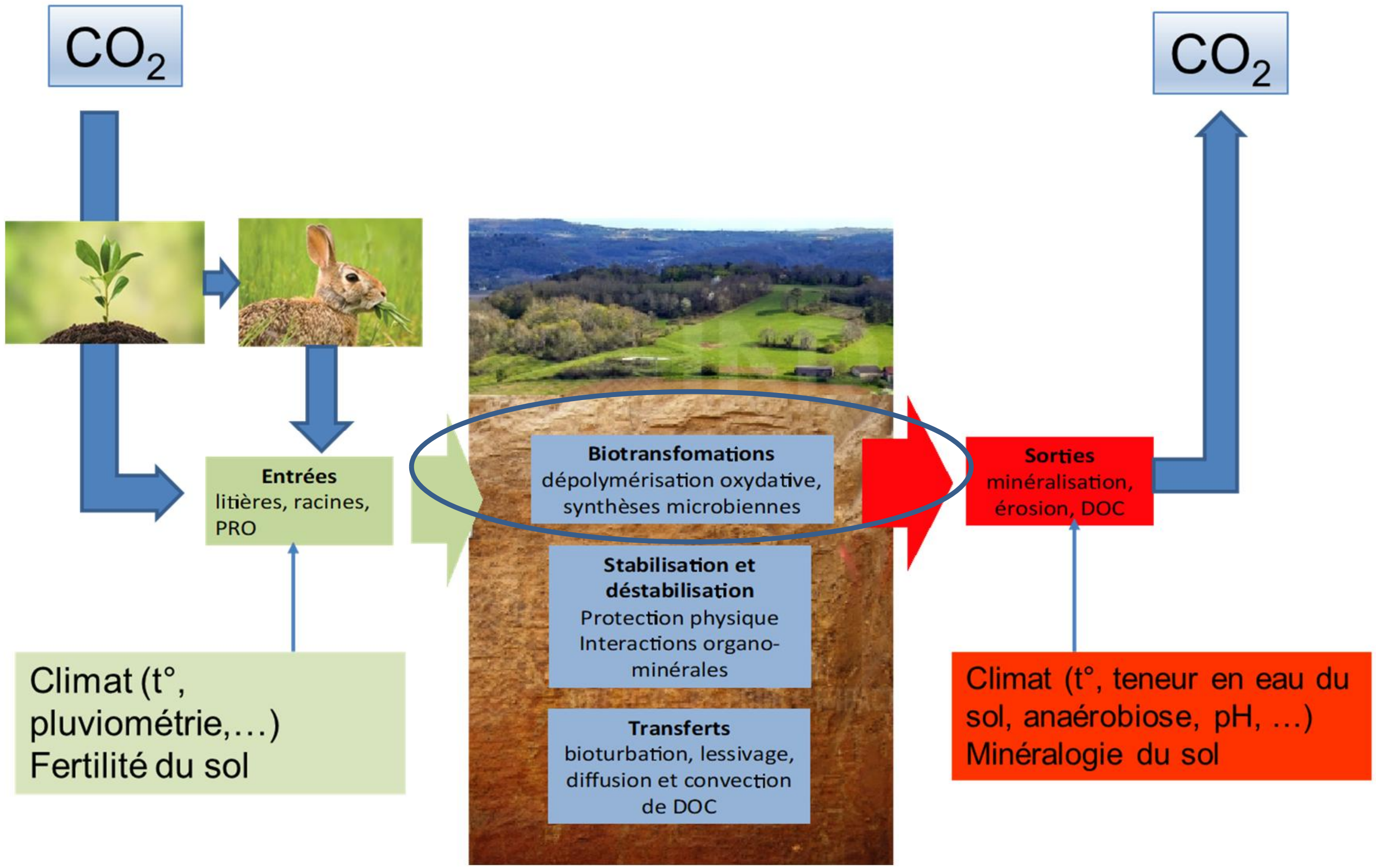

SOIL
Minerals
90-99%
Organic matter
1-10%
ORGANIC MATTER
Dead organic
matter
95%
5%
Living
organisms
60-99 %
1-40%
20-80%
20-80%
5-30%
5-10%
Organic molecules
(80% from microorganisms)
Particulate
organic
matter
(plant residues)
Microorganisms
Bacteria
Fungi
Fauna
Roots
Simple
assimilable
molecule
Macromolecules
600 Da
nanometer
(10⁻⁹ m)
micrometer
(10⁻⁶ m)
millimeter
(10⁻³ m)
micrometer
(10⁻⁶ m)
millimeter
(10⁻³ m)
meter
(m)

Le carbone organique du sol provient du retour au sol des résidus végétaux, élaborés par assimilation chlorophyllienne du CO_2 atmosphérique par les végétaux

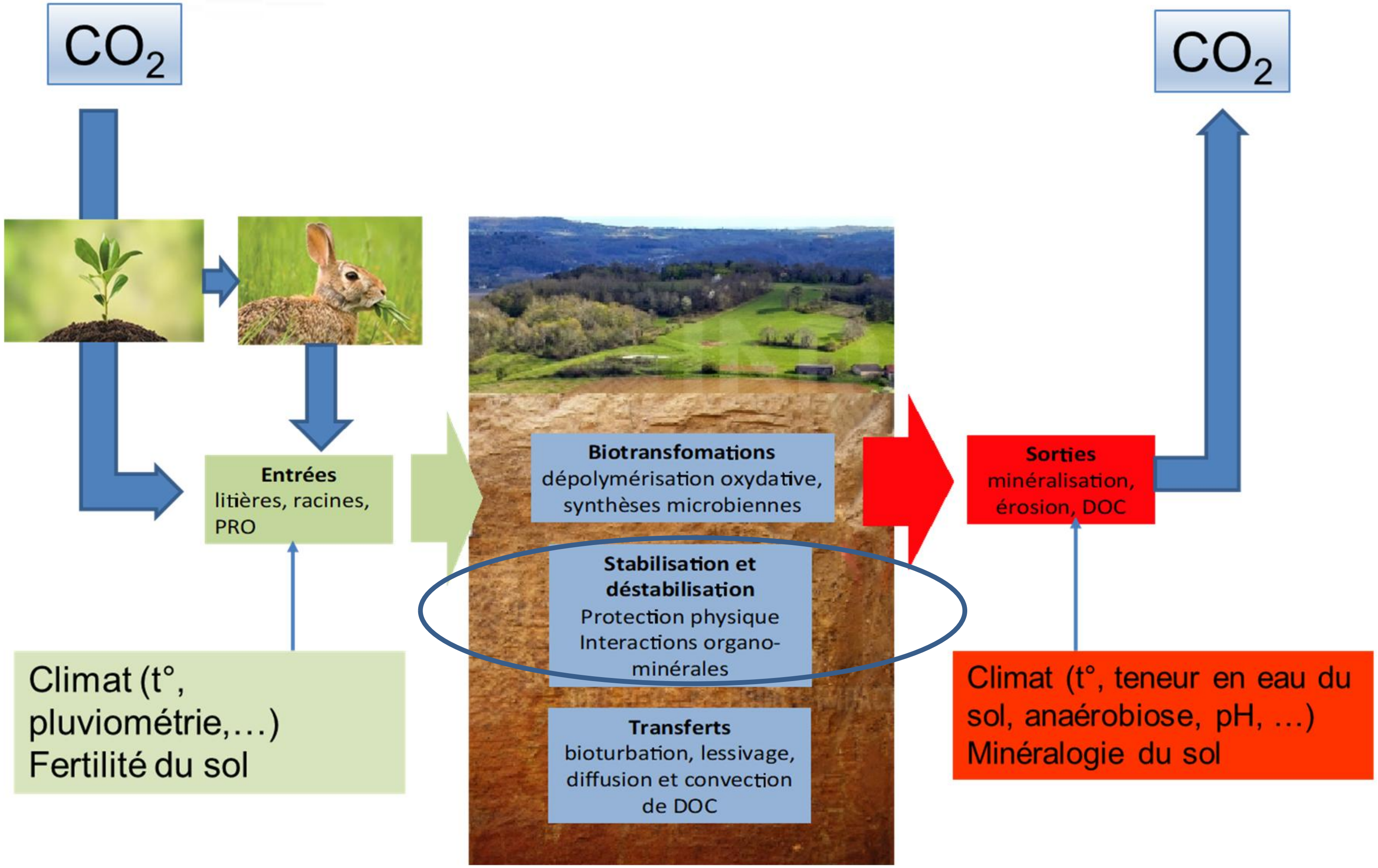


Chenu, 2016

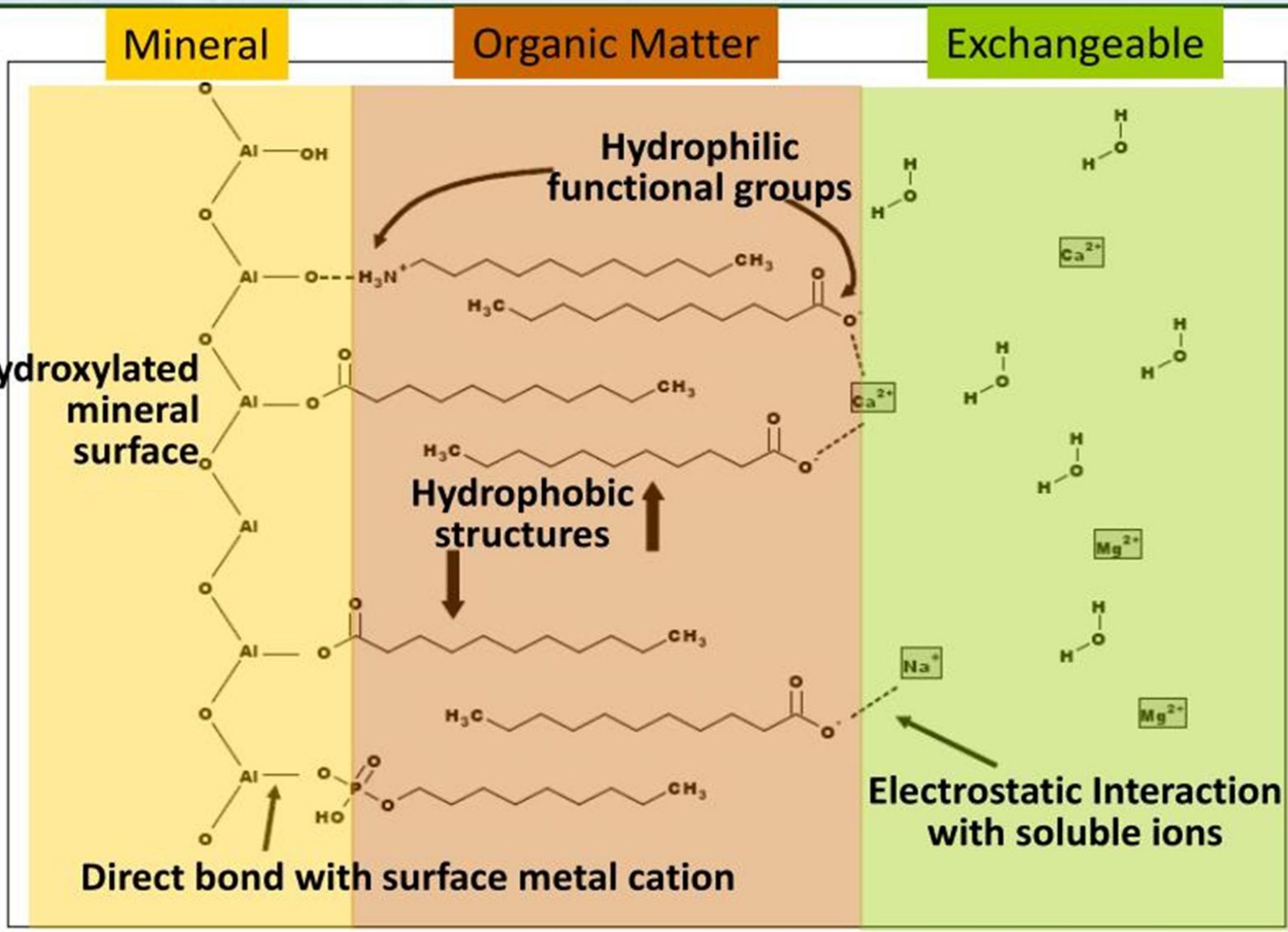
Les matières organiques “entrantes” dans le sol sont transformées sous l’effet de la faune et la biomasse microbienne (dépolymérisation oxydative et synthèses microbiennes)



