Changes in nutrient and carbon stocks in French forest soils under decreasing atmospheric deposition

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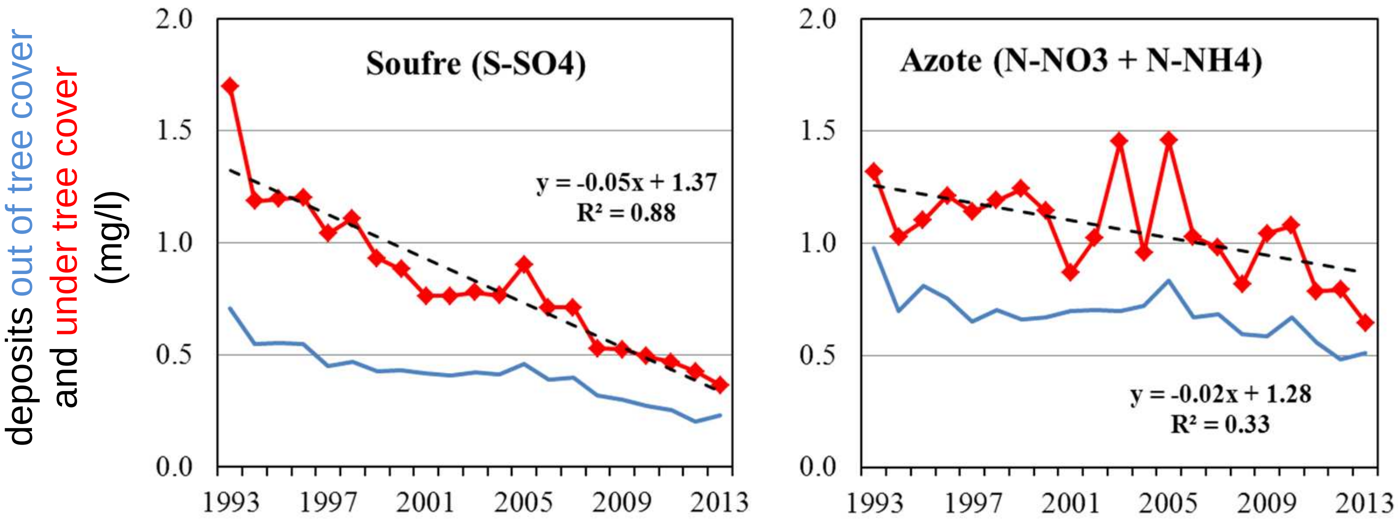
19th Expert Panel Meeting of Soil and Soil Solution of ICP Forests

22- 24 April 2015, Göttingen, Germany

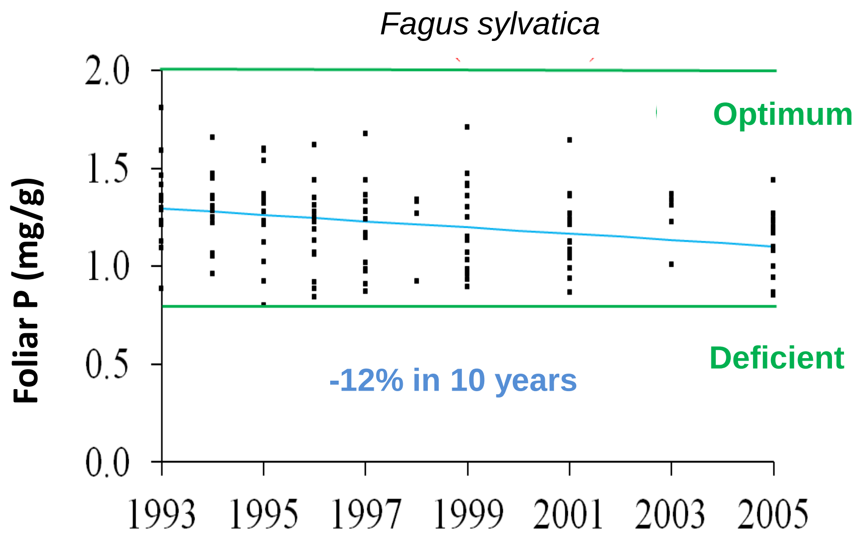
What changes can we detect with repeated soil sampling?

- Do forest soils play a role of C sink or C source?
- Has soil N increased due to continuously high N deposition?
- Have the forest soils recovered from the effect of former acidifying atmospheric deposition?



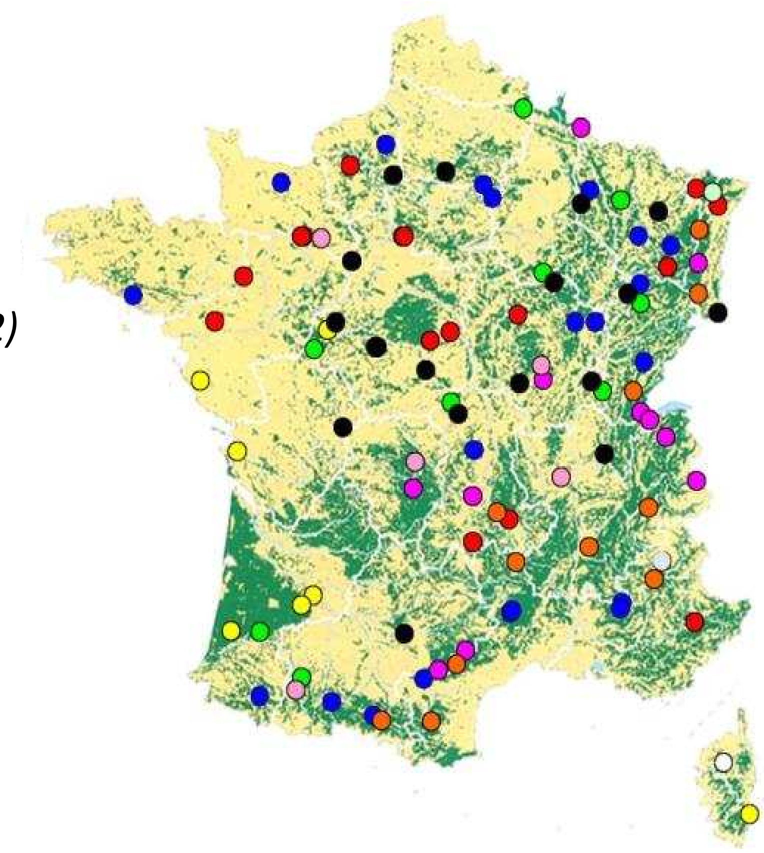
What changes can we detect with repeated soil sampling?

- Do forest soils play a role of C sink or C source?
- Has soil N increased due to continuously high N deposition?
- Have the forest soils recovered from the effect of former acidifying atmospheric deposition?
- Has available P declined in soils as it has in tree foliar nutrition?



RENECOFOR monitoring network

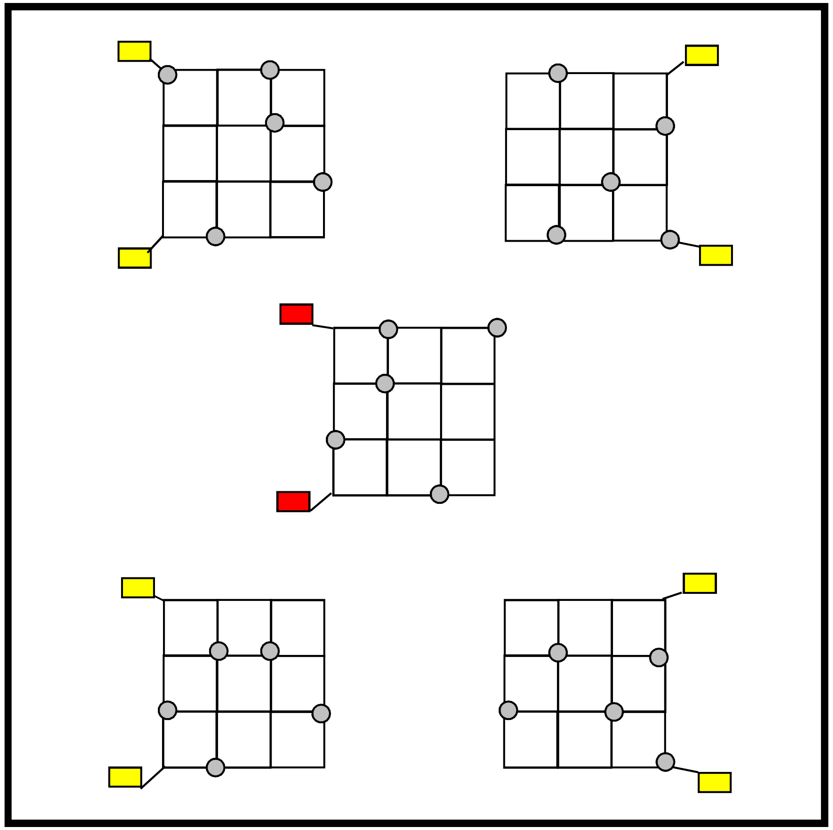
- *Fagus sylvatica (20)*
- *Quercus petraea (19)*
- *Quercus robur (9)*
- *Mixed Quercus petraea & robur (2)*
- *Pinus sylvestris (14)*
- *Picea abies (11)*
- *Abies alba (11)*
- *Pinus pinaster (7)*
- *Pseudotsuga menziesii (6)*
- *Pinus nigra subsp laricio (2)*
- *Larix decidua (1)*