Une fraction des molécules organiques issues de ces biotransformations est “stabilisée” par des interactions organo-minerales

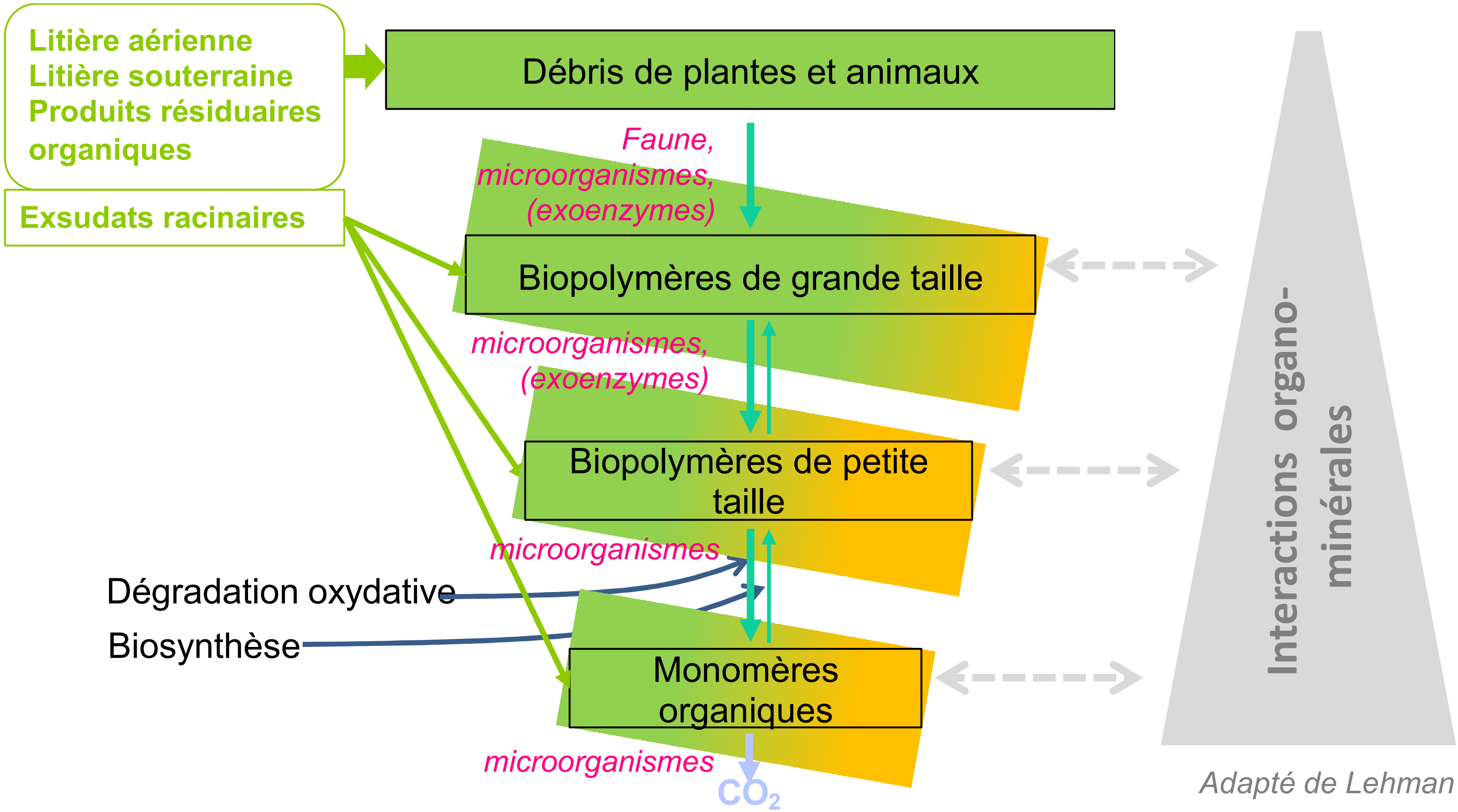


Organo-mineral interaction



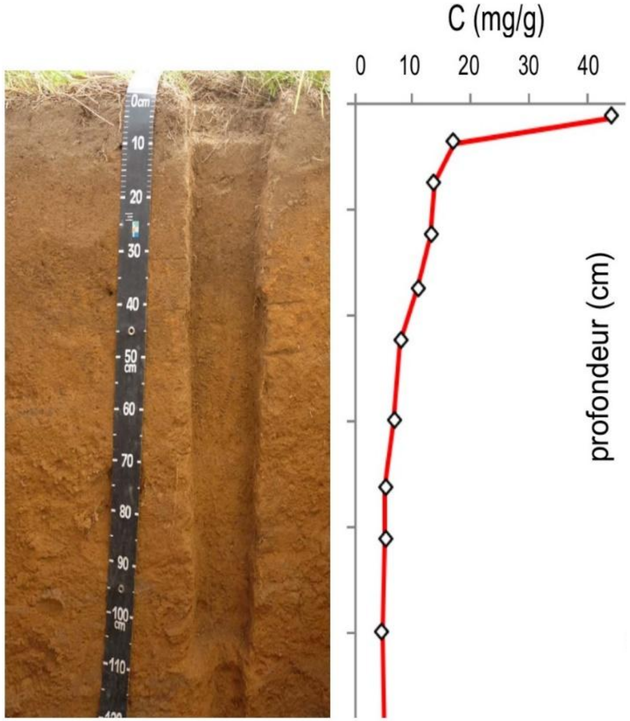
(Kleber et al. 2007, Biogeochemistry)

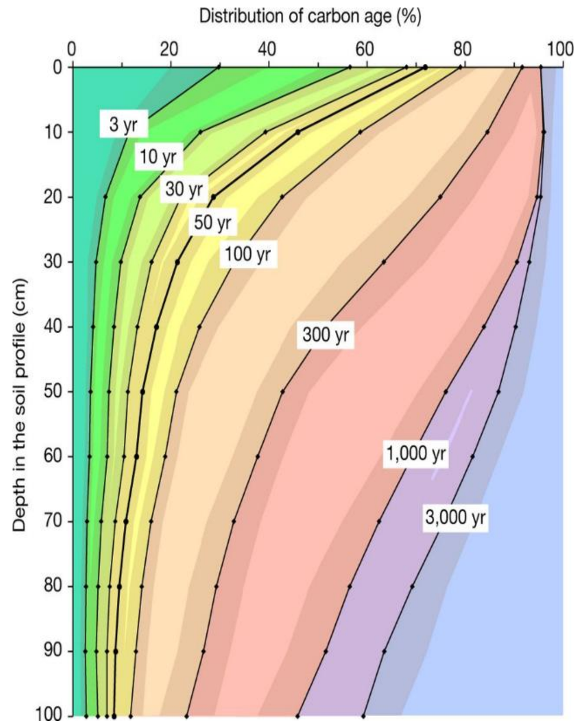
Biotransformation et stabilisation des matières organiques



Adapté de Lehman & Kleber, 2015

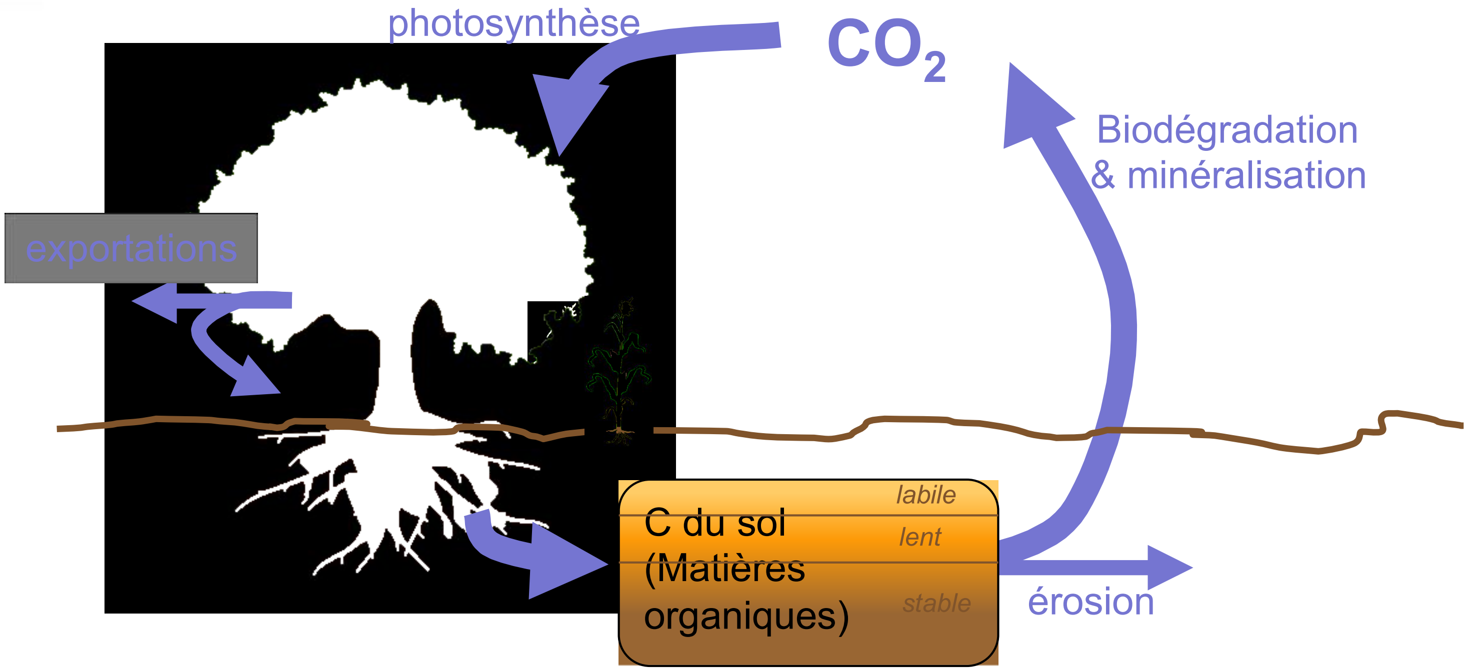
Cette « stabilisation » des matières organiques du sol par des interactions organo-minérales fait que le temps de résidence du carbone dans le sol peut atteindre plusieurs décennies, voire plusieurs siècles