- 102 permanent plots installed in 1992 and distributed among the main productive forest ecosystems

Soil sampling design

Layout of a RENECOFOR plot



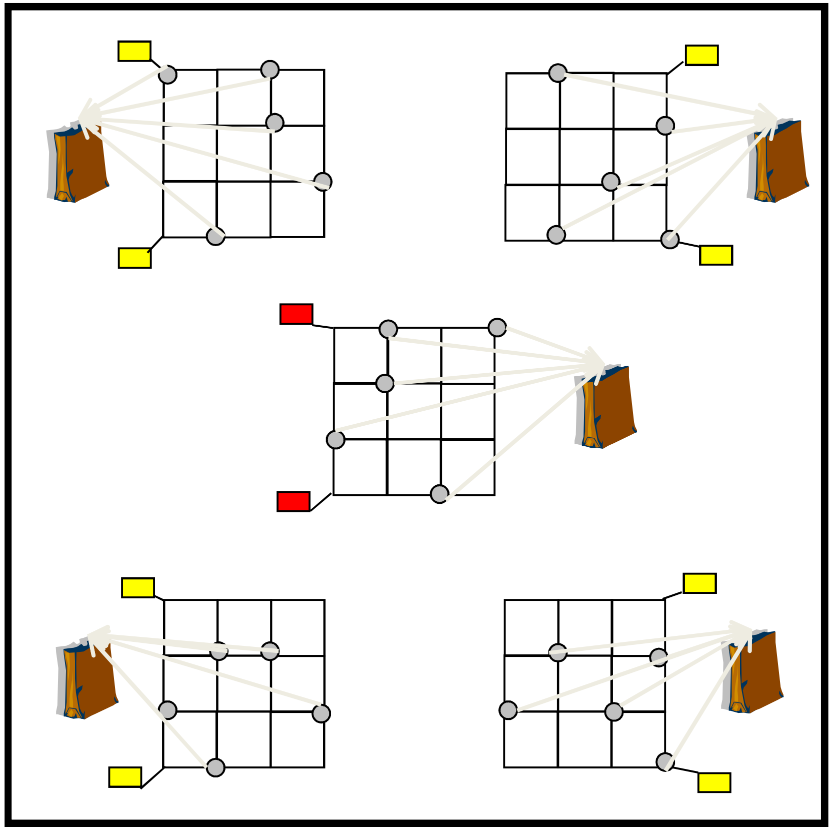
First campaign: 1993-1995

- 5 subplots per plot (13.5 x 13.5m)
- 5 sampling points per subplot

Soil sampling design

First campaign: 1993-1995

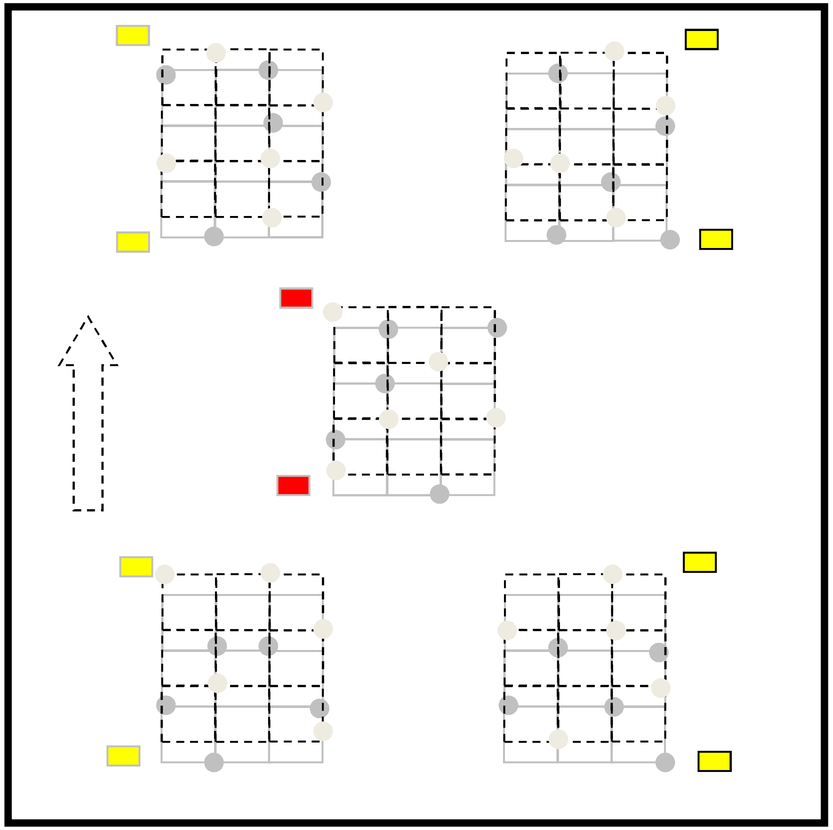
- 5 subplots per plot (13.5 x 13.5m)
- 5 sampling points per subplot
- 1 composite sample per subplot and per layer



Soil sampling design

First campaign: 1993-1995

- 5 subplots per plot (13.5 x 13.5m)
- 5 sampling points per subplot
- 1 composite sample per subplot and per layer



Second campaign: 2007-2012

- Moving subplots by 1.5m

Soil sampling design

- Sampling of 4 to 6 layers
  - 1 to 3 holorganic horizons (OL, OF, OH)
  - 0-10cm
  - 10-20cm
  - 20-40cm

  $\left.\begin{matrix}\text{0-10cm}\\ \text{10-20cm}\\ \text{20-40cm}\end{matrix}\right\}$ Mineral soil

- Holorganic horizon: sampling with a fixed surface
- Subsequent mineral layers: systematic sampling of bulk density with 250 cm^3 Kopecky cylinders

Soil analyses

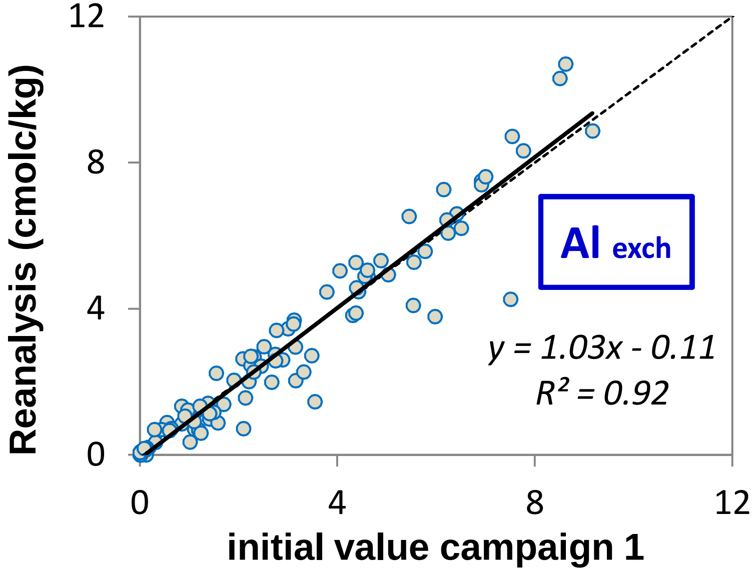
- Soil analyses : same methods used for both campaigns and performed by the same lab (LAS, INRA Arras)

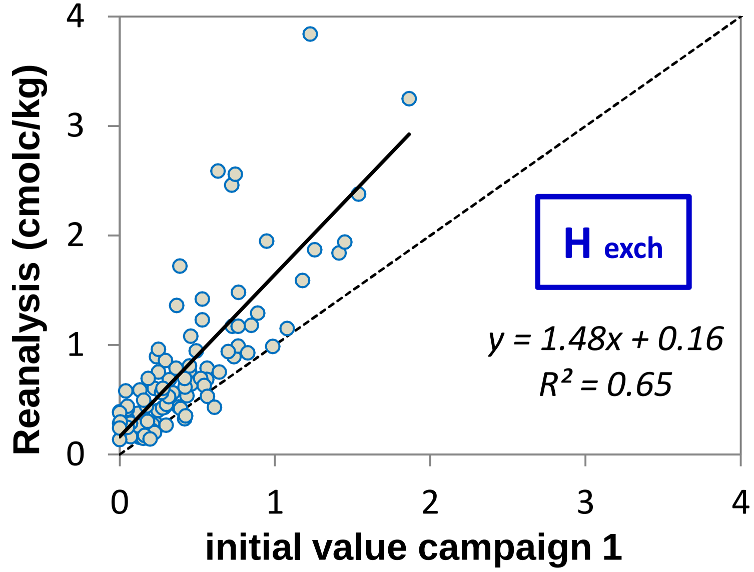
Chemical parameters	Analytical methods	Litter			Mineral soil		
		OL	OF	OH	0-10	10-20	20-40
Total Ca, Mg, K	HF	X	X	X			
Total Cd, Cu, Ni, P, Pb, Zn	Acid extraction			X			
Exchangeable Ca, Mg, K, Mn, Al, H	$BaCl_2$ extraction			X	X	X	X
pH H_2O / pH $CaCl_2$	NF ISO			X	X	X	X
P extractible	P Dyer (pH $CaCl_2$ < 6.5), P Joret-Hébert (pH $CaCl_2$ >6.5)			X	X	X	X
Organic Carbon	Combustion sèche	X	X	X	X		
	Anne method					X	X
Total Nitrogen	Dry combustion	X	X	X	X		
	Kjeldahl method					X	X
ECEC	ECEC = (Ca+Mg+K+Al)éch			X	X	X	X
BS (Base Saturation rate)	$BS = \frac{(Ca + Mg + K)_{ech}}{ECEC}$			X	X	X	X

Controlling the quality of procedures

- Reanalyses: verification of the repeatability and reproducibility of analyses

→ H_{exch} and Mn_{exch} eliminated from calculations (minor part of acidity).





- Elimination of outliers and problematic samples
- Harmonization of quantification limits between the two campaigns
- Verification of the absence of significant change of bulk density (BD) between the two campaigns: stock calculations based on the BD of the first campaign.

Statistical analyses

- **Detection of chemical parameters evolution between the two campaigns using mixed model** (fixed effect, random effect)

model = lme(parameter~ **Campaign**, random=~1|**Plot**, data=dataMM)

model = lme(parameter~ **Campaign + Group + Campaign*Group**, random=~1|**Plot**, data=dataMM)

- **Evaluation of the effect size** (Eta^2, Cohen d, Bravais-Pearson correlation coefficient)

	Ecological factors	Classes *(nb plots)*
1	**Tree species**	Broadleaves *(51)* Coniferous *(51)*
2	**Trophic level**	pH H_2O <4,5 *(54)* pH H_2O 4,5 - 5,5 *(33)* pH H_2O > 5,5 *(15)*
3	**Soil texture**	Clay soil *(18)* Silty soil *(40)* Sandy soil *(44)*
4	**Water regime**	Hydromorphic *(23)* Non hydromorphic *(79)*
5	**Climate type**	Oceanic *(37)* Mountaineous *(29)* Continental *(36)*

Results

Results: Many significant changes detected

Detection of changes in the mineral soil

Ecological category	Soil layer	pH H2O	pH CaCl2	Corg (g/kg)	Ntot (g/kg)	C/N	P (g/kg)	ECEC (cmolc/kg)	BS (%)	Al exch (cmolc/kg)	Ca exch (cmolc/kg)	Mg exch (cmolc/kg)	K exch (cmolc/kg)
All plots	0-10 cm	↘	↘↘	↗↗	↗↗	↗↗	0	↗↗	↗	↗↗	↗	↗↗↗	↗↗↗
	10-20 cm	0	↘	0	↘↘	↗↗↗	0	↗↗	↘	↗↗	↗	↗↗	↗↗
	20-40 cm	↗	0	↘	↘↘↘	↗↗↗	0	↗	↘	0	↗	0	↗
	0-40 cm	0	↘	↗↗	↘	↗↗↗	0	↗↗	↘	↗	0	↗↗	↗↗

- Forest ecosystems quickly respond to environmental changes and are not in a steady state.

0	*Non significant change (p>0.05)*
↘	*Small significant decrease*
↘↘	*Medium significant decrease*
↘↘↘	*High significant decrease*
↗	*Small significant increase*
↗↗	*Medium significant increase*
↗↗↗	*High significant increase*

Results: Accumulation of Corg

Detection of changes in the mineral soil

Ecological category	Soil layer	pH H2O	pH CaCl2	Corg (g/kg)	Ntot (g/kg)	C/N	P (g/kg)	ECEC (cmolc/kg)	BS (%)	Al exch (cmolc/kg)	Ca exch (cmolc/kg)	Mg exch (cmolc/kg)	K exch (cmolc/kg)
All plots	0-10 cm	↘	↘↘	↗↗	↗↗	↗↗	0	↗↗	↗	↗↗	↗	↗↗↗	↗↗↗
	10-20 cm	0	↘	0	↘↘	↗↗↗	0	↗↗	↘	↗↗	↗	↗↗	↗↗
	20-40 cm	↗	0	↘	↘↘↘	↗↗↗	0	↗	↘	0	↗	0	↗
	0-40 cm	0	↘	↗↗	↘	↗↗↗	0	↗↗	↘	↗	0	↗↗	↗↗

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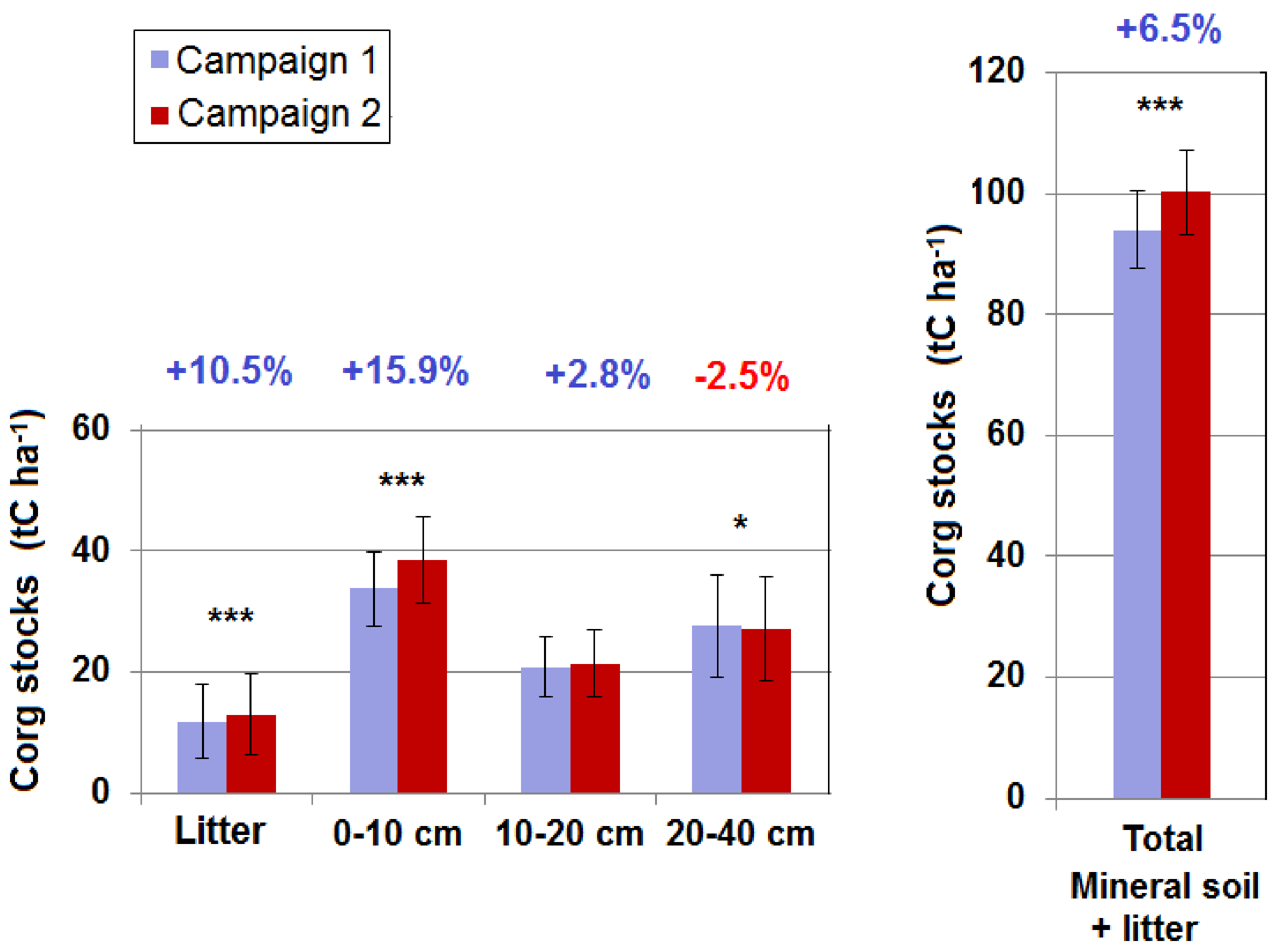
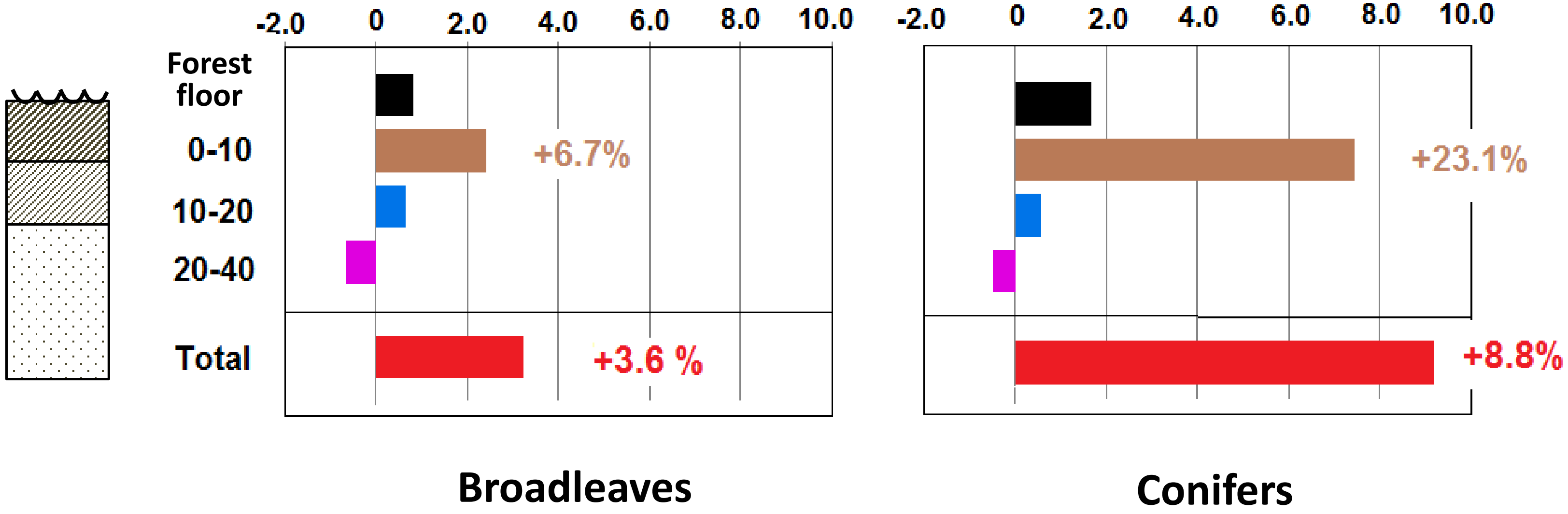
Results: Accumulation of Corg