Distribution verticale de la concentration en carbone organique et de son age pour 25 sols tropicaux sous forêt et prairies, d’après Balesdent et al., 2018)

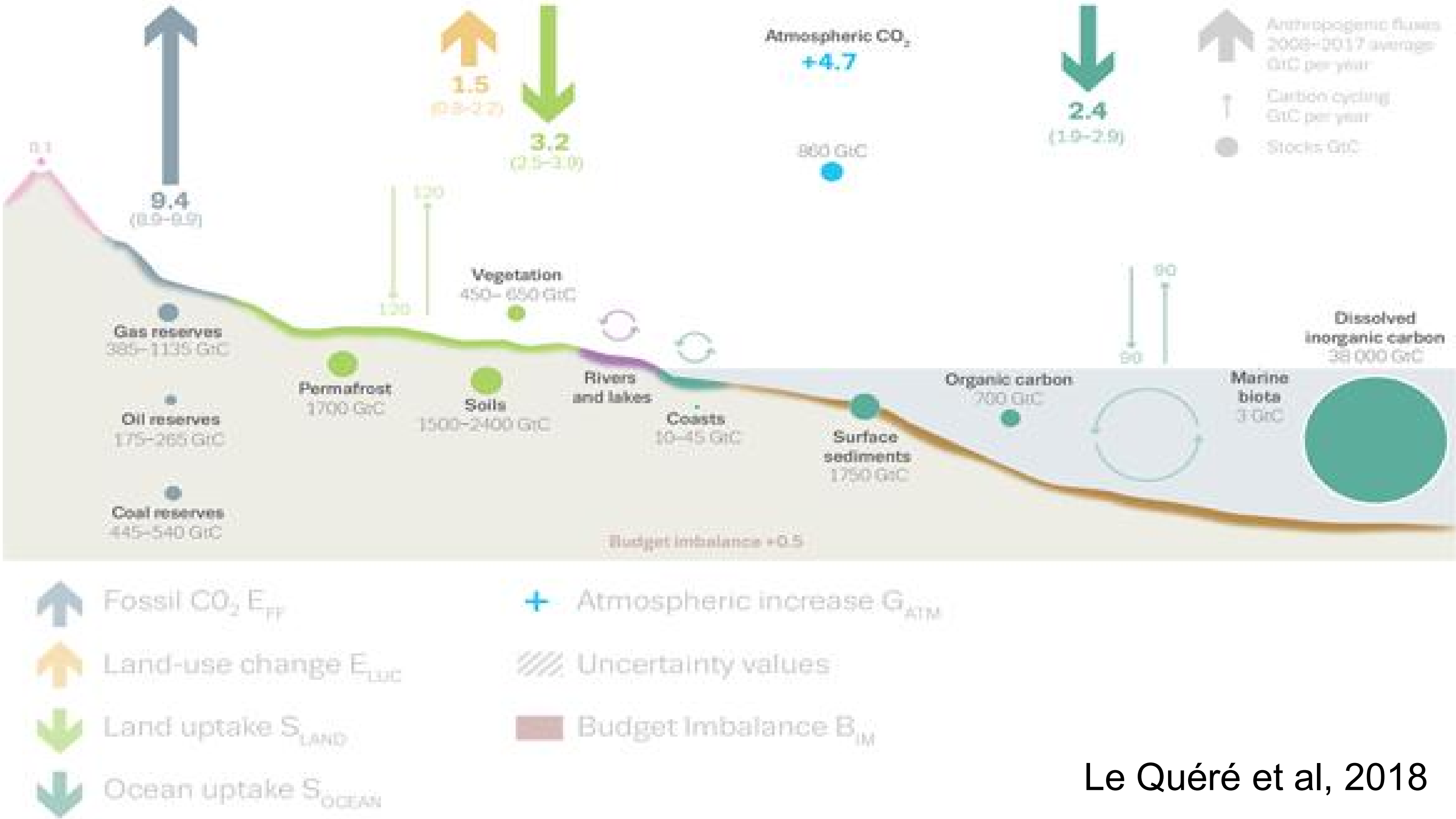
L'existence d'un stock de carbone organique dans les sols, à temps de résidence long, contribue à l'atténuation du changement climatique…



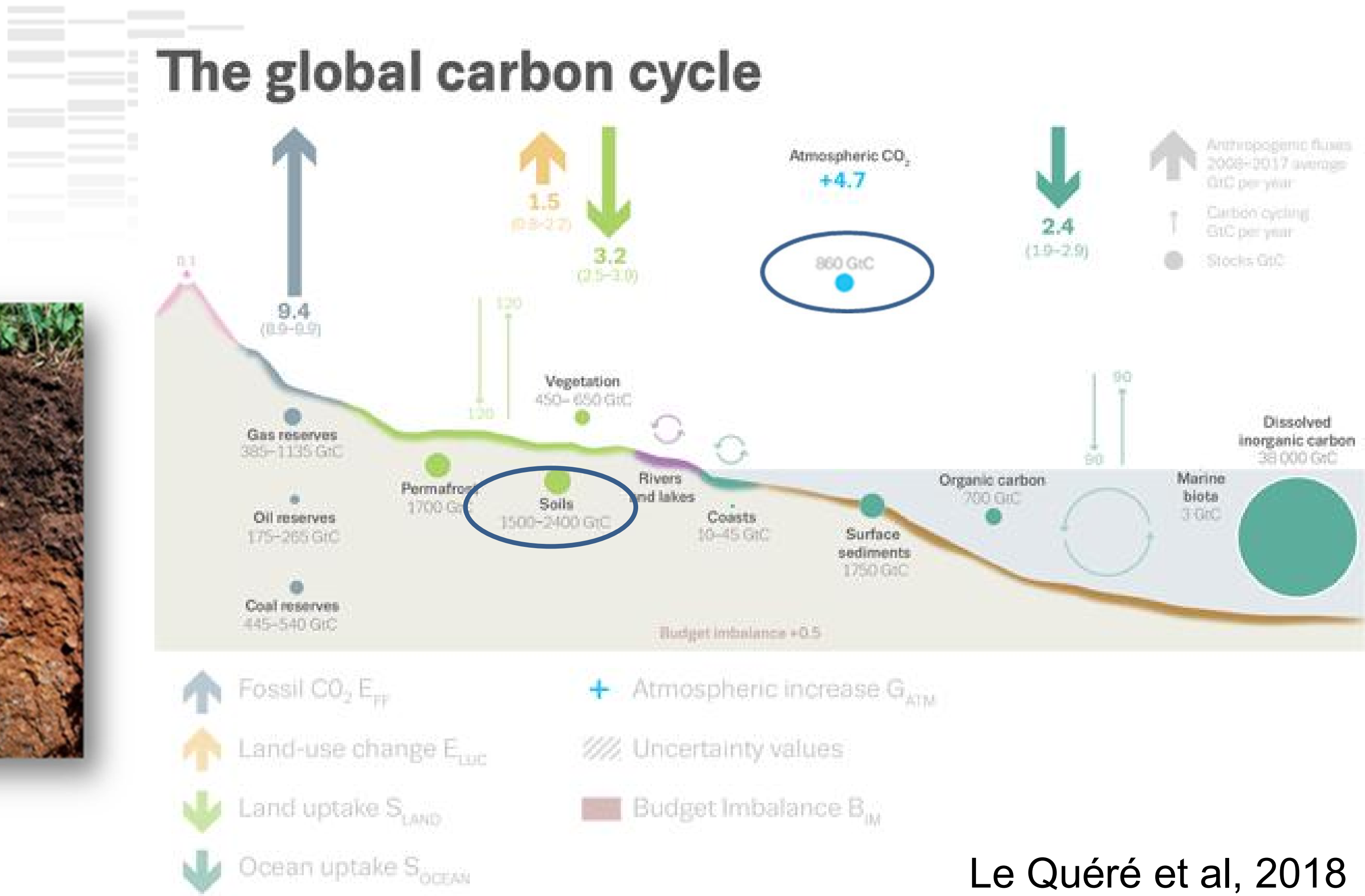
…car ce carbone, tant qu'il est piégé dans la matière organique du sol, n'est pas sous forme de CO_2 dans l'atmosphère!