- 1993 - 2012 : Average gain of **6.2 TC.ha^{-1}**
- C accumulation rate = **0.34 ± 0.06 TC.ha^{-1}.year^{-1}**

Results: Accumulation of Corg

Corg stocks variations between the two campaigns (TC.ha^{-1})

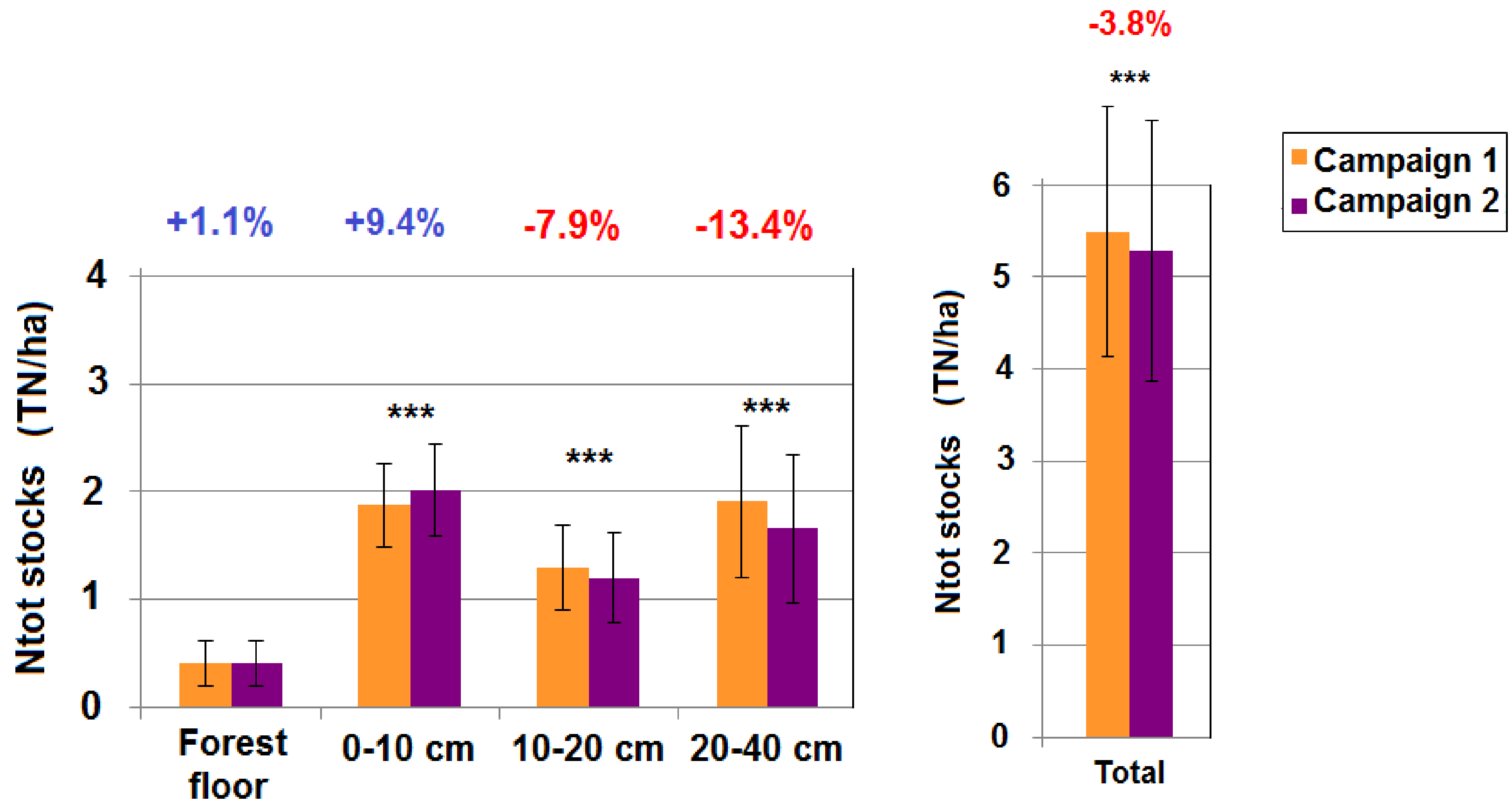


- **Corg accumulation 2 - 3 times higher under conifers than under broadleaves**

Results: Decrease of total N

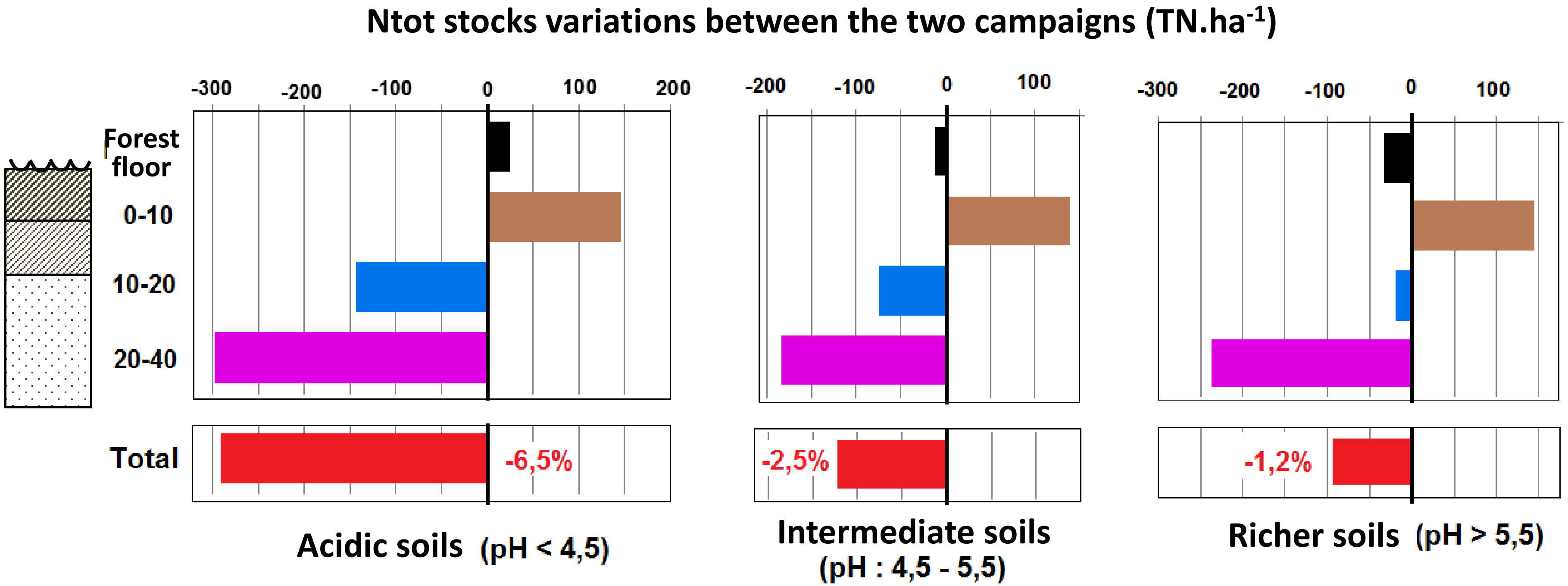
Ecological category	Soil layer	pH H2O	pH CaCl2	Corg (g/kg)	Ntot (g/kg)	C/N	P (g/kg)	ECEC (cmolc/kg)	BS (%)	Al exch (cmolc/kg)	Ca exch (cmolc/kg)	Mg exch (cmolc/kg)	K exch (cmolc/kg)
All plots	0-10 cm	↘	↘↘	↗↗	↗↗	↗↗	0	↗↗	↗	↗↗	↗	↗↗↗	↗↗↗
	10-20 cm	0	↘	0	↘↘	↗↗↗	0	↗↗	↘	↗↗	↗	↗↗	↗↗
	20-40 cm	↗	0	↘	↘↘↘	↗↗↗	0	↗	↘	0	↗	0	↗
	0-40 cm	0	↘	↗↗	↘	↗↗↗	0	↗↗	↘	↗	0	↗↗	↗↗

Results: Decrease of total N



➢ 1993 - 2012 : Average loss of **0.2 TN.ha^{-1}**

Results: Decrease of total N



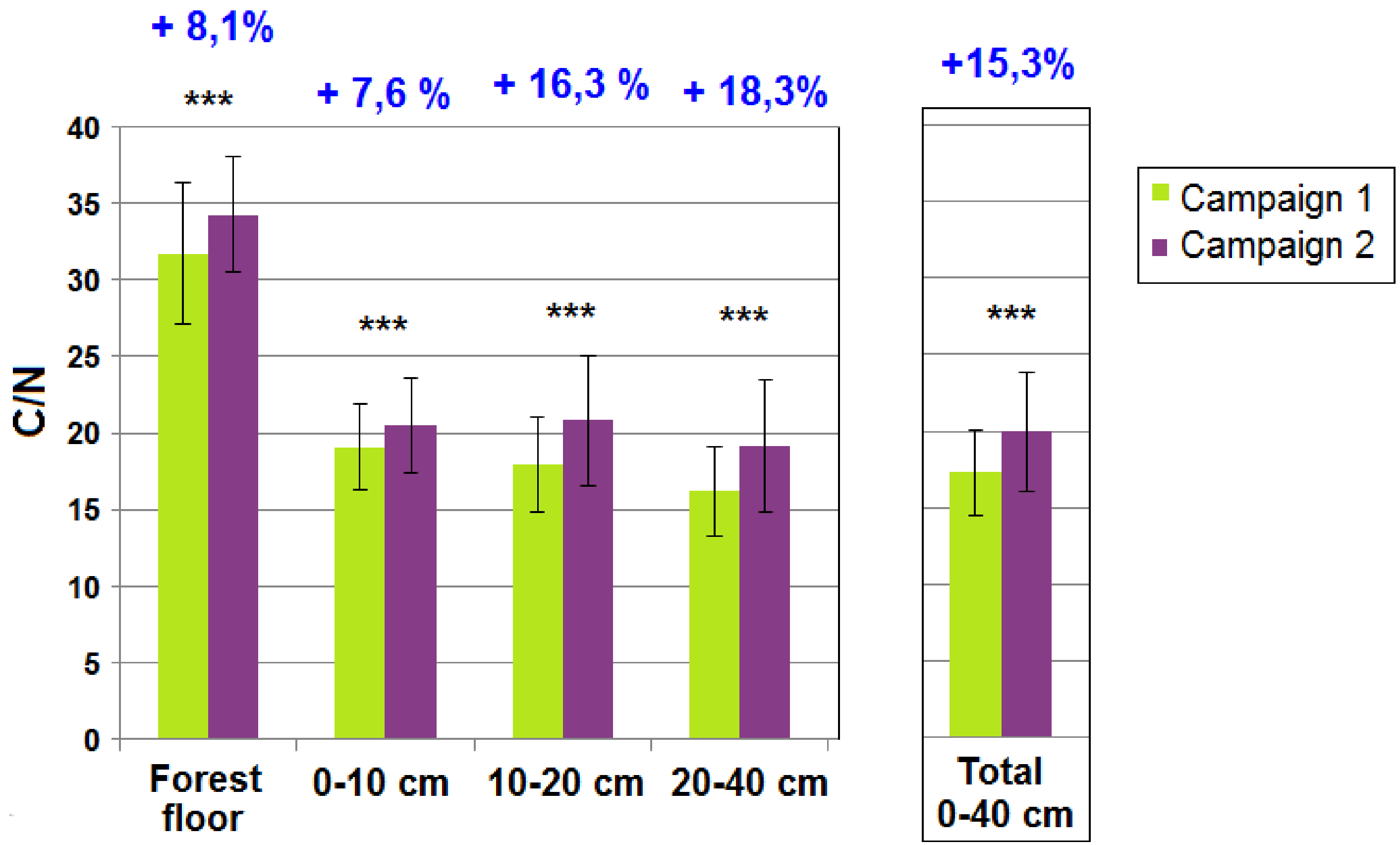
- High losses of Ntot in 10-20 cm and 20-40 cm soil layer