Chenu, 2016

The global carbon cycle

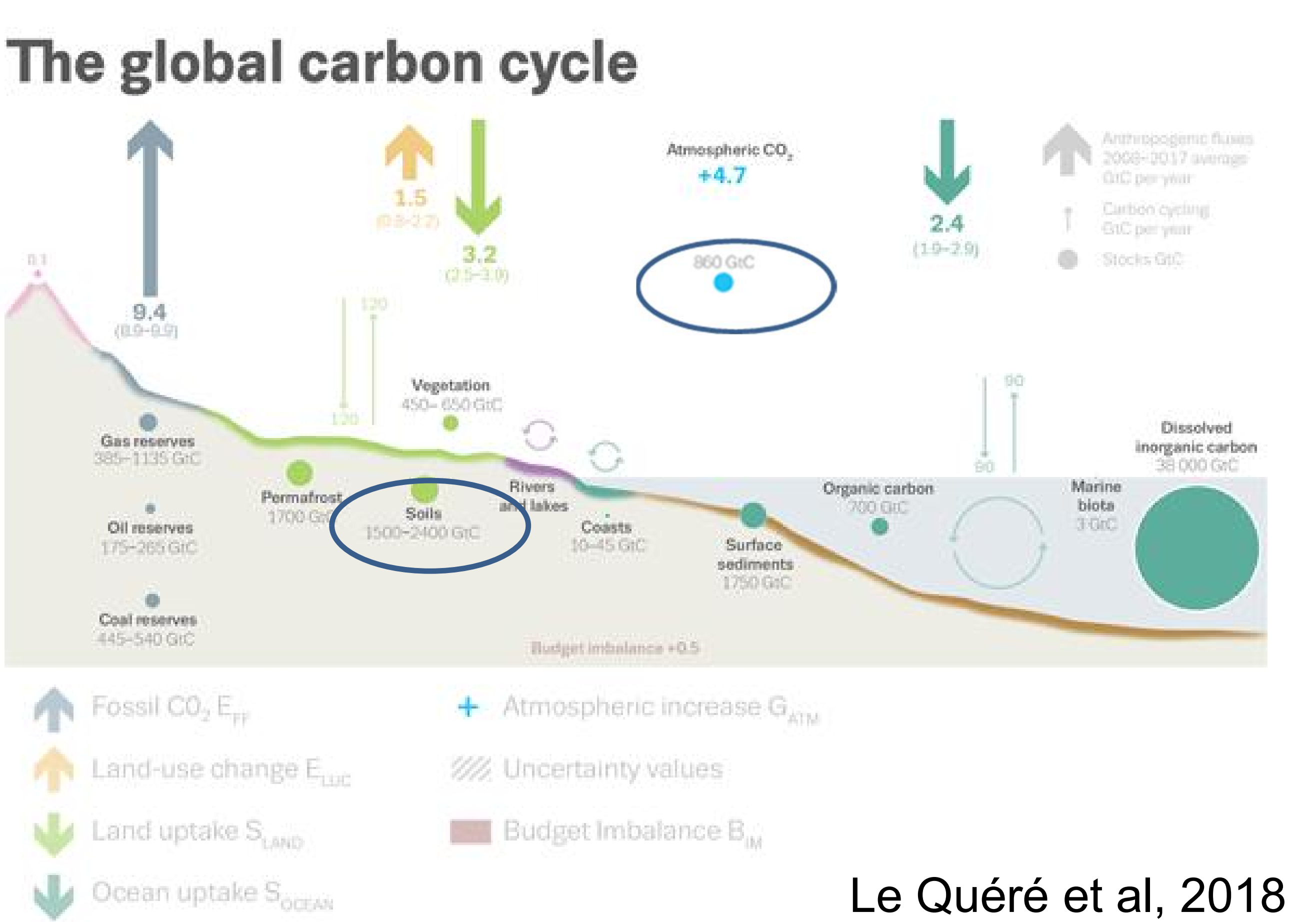


Le Quéré et al, 2018



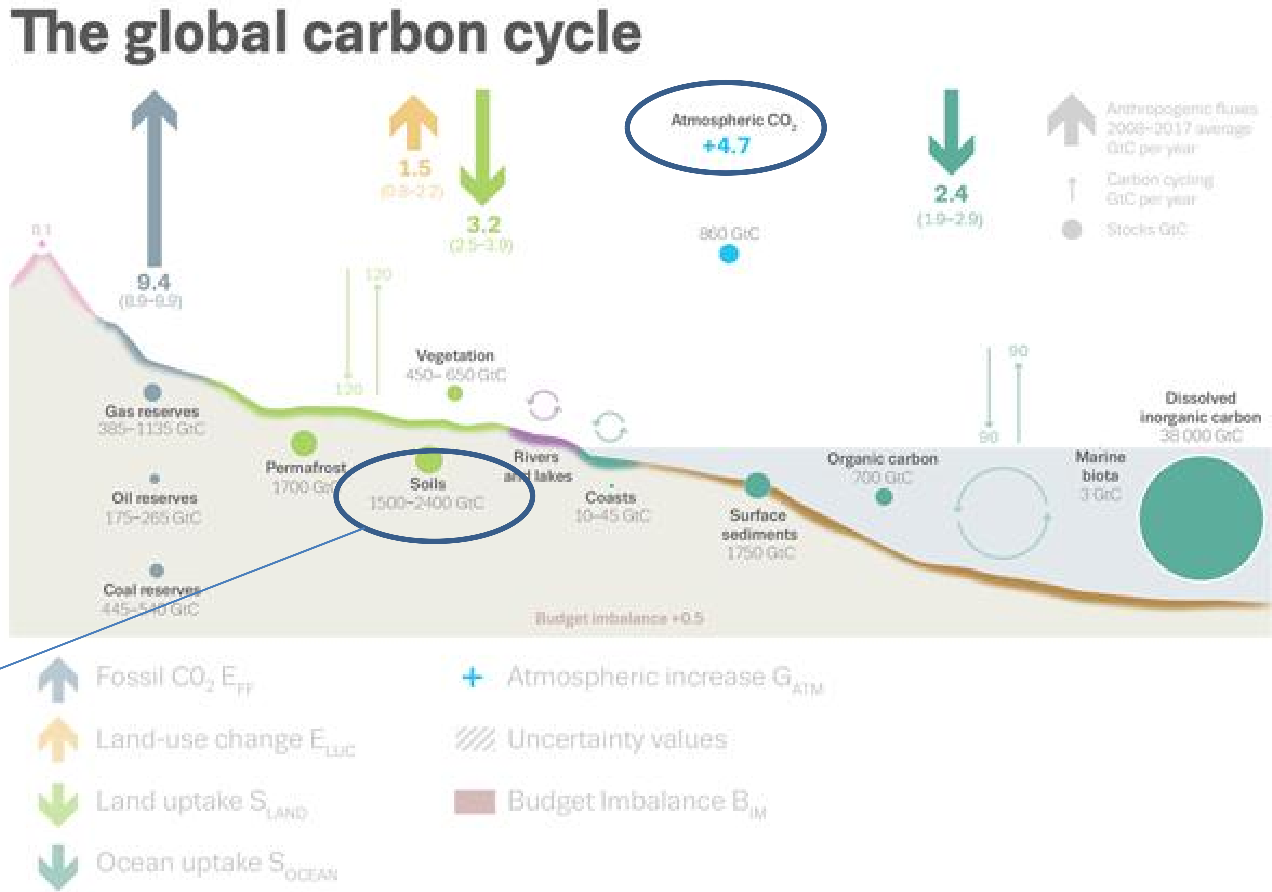
Le Quéré et al, 2018

Soils contain between two and three times more carbon than the atmosphere



Le Quéré et al, 2018

Basic idea of the 4‰ international initiative: increasing soil C stocks by 4 ‰ per year (2400 X 4/1000 = 9,6 Gt C) would almost compensate anthropogenic emissions (9,4+1,5=10,9 Gt C) (https://www.4p1000.org/)



830 Gt C in the upper layer (0-30cm)

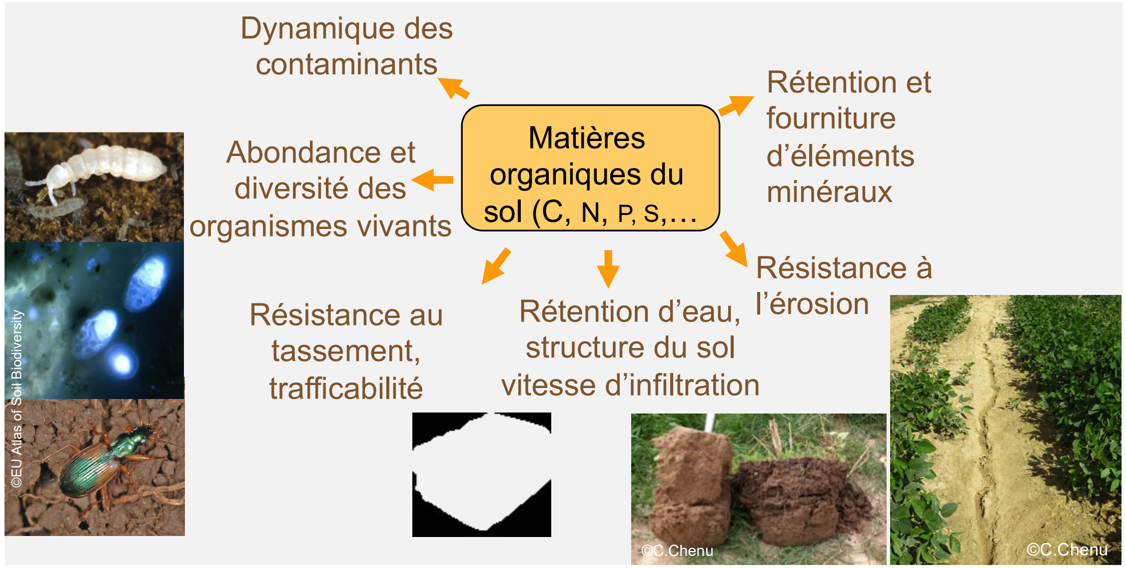
Other calculation (also yielding the 4‰ aspirational value) : increasing soil C stocks by 4 ‰ per year in the upper layer (830 X 4/1000 = 3,3 Gt C) would almost compensate the net increase in the atmosphere if land use change (esp. deforestation) is stopped (+4,7-1,5 = 3,2 Gt C)

PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

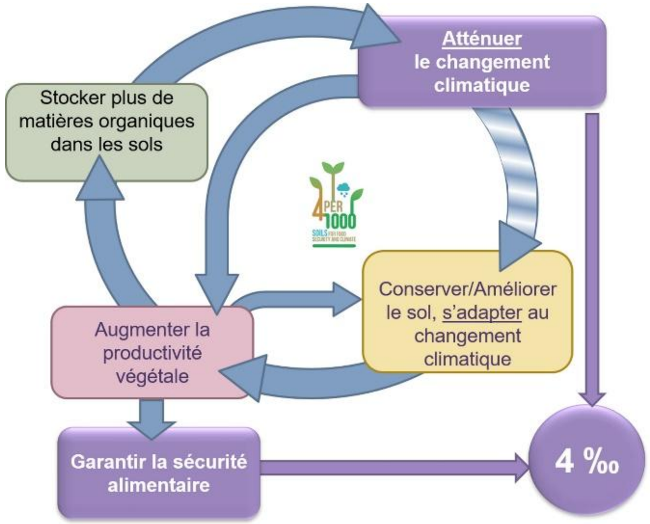
4 POUR 1000
LES SOLS POUR LA SÉCURITÉ ALIMENTAIRE ET LE CLIMAT

Concept of “Carbon farming” = managing carbon pools, flows and greenhouse gases at farm level to mitigate climate change

An interesting option, because increasing soil carbon content has many co-benefits (not only for climate, but also for soil fertility, water holding capacity, soil biodiversity…)



D’après C. Chenu



D’après D. Arrouays

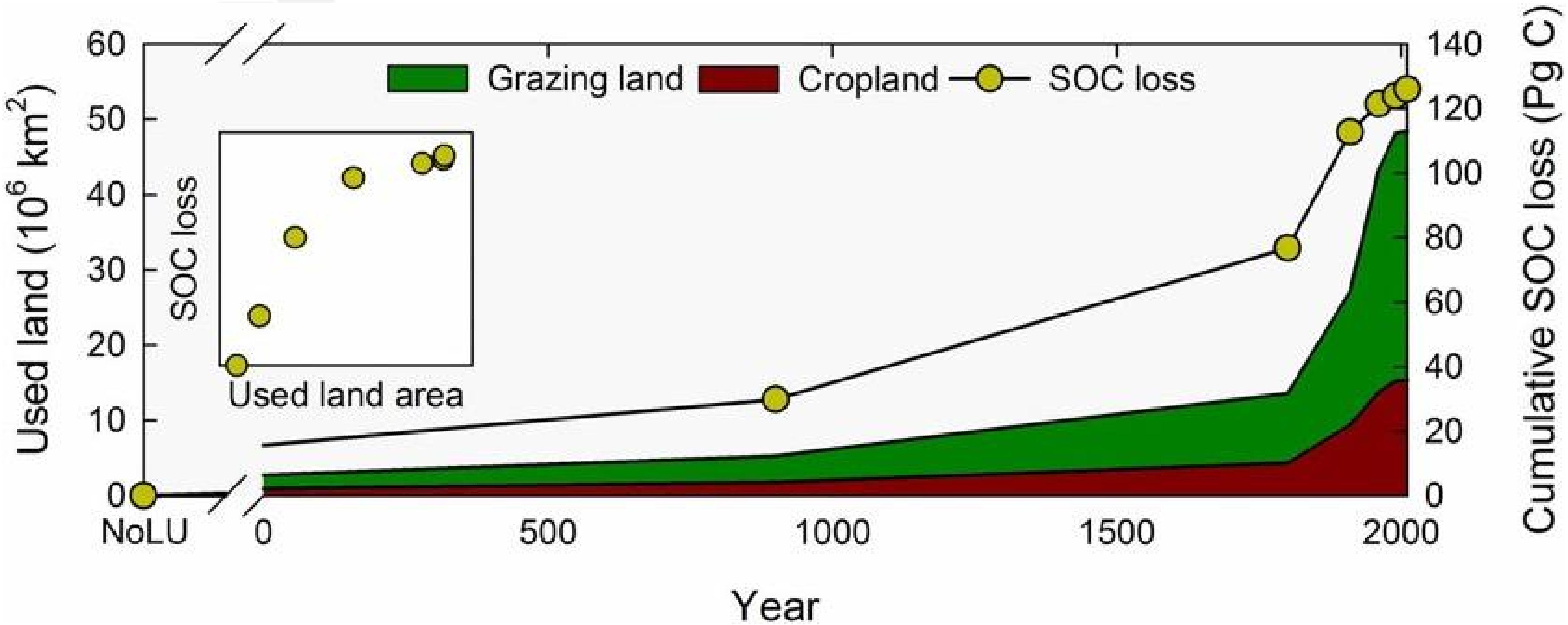
Des co-bénéfices avérés, mais quantitativement limités

Effet d'une augmentation de la teneur en carbone de sols de 4p1000 par an en moyenne pendant 30 ans sur quelques propriétés de sols pour trois sols de texture contrastée

		argileux	limoneux	sableux
texture (%)	argile	42	17	6
	limon fin	21	29	4
	limon grossier	20	45	10
	sable fin	6	7	75
	sable grossier	11	2	5
teneur en carbone	t0	1,4	1	0,9
	t+30 ans	1,58	1,13	1,02
CEC (cmole kg-1)	t0	19,4	9	4,7
	t+30 ans	19,8	9,4	5,0
	variation relative (%)	*2%*	*4%*	*6%*
Masse volumique apparente (cm3/cm3)	t0	1,33	1,32	1,57
	t+30 ans	1,34	1,33	1,58
	variation relative (%)	*0,3%*	*0,2%*	*0,2%*
Réserve utile (cm3/cm3)	t0	14,4	20,3	8,9
	t+30 ans	14,2	20,6	9,4
	variation relative (%)	*-1%*	*1%*	*5%*
Indice de battance	t0	0,70	2,26	0,63
		non battant	*très battant*	*non battant*
	t+30 ans	0,67	2,12	0,58
		non battant	*très battant*	*non battant*

D'après C Chenu

The « carbon debt »



SOC losses (grazing land, croplands)	
0-30 cm	37 PgC
0-100 cm	75 PgC
0-200 cm	133 PgC

Sanderman et al. PNAS

But scientific controversies

OPINION

PNAS

OPINION

Soil carbon sequestration is an elusive climate mitigation tool

Ronald Amundson[a,1] and Léopold Biardeau[b]

The need to stabilize the greenhouse gas concentrations of the atmosphere is the great environmental challenge of this century. To control these concentrations, humanity can reduce fossil fuel emissions and/or identify mechanisms to remove greenhouse gases once they have been emitted. The scope of the problem is challenging because of the size of the fluxes involved. Presently, industry, transportation,

alternate way to help stem the rate of greenhouse gas growth and associated changes in our climate.

For nearly 2 decades, researchers in the soil science community have studied and estimated the potential of sequestering carbon in soil organic matter (2, 3). The premise is inherently rational: nearly 10,000 years of cultivated agriculture has reduced global soil carbon by 116 Gt (4), an amount equivalent to more than a

Geoderma 309 (2018) 118–123

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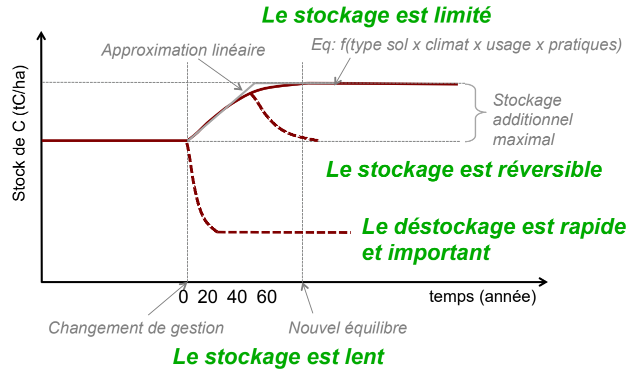
Letter to Editor

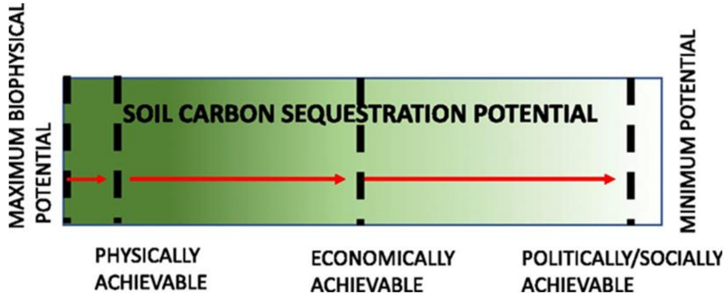
The "4 per 1000" initiative: A credibility issue for the soil science community?

CrossMark

But scientific controversies

- Increasing soil carbon stocks in only possible during a limited period (new equilibrium, soil carbon saturation)
- It is a reversible process; how to ensure permanence?
- It requires additional carbon inputs: how to produce them? What about competition for other use?
- Because of stochiometric constraints, storing more carbon requires additionnal N and P
- Because of adoption barriers, the politically/socially sequestration potential is far behind the physically achievable potential
- Climate change itself will foster C losses by mineralisation





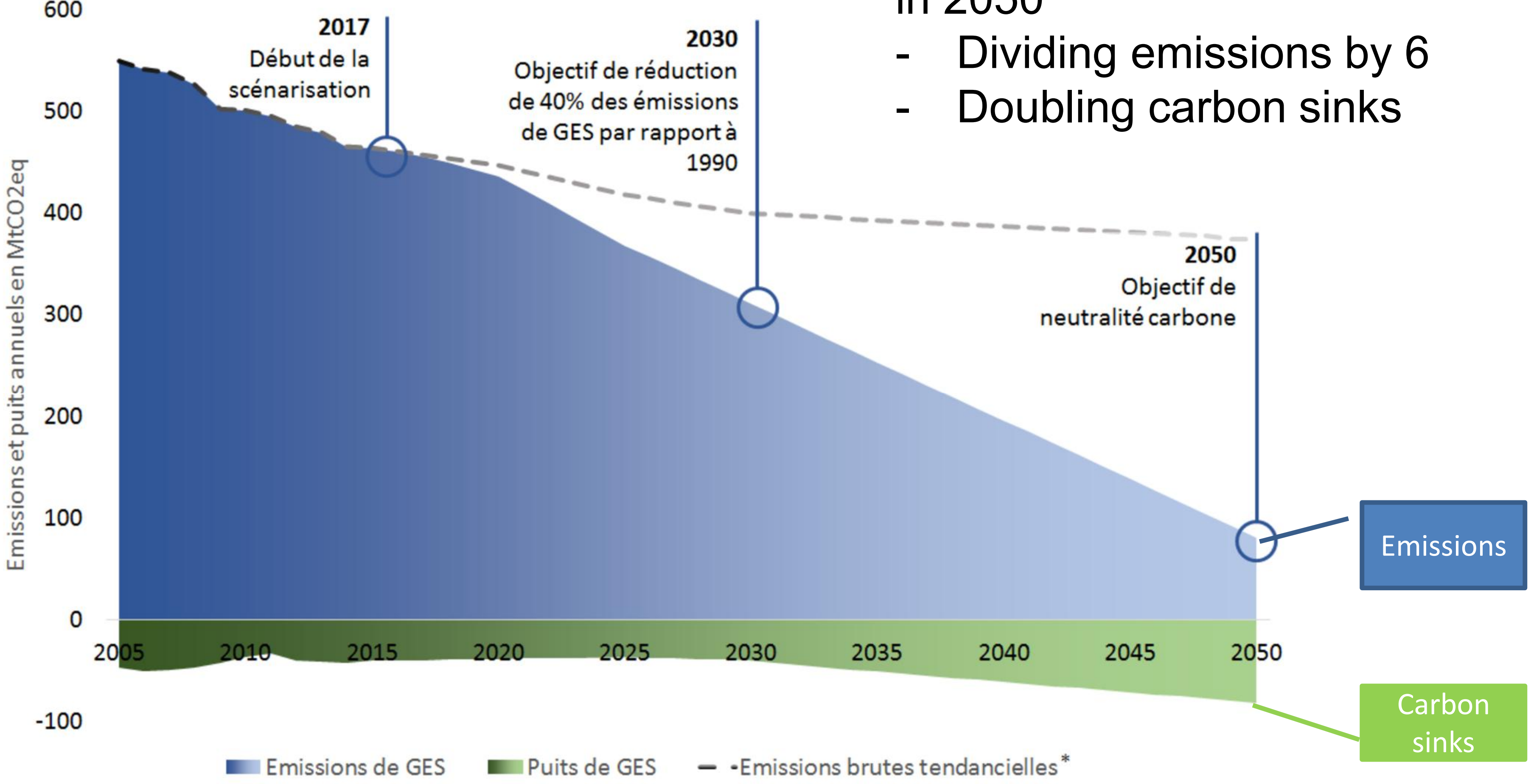
Last but not least: there is a risk to weaken the most important message which is the urgent need to reduce emissions

And many remaining questions

- How far can a soil carbon storage strategy contribute to a mitigation strategy?
- How to quantify the soil carbon storage potential?
- How to increase carbon C stocks? Which farming practices?
- How to incentive their adoption?
- What are their side-effects?
- What will be the effect of climate change on this potential?