- Higher Ntot losses in acid contexts (soil pH_{H_2O} < 4.5, oceanic climate, sandy soils)
- Ntot stocks patterns are similar between tree species (broadleaves/coniferous)

Results: Increase of C/N ratio

Ecological category	Soil layer	pH H2O	pH CaCl2	Corg (g/kg)	Ntot (g/kg)	C/N	P (g/kg)	ECEC (cmolc/kg)	BS (%)	Al exch (cmolc/kg)	Ca exch (cmolc/kg)	Mg exch (cmolc/kg)	K exch (cmolc/kg)
All plots	0-10 cm	↘	↘↘	↗↗	↗↗	↗↗	0	↗↗	↗	↗↗	↗	↗↗↗	↗↗↗
	10-20 cm	0	↘	0	↘↘	↗↗↗	0	↗↗	↘	↗↗	↗	↗↗	↗↗
	20-40 cm	↗	0	↘	↘↘↘	↗↗↗	0	↗	↘	0	↗	0	↗
	0-40 cm	0	↘	↗↗	↘	↗↗↗	0	↗↗	↘	↗	0	↗↗	↗↗

- General increase of C/N : all soil layers, all ecological contexts.
  - Top soil (litter and 0-10 cm): Ntot increased but less than Corg
  - Deep soil (10-20 and 20-40 cm): Ntot decreased while Corg was quite stable

Results: General increase of C/N ratio



- ➢ Up to + 5 C/N points in acid contexts (soil pH_H_2O < 4.5, oceanic climate, sandy soils, layers 10-20 cm and 20-40 cm).