The French national low carbon strategy

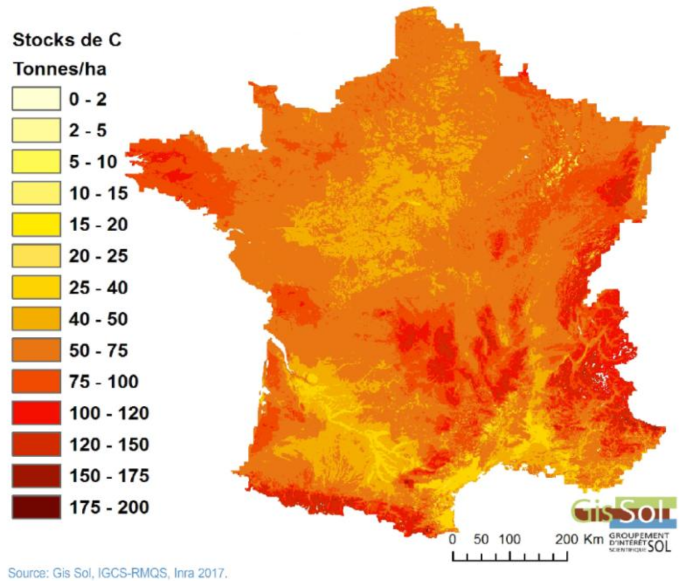
Objective: carbon neutrality in 2050
- Dividing emissions by 6
- Doubling carbon sinks



SNBC, 2017

Soil C stocks in France

- Higher in mountainous areas (Alps, Pyrénées, Vosges, Jura, Massif central); lower in plain areas
- Higher under forests and permanent grasslands, lower under croplands



	min	mean	max	Standart deviation
Carbon stocks under permanent grasslands (t/ha)	18,1	**84,6**	309	35.0
Carbon stocks under arable crops (t/ha)	9,92	**51,6**	137	16.2
Carbon stocks under forests (t/ha)	6.87	**81.0**	230	35.4

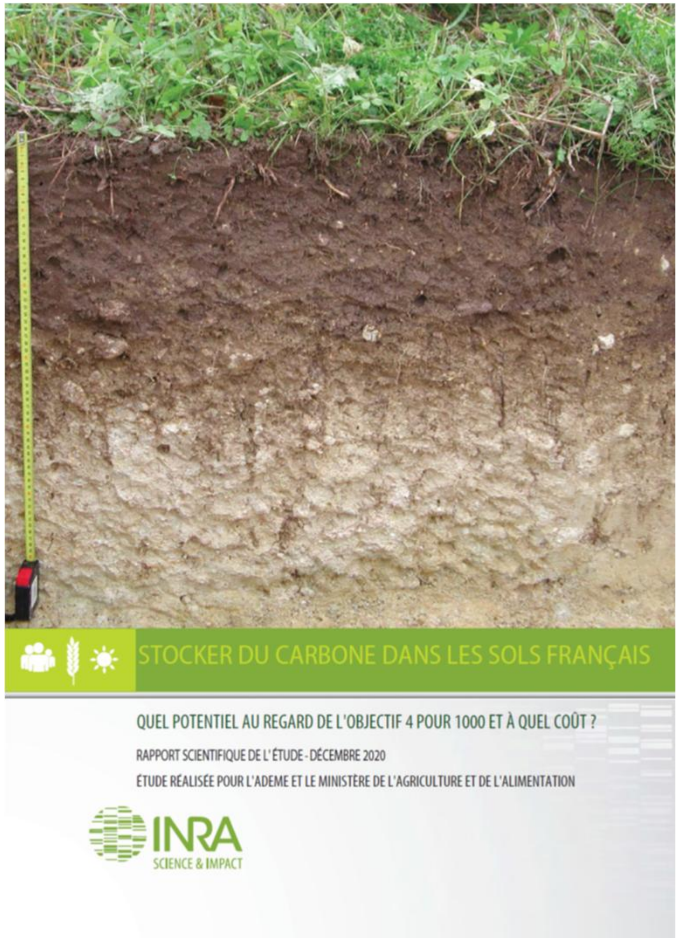
Data RMQS GIS Sol

The « 4 per mille » initiative at the French level

INRAE has been committed by the French Ministry of Agriculture to produce a report on the potential for additional carbon storage in agricultural soils in mainland France

Objectives

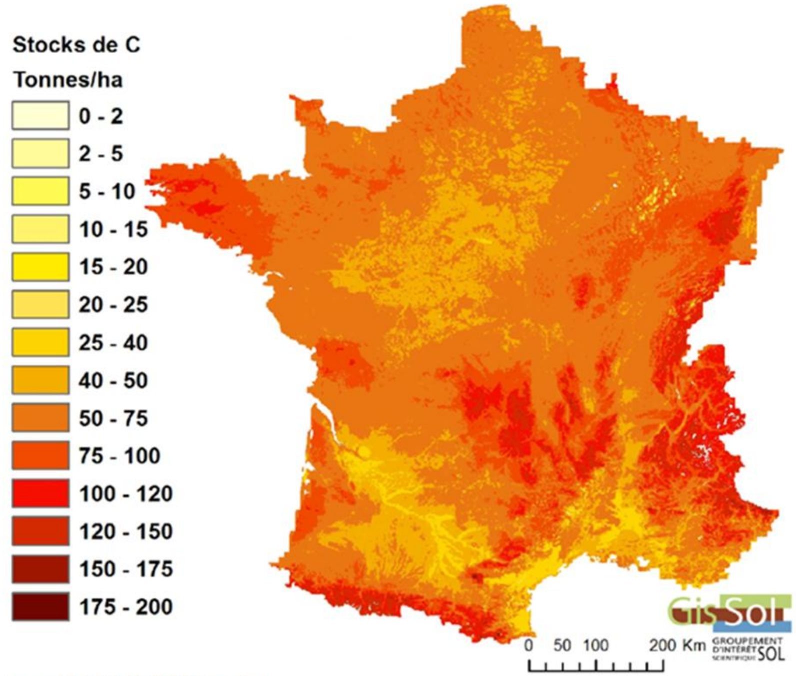
- To assess and map the potential for additional carbon storage in agricultural soils in mainland France following the implementation of soil C storing practices
- To assess their implementation cost
- To propose an optimal cost-efficient strategy for additional soil C storage at the national scale



The « 4 per mille » initiative at the French level

- In France the soil organic C stock is about 3580 Mt C (0-30cm soil layer)

- Increasing this stock by 4‰ per year (3580 x 0,004 x 3,67 = 52,5 Mt CO_2e) would compensate « only » 12 % of national emissions (436 Mt CO_2e)



Source: Gis Sol, IGCS-RMQS, Inra 2017.

→ For an industrial country like France additional carbon storage in soils can help to reach carbon neutrality but drastic efforts to reduce emissions remain dispensable

Method

Nine soil C storing practices were selected, based on a literature review

- expansion of cover crops (longer and more frequent cover crops)
- no-tillage
- new C inputs (not already spread on agricultural soils under current management practices)
- expansion of temporary grasslands (instead of silage maize)
- agroforestry
- hedges
- moderate intensification of extensive grasslands (+50kgN/ha)
- animal grazing instead of mowing
- grass cover of vineyard

For each selected practice, its potential applicability was calculated considering technical constraints (ex no reduced tillage for sugar beet, no cover crop for intercrop period < 2 months, no agroforestry if soil depth < 1m or plot size < 1ha…)

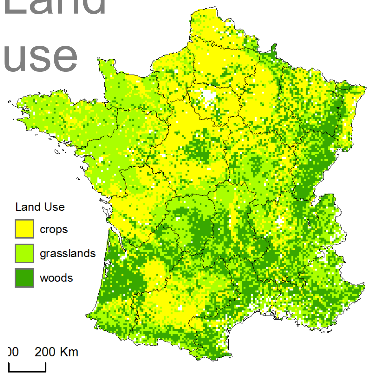
Method

The additional C storage following the implementation of C storing practices was assessed using a modelling approach at a fine spatial-scale resolution (≈1 km^2)

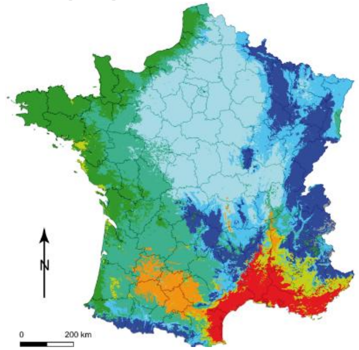
Each grid cell was characterized by its:

- dominant land-use
- local climate
- dominant soil type
- dominant cropping system (crop rotation and current farming practices)
- initial soil C stock value

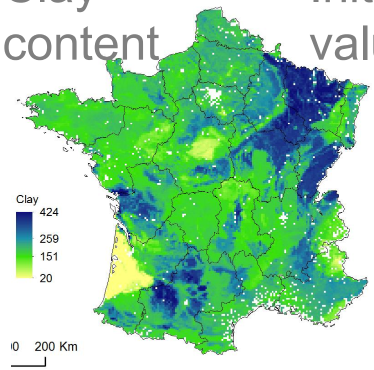
Land use



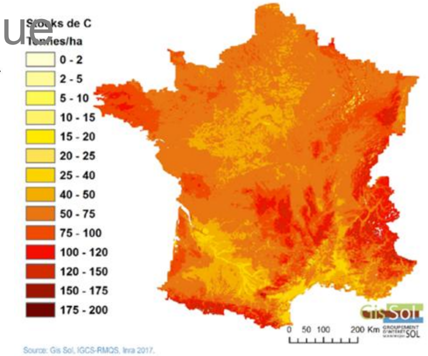
Climate



Clay content



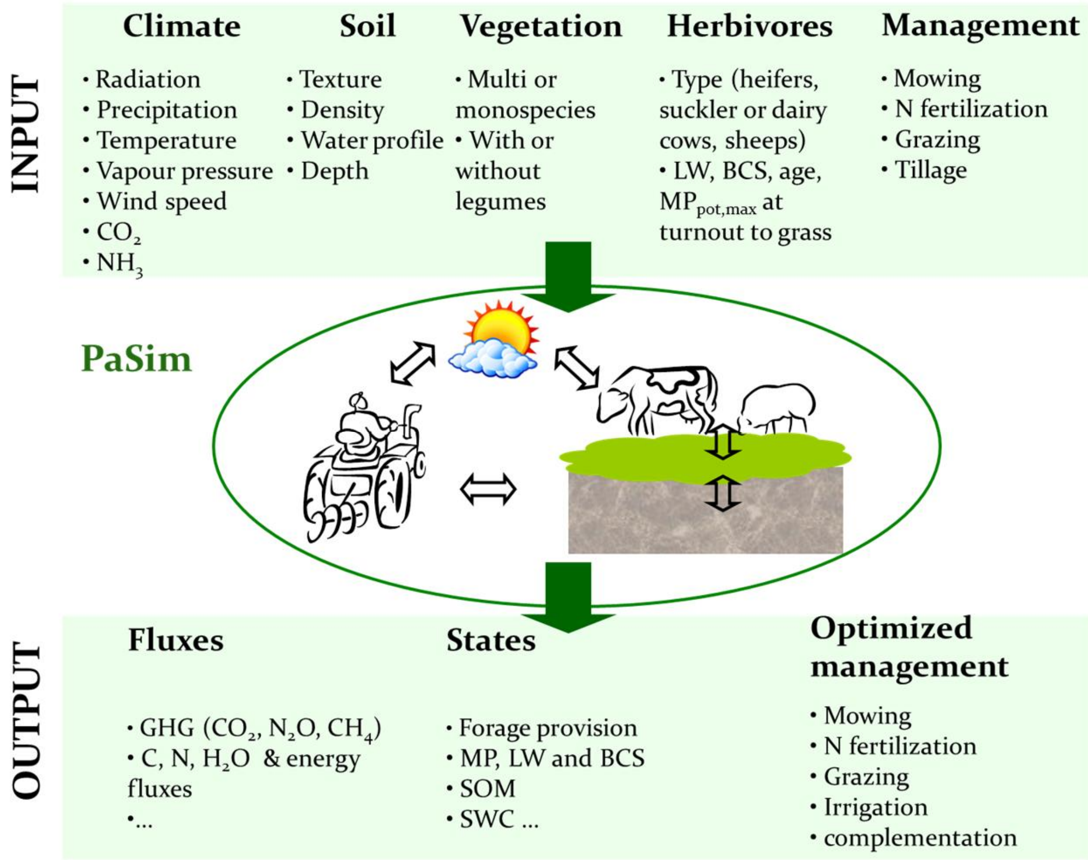
Initial soil C stock value



Method

Two models were used for simulations
- STICS for arable crops
- PaSim for permanent grasslands

Both models include an explicit representation of the C cycle



Method

For each grid cell, changes in soil C stock were simulated for a period of 30 years

- under current management practices (= baseline)
- under C storing management practices (ex expansion of cover crops)

The **additional C storage** was calculated as the difference between the simulated soil C stock under C storing practices and the simulated soil C stock under current management practices

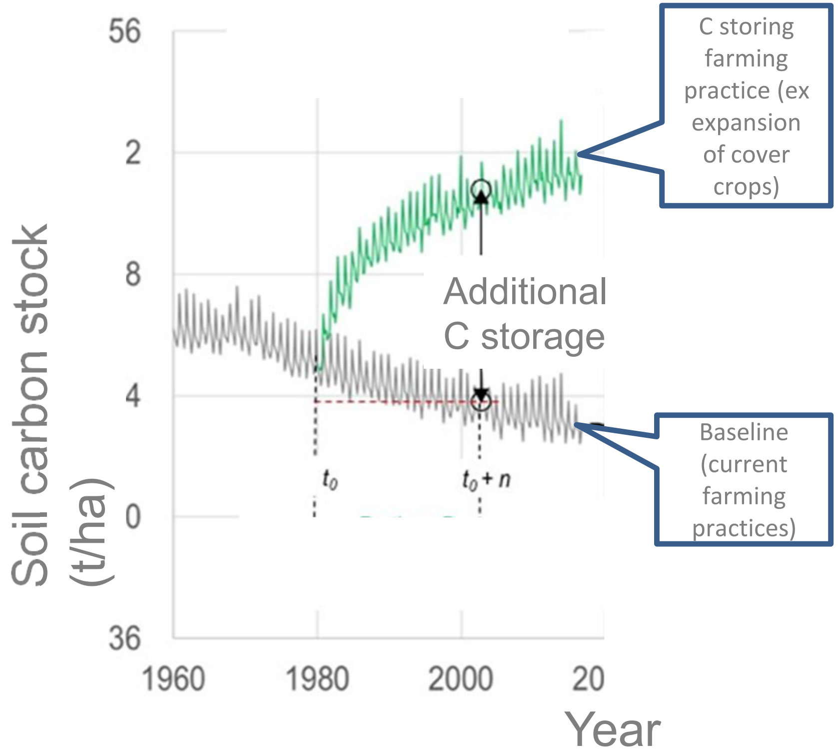
Additional C storage (tC/ha/yr) =

$$\frac{(SOC\ stock\ storing\ practice - SOC\ stock\ baseline)}{30}$$

Simulations were performed for the 0-30cm horizon, and then extrapolated to the whole soil profile

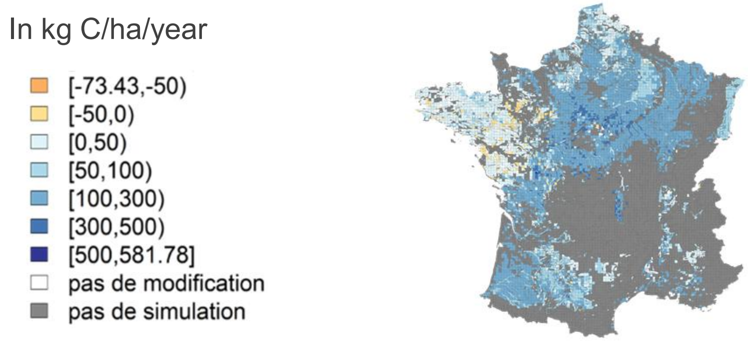
For each C storing practice, a complete GHG budget was calculated

Simulations were performed under current climatic conditions (period 1983-2013)



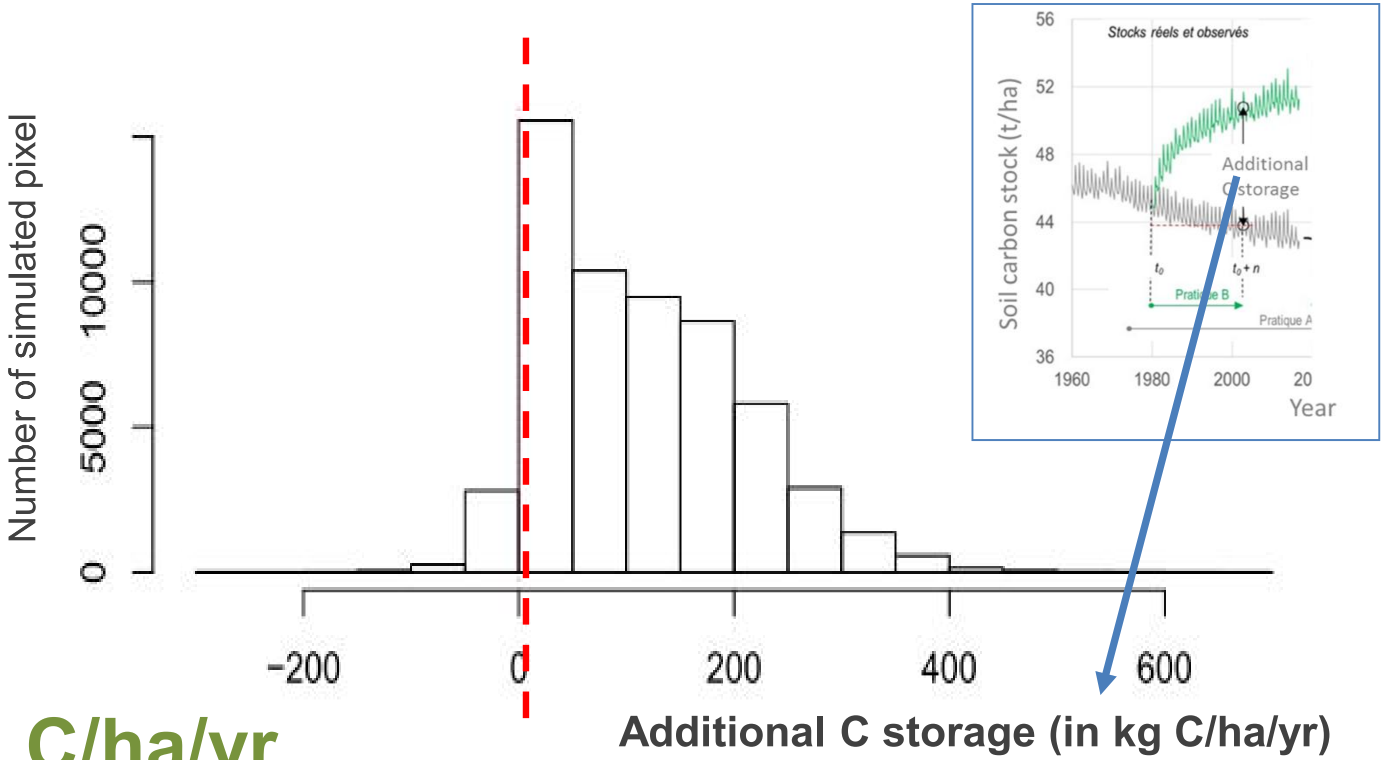
Example of results

Additional carbon storage provided by the expansion of cover crops



Average additional C storage

+126 ± 93 kg C/ha/yr



Pellerin, Bamière et al, 2019

Aggregated results for all C-storing practices

	Additional C storage 0-30 cm soil layer	Potential applicability	Potential additional C storage at the national level 0-30 cm soil layer	Relative yearly increase of soil C stocks (=949 Mt C for cropland soils in mainland France)
	Kg C/ha/an	Mha	Mt C/year	‰ /year
Arable cropping systems				
Expansion of cover crops	+126	16.03	+2.019	
No tillage	+60	11.29	+0.677	
New carbon inputs	+57	1.46	+0.084	
Expansion of temporary grasslands	+127	6.63	+0.840	
Agroforestry	+207	5.33	+1.103	
Hedges	+17	8.83	+0.150	
Total for croplands			+4.873	+5.1 ‰

Pellerin, Bamière et al, 2019

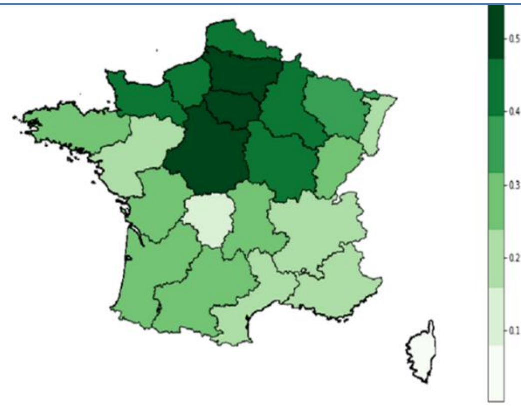
Aggregated results for all C-storing practices

	Additional C storage Horizon 0-30 cm	Potential applicability	Potential additional C storage at the national level Horizon 0-30 cm	Relative yearly increase of the soil C stock
	Kg C/ha/year	Mha	Mt C/year	‰ /year
Permanent grasslands				
Moderate intensification of extensive grasslands	+176	3.94	+0.694	
Grazing instead of mowing	+265	0.09	+0.023	
Total for permanent grasslands			+0.717	+0.9 ‰
Vineyard				
Grass cover	+182	0,56	+0.103	
Total for vineyard			+0.103	+3.7 ‰
Total for French agricultural soils (without forests)			5,69	+3,2 ‰