Results: Soil acidification recovery

Ecological category	Soil layer	pH H2O	pH CaCl2	Corg (g/kg)	Ntot (g/kg)	C/N	P (g/kg)	ECEC (cmolc/kg)	BS (%)	Al exch (cmolc/kg)	Ca exch (cmolc/kg)	Mg exch (cmolc/kg)	K exch (cmolc/kg)
All plots	0-10 cm	↘	↘↘	↗↗	↗↗	↗↗	0	↗↗	↗	↗↗	↗	↗↗↗	↗↗↗
	10-20 cm	0	↘	0	↘↘	↗↗↗	0	↗↗	↘	↗↗	↗	↗↗	↗↗
	20-40 cm	↗	0	↘	↘↘↘	↗↗↗	0	↗	↘	0	↗	0	↗
	0-40 cm	0	↘	↗↗	↘	↗↗↗	0	↗↗	↘	↗	0	↗↗	↗↗

- Overall results:
  - no clear or weak changes in pH and Base Saturation
  - Increase of ECEC and of both acidic (Al) and base cations (Mg, K)
  - Topsoil: pH decrease associated to BS increase might result from Corg increase

Results: Soil acidification recovery

Ecological category	Soil layer	pH H2O	pH CaCl2	Corg (g/kg)	Ntot (g/kg)	C/N	P (g/kg)	ECEC (cmolc/kg)	BS (%)	Al exch (cmolc/kg)	Ca exch (cmolc/kg)	Mg exch (cmolc/kg)	K exch (cmolc/kg)
Sol pH < 4,5	0-10 cm	↘↘	↘↘	↗↗	↗	↗↗	0	↗↗	↗	↗↗	0	↗↗↗	↗↗↗
	10-20 cm	↘	↘↘	0	↘↘↘	↗↗↗	0	↗↗	↘	↗↗	↘	↗	↗↗
	20-40 cm	0	↘	↘	↘↘↘	↗↗↗	0	↗	↘↘	↗	↘↘	0	↗
	0-40 cm	↘↘	↘↘	↗	↘↘	↗↗↗	0	↗↗	↘	↗↗	0	↗↗	↗↗
Sol pH 4,5 - 5,5	0-10 cm	0	↘	↗↗↗	↗↗	↗↗↗	0	↗↗	↗	0	↗↗	↗↗↗	↗↗↗
	10-20 cm	0	0	↗	↘	↗↗↗	0	↗	0	↗	0	↗↗	↗↗
	20-40 cm	↗↗	0	0	↘↘	↗↗↗	0	0	0	0	0	0	0
	0-40 cm	↗	↘	↗↗	0	↗↗↗	0	↗↗	0	0	0	↗↗	↗↗
Sol pH > 5,5	0-10 cm	0	0	↗↗	0	↗↗↗	0	↗↗↗	0	0	↗↗	↗↗↗	↗↗
	10-20 cm	0	0	↗	0	↗↗↗	↘↘	↗↗	0	0	↗↗	↗↗	↗↗
	20-40 cm	↗↗	0	0	↘↘	↗↗	0	0	0	↘↘	↗	0	↗↗
	0-40 cm	↗	0	0	0	↗↗↗	0	↗↗↗	0	0	↗↗↗	0	↗↗

- In detail, by soil pH category:
  - The less acidic soils (pH > 4,5) kept stable or rather recovered from acidification
  - For the most acidic soils (pH < 4,5):
    - both pH and BS decreased ⇨ indicators of further acidification
    - **But** the stocks of base cations didn't decrease (Mg and K even increased) since the ECEC increased

Results: Soil extractable phosphorus

Mineral soil

Soil layer	Chemical parameters											
	pH H_2O	pH $CaCl_2$	Corg (g/kg)	Ntot (g/kg)	C/N	P (g/kg)	ECEC (cmolc/kg)	S/T (%)	Al éch. (cmolc/kg)	Ca éch. (cmolc/kg)	Mg éch. (cmolc/kg)	K éch. (cmolc/kg)
0-10 cm	↘	↘↘	↗↗	↗↗	↗↗	0	↗↗	↗	↗↗	↗	↗↗↗	↗↗↗
10-20 cm	0	↘	0	↘↘	↗↗↗	0	↗↗	↘	↗↗	↗	↗↗	↗↗
20-40 cm	↗	0	↘	↘↘↘	↗↗↗	0	↗	↘	0	↗	0	↗
0-40 cm	0	↘	↗↗	↘	↗↗↗	0	↗↗	↘	↗	0	↗↗	↗↗

Légende

0	Evolution non significative (seuil de significativité de 5%)
↘	Diminution significative - Taille de l'effet faible
↘↘	Diminution significative - Taille de l'effet moyen
↘↘↘	Diminution significative - Taille de l'effet fort
↗	Augmentation significative - Taille de l'effet faible
↗↗	Augmentation significative - Taille de l'effet moyen
↗↗↗	Augmentation significative - Taille de l'effet fort

- Few changes observed for P (Dyer/ Joret-Hébert)

Conclusions / Research perspectives

Many significant changes in soil chemistry over 15 years

- Changes mainly influenced by organic matter dynamics:
  - Soils significantly accumulated Corg (+0.34 t/ha/yr in average), and even more in coniferous plots ⇨ ECEC ↗, simultaneous pH ↘ and BS ↗ in topsoil (0-10 cm)
  - N stocks decreased (-13 kg/ha/yr), mostly in deep layers ⇨ Was N absorbed into wood biomass or leached? Is N becoming limiting?
- Acidification: recovery in less acidic soils (pH > 4,5) and paradoxal indicators in acidic soils (both pH and BS ↘, but base cation stocks remain stable or even increased for Mg and K)
- Extractable P: no significant change to be related to the P decreasing trend in foliar nutrition

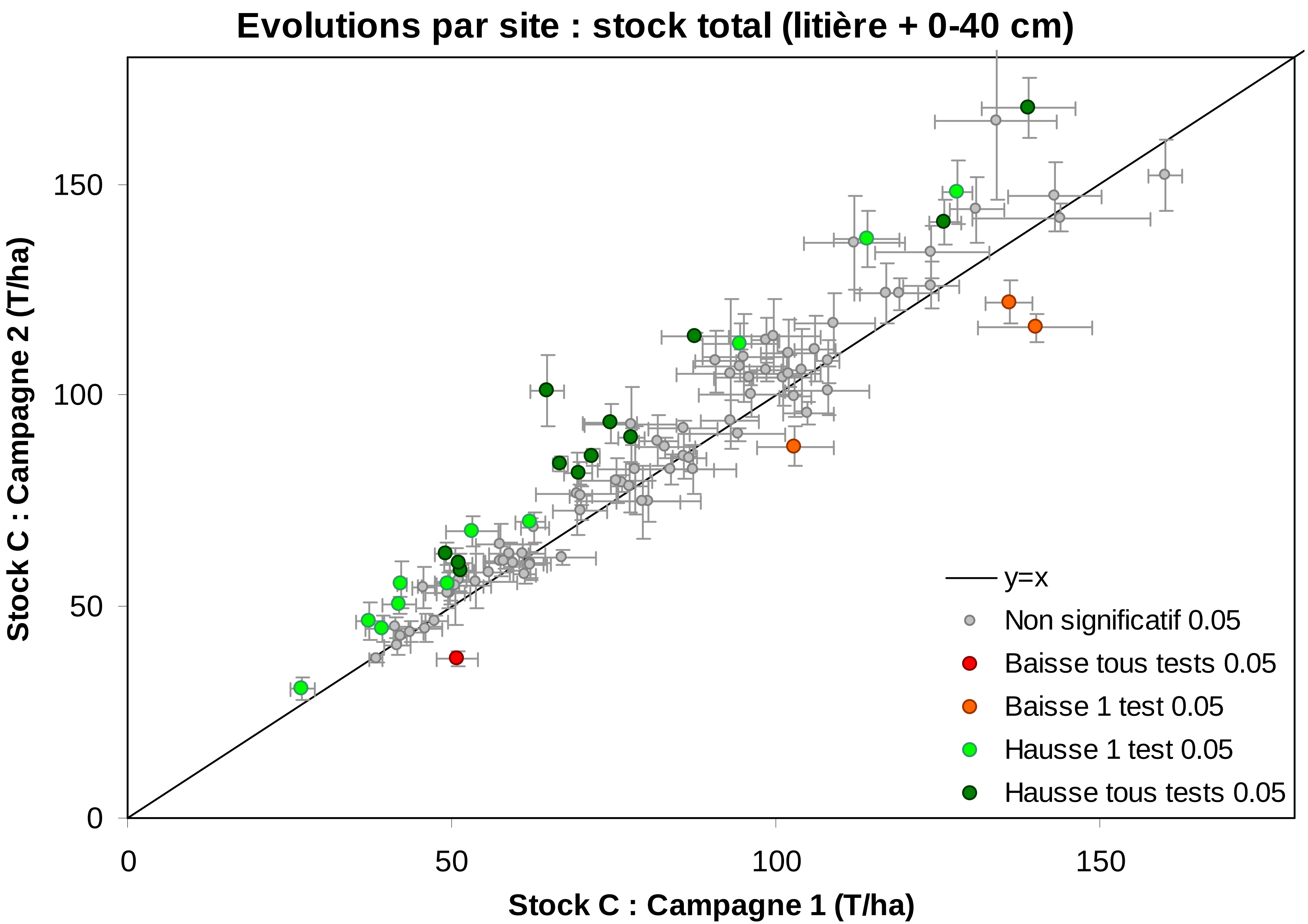
Aknowledgements

Many thanks to people who brought their input into the data evaluation and interpretation: *B. De Vos (INBO), C. Jolivet (INRA), N. Proix (INRA), A. Brêthes (ONF), N. Pousse (ONF)*