Pellerin, Bamière et al, 2019

- A potential for additional C storage of about 5.69 Mt C/year (in the 0-30cm soil layer)

Additional C storage potential (in tC/ha/yr



- This represents an annual increase of
  - +5,1 ‰ for croplands
  - +0,9 ‰ for grasslands
  - +3,2 ‰ for all agricultural soils

- This potential is mainly found in arable soils (86% of the total potential), partly because initial soil C stocks are low

- Three key storing practices: cover crops, temporary pastures, agroforestry

- Extrapolated to the whole soil profile (5,69 → 8,15 MtC = 29,9 $MtCO_2e$), this additional C storage would compensate 6,5% of national GHG emissions (458 $MtCO_2e$)

Costs

C storing practice		Potential applicability (Mha)	Cost for farmer (€/ha/year)	Storage cost (€/tC) Whole soil profile
Grass cover of vineyards	permanent	0,15	-26	-56
	In winter	0,41	-15	-51
Expansion of cover crops		16,03	39	180
No tillage		11,29	13	-
New carbon inputs		1,46	23	231
Moderate intensification of extensive grasslands		3,94	28	130
Grazing instead of mowing		0,09	73	203
Expansion of temporary grasslands		6,63	91	423
Agroforestry		5,33	118	302
Hedges		8,83	73	2322

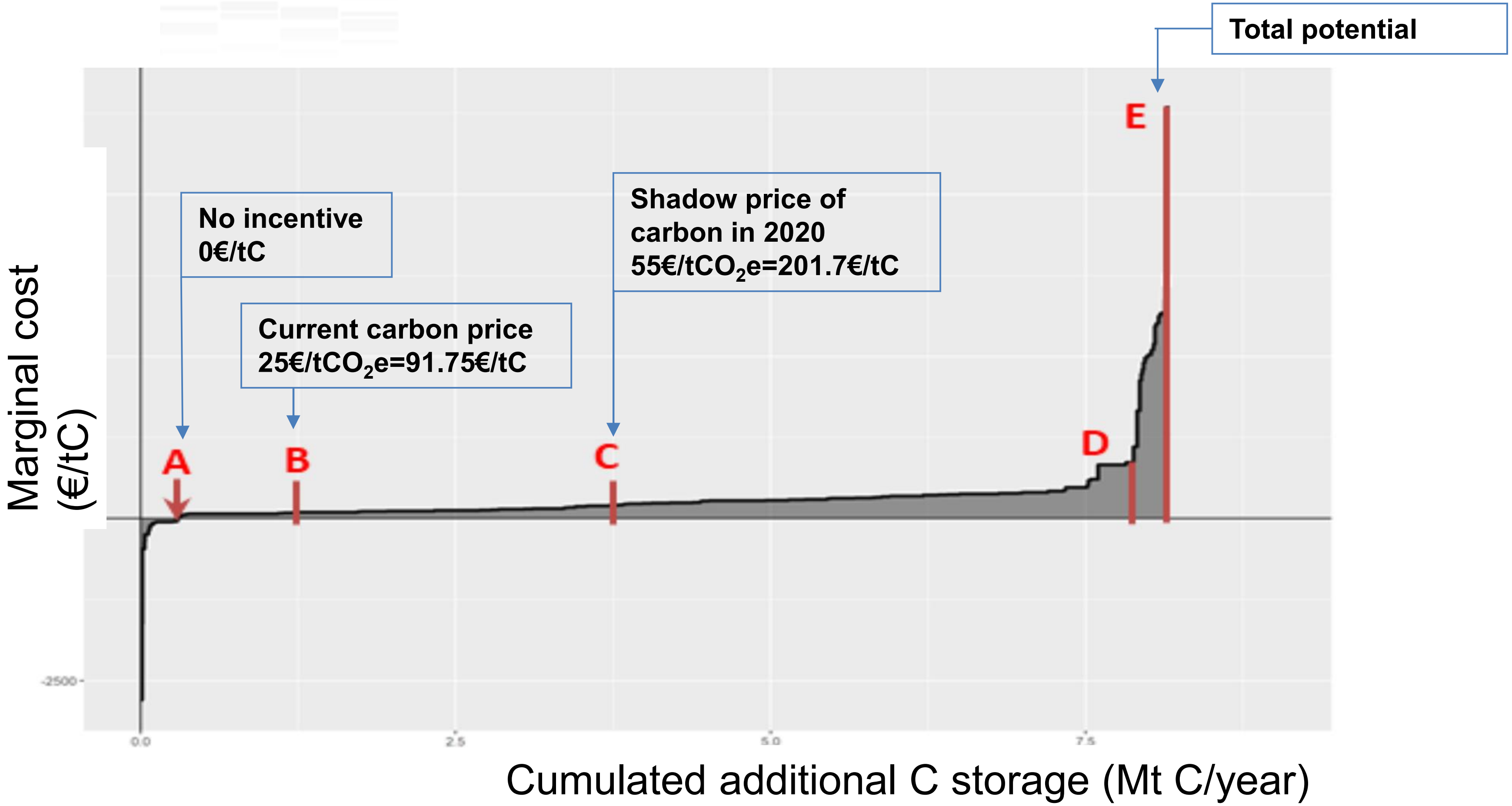
Negative cost

Intermediate cost (<250€/tC)

High cost (>250€/tC)

Pellerin, Bamière et al, 2019

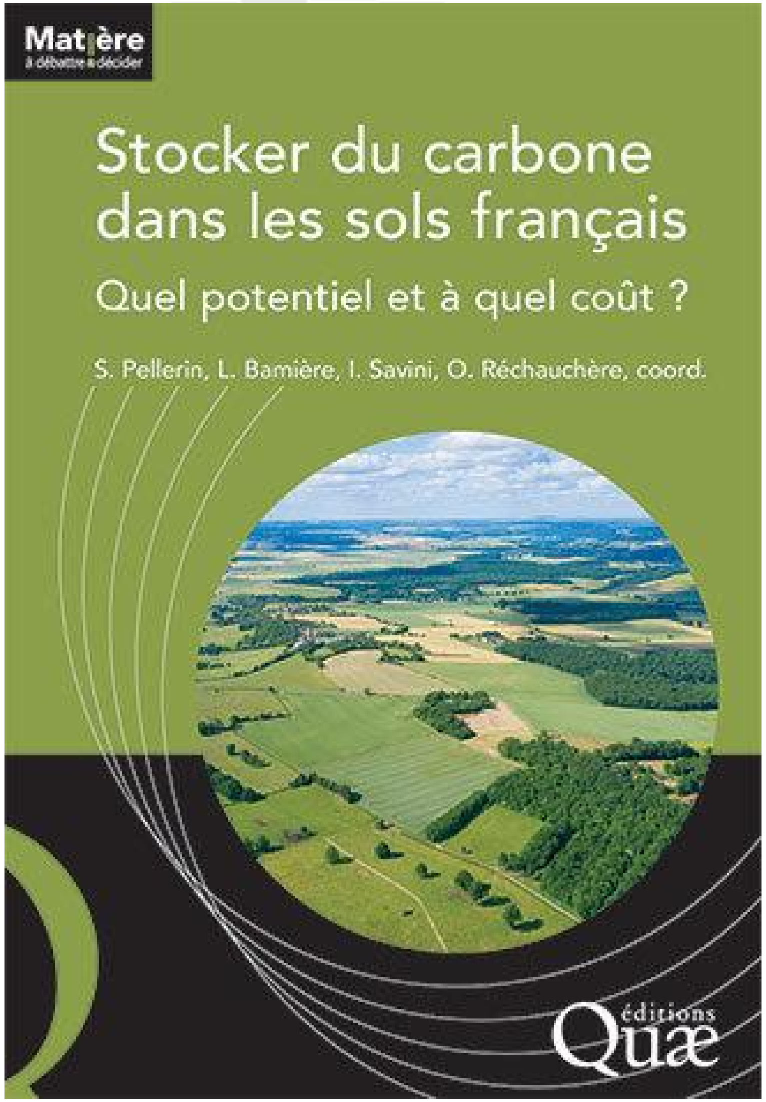
Marginal carbon storage cost curve



Pellerin, Bamière et al, 2019

Summary

- A potential for additional C storage of about 5,69 Mt C/year (in the 0-30cm soil layer)
- This represents a relative increase of +3,2‰ for agricultural soils (+ 5,1‰ if only arable soils are considered)
- This potential is mainly found in arable soils (86% of the total potential), partly because initial soil C stocks are low
- Extrapolated to the whole soil profile (5.69 → 8.15 MtC = 29,9 $MtCO_2e$), this additional C storage would compensate 6.5% of national GHG emissions (458 $MtCO_2e$)
- About half of this potential is at a lower cost than the shadow price of carbon in 2020
- The optimal combination of C storing practices depends on the regional context
- Increasing soil C stocks where they are low makes sense only if high soil C stocks are protected in parallel (grasslands, forests)
- A key remaining question: the effect of climate change



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PRIMARY RESEARCH ARTICLE

Global Change Biology WILEY

Feasibility of the 4 per 1000 aspirational target for soil carbon: A case study for France

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Abstract

Increasing soil organic carbon (SOC) stocks is a promising way to mitigate the increase in atmospheric CO_2 concentration. Based on a simple ratio between CO_2 anthropogenic emissions and SOC stocks worldwide, it has been suggested that a 0.4% (4 per 1000) yearly increase in SOC stocks could compensate for current anthropogenic CO_2 emissions. Here, we used a reverse RothC modelling approach to estimate the amount of C inputs to soils required to sustain current SOC stocks and to increase them by 4‰ per year over a period of 30 years. We assessed the feasibility of this aspirational target first by comparing the required C input with net primary productivity (NPP) flowing to the soil, and second by considering the SOC saturation concept. Calculations were performed for mainland France, at a 1 km grid cell resolution. Results showed that a 30%–40% increase in C inputs to soil would be needed to obtain a 4‰ increase per year over a 30-year period. 88.4% of cropland areas were considered unsaturated in terms of mineral-associated SOC, but characterized by a below target C balance, that is, less NPP available than required to reach the 4‰ aspirational target. Conversely, 90.4% of unimproved grasslands were characterized by an above target C balance, that is, enough NPP to reach the 4‰ objective, but 59.1% were also saturated. The situation of improved grasslands and forests was more evenly distributed among the four categories (saturated vs. unsaturated and above vs below target C balance). Future data from soil monitoring networks should enable to validate these results. Overall, our results suggest that, for mainland France, priorities should be (1) to increase NPP returns in cropland soils that are unsaturated and have a below target carbon balance and (2) to preserve SOC stocks in other land uses.

KEYWORDS
4 per 1000, climate change mitigation, net primary productivity, RothC, SOC saturation, soil organic carbon

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Merci pour votre attention!