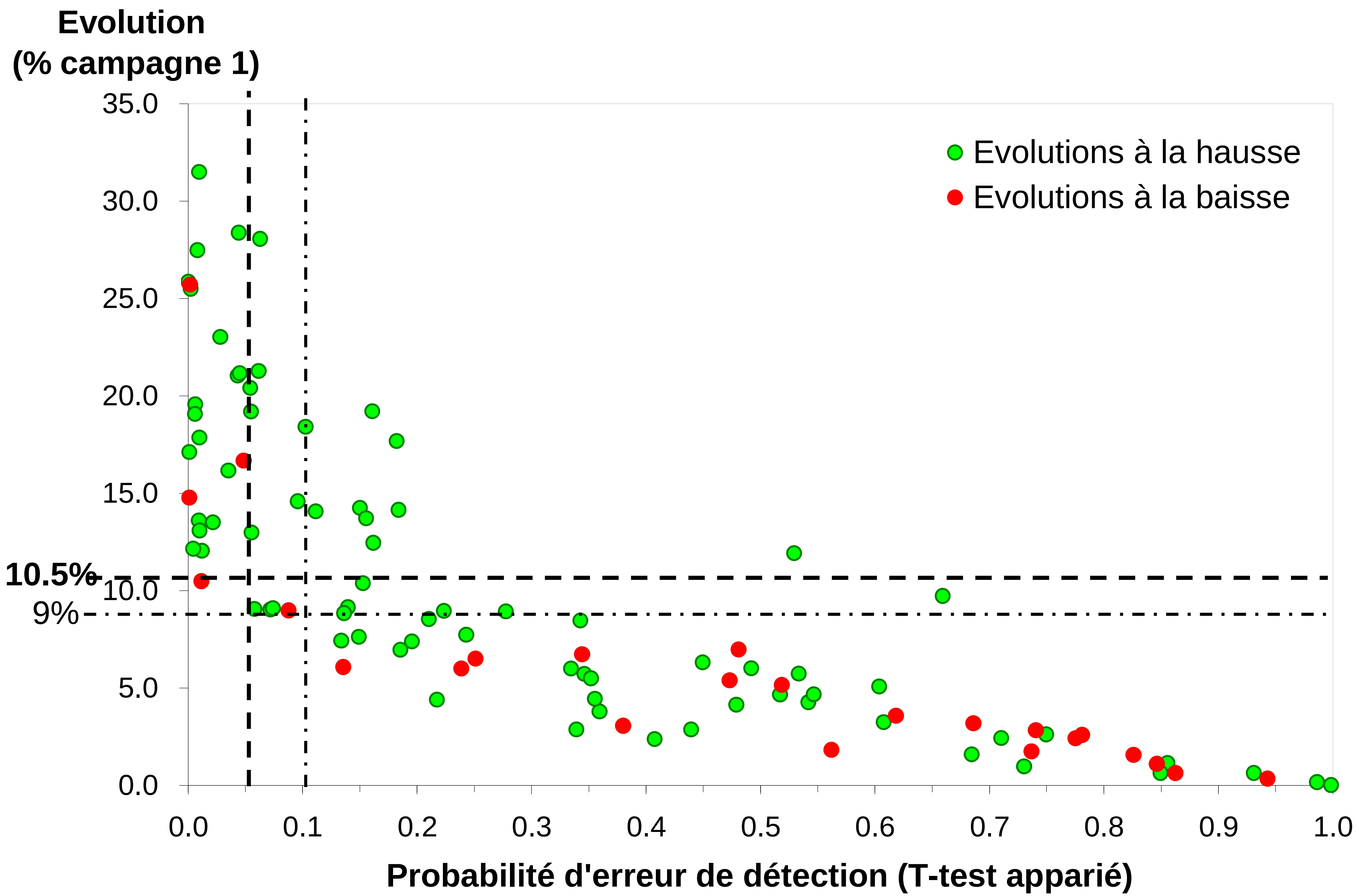
Many thanks also to all foresters, technicians and scientists who participated to soil sampling and analyses (that was a huge work!)

Thank you for your attention

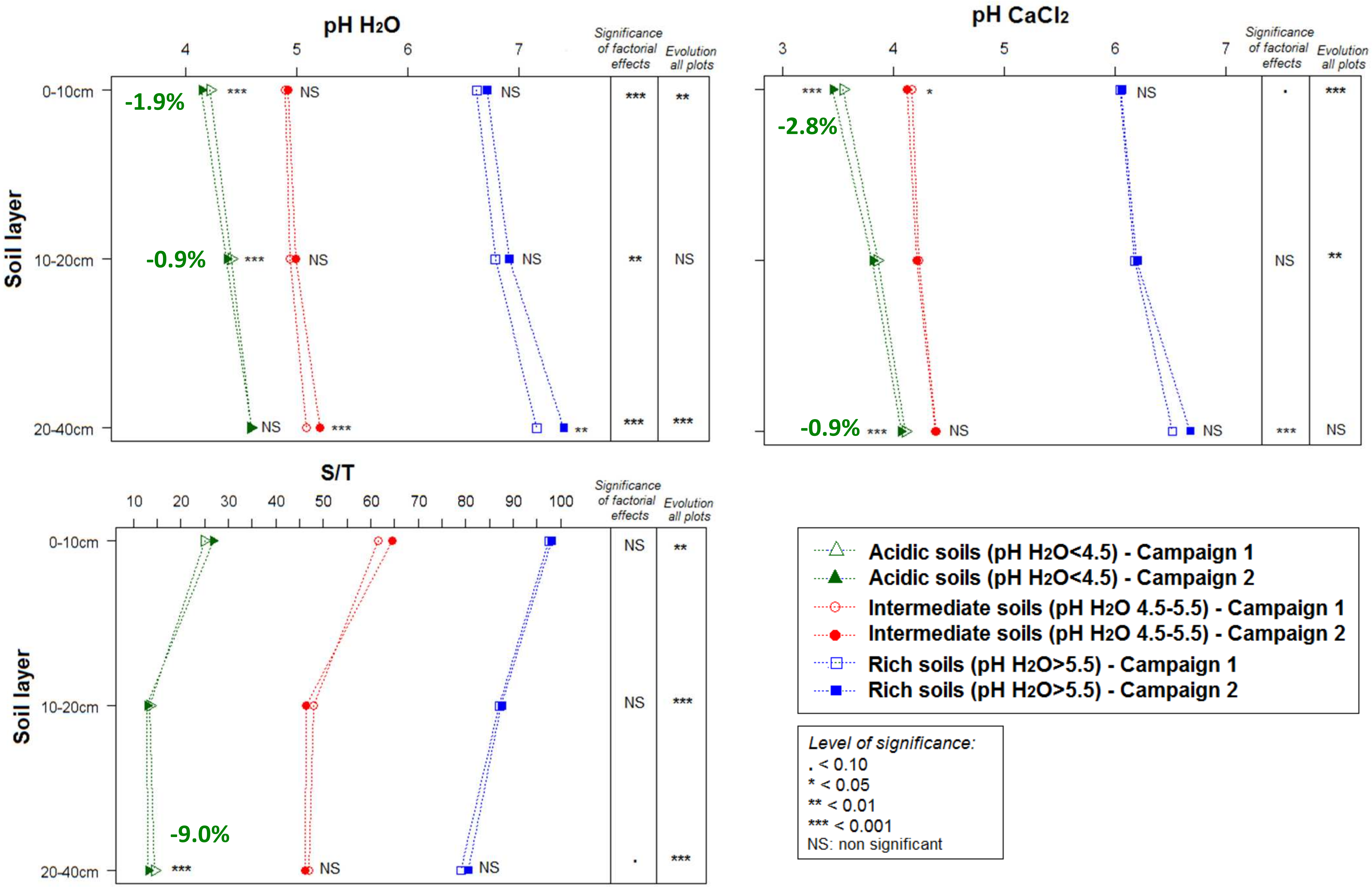
Plotwise Corg changes



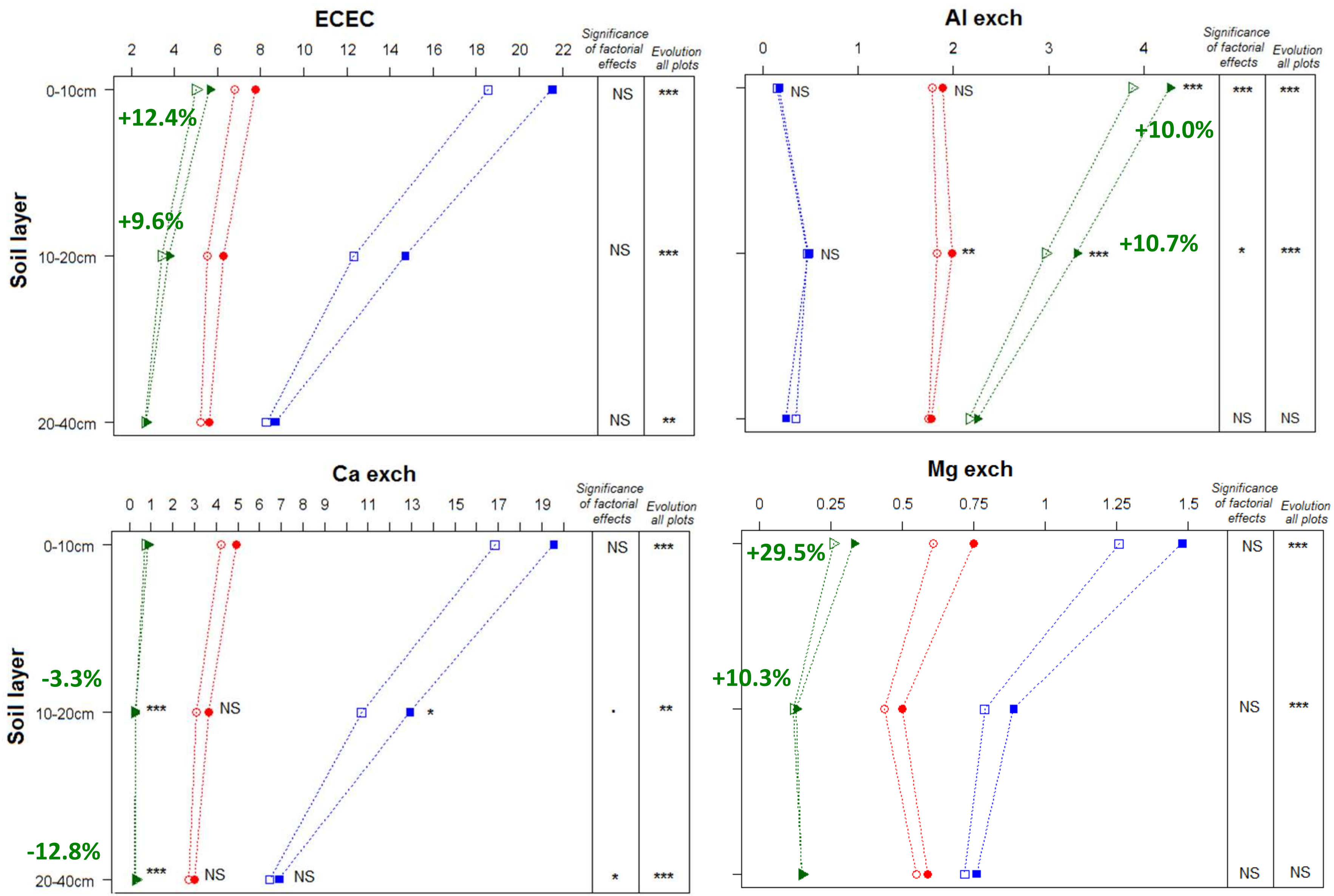
Plotwise Corg changes



Results: Soil acidification recovery



Results: Soil acidification recovery



Results: Holorganic horizons

Holorganic horizons

Paramètres chimiques	Niveau de significativité et taille de l'effet	Pourcentage d'évolution
Ca tot	↗	+ 0,6 %
Mg tot	↗	+ 10,7 %
K tot	0	- 1,8 %
Cd	0	+ 1,7 %
Cu	0	+ 8,1 %
Ni	0	- 14,5 %
Pb	↘↘↘	- 28,7 %
Zn	↘↘	- 12,0 %
P	↗↗	+ 14,5 %
C tot	↗↗	+ 10,5 %
N tot	0	+ 1,1 %
C/N	↗↗	+ 8,1 %
Masse litière	0	- 1,5 %

Légende

0	Evolution non significative (seuil de significativité de 5%)
↘	Diminution significative - Taille de l'effet faible
↘↘	Diminution significative - Taille de l'effet moyen
↘↘↘	Diminution significative - Taille de l'effet fort
↗	Augmentation significative - Taille de l'effet faible
↗↗	Augmentation significative - Taille de l'effet moyen
↗↗↗	Augmentation significative - Taille de l'effet fort

- Sharp decrease in trace metal elements

Results: Soil acidification recovery

		Chemical parameters											
Ecological category	**Soil layer**	**pH H2O**	**pH CaCl2**	**Corg** (g/kg)	**Ntot** (g/kg)	**C/N**	**P** (g/kg)	**ECEC** (cmolc/kg)	**BS** (%)	**Al exch** (cmolc/kg)	**Ca exch** (cmolc/kg)	**Mg exch** (cmolc/kg)	**K exch** (cmolc/kg)
All plots	**0-10 cm**	↘	↘↘	↗↗	↗↗	↗↗	**0**	↗↗	↗	↗↗	↗	↗↗↗	↗↗↗
	10-20 cm	**0**	↘	**0**	↘↘	↗↗↗	**0**	↗↗	↘	↗↗	↗	↗↗	↗↗
	20-40 cm	↗	**0**	↘	↘↘↘	↗↗↗	**0**	↗	↘	**0**	↗	**0**	↗
	0-40 cm	**0**	↘	↗↗	↘	↗↗↗	**0**	↗↗	↘	↗	**0**	↗↗	↗↗
Sol pH < 4,5	**0-10 cm**	↘↘	↘↘			↗↗				↗↗			
	10-20 cm	↘			↘↘↘	↗↗↗	**0**			↗↗			
	20-40 cm	**0**	↘	↘	↘↘↘	↗↗↗					↘↘		
	0-40 cm	↘↘	↘↘			↗↗↗				↗↗			
Sol pH 4,5 - 5,5	**0-10 cm**	**0**	↘			↗↗↗				**0**			
	10-20 cm	**0**			↘	↗↗↗	**0**			↗			
	20-40 cm	↗↗	**0**	**0**	↘↘	↗↗↗					**0**		
	0-40 cm	↗	↘			↗↗↗				**0**			
Sol pH > 5,5	**0-10 cm**	**0**	**0**			↗↗↗				**0**			
	10-20 cm	**0**			**0**	↗↗↗	↘↘			**0**			
	20-40 cm	↗↗	**0**	**0**	↘↘	↗↗					↗		
	0-40 cm	↗	**0**			↗↗↗				**0**			

Results: Many significant changes detected – by groups

Facteurs écologiques	Couches	pH H_2O	pH $CaCl_2$	Corg (g/kg)	Ntot (g/kg)	C/N	P (g/kg)	ECEC (cmolc/kg)	Taux saturation (%)	Al éch. (cmolc/kg)	Ca éch. (cmolc/kg)	Mg éch. (cmolc/kg)	K éch. (cmolc/kg)
Feuillus	0-10 cm	0	↘	↗↗	0	↗↗	↘	↗↗	0	↗	0	↗↗	↗↗
	10-20 cm	0			↘↘	↗↗↗				↗			
	20-40 cm				↘↘	↗↗↗			0		↗		↗↗
	0-40 cm	↗		↗		↗↗↗	↘			↗		↗↗	
Résineux	0-10 cm	↘↘	↘↘	↗↗↗	↗↗	↗↗	0	↗↗	↗	↗↗	↗↗	↗↗↗	↗↗↗
	10-20 cm	0			↘↘	↗↗↗				↗↗			
	20-40 cm				↘↘	↗↗↗			↘↘		↗↗		0
	0-40 cm	0		↗↗		↗↗↗	0			↗↗		↗↗	
Sols hydromorphes	0-10 cm			↗↗	0	↗↗	↘↘	↗↗	0	0	0	↗↗↗	
	10-20 cm			0			0	0		0			↗
	20-40 cm					↗↗↗		0	0				
	0-40 cm					↗↗↗		0		0	↗		
Sols non hydromorphes	0-10 cm			↗↗	↗↗	↗↗	0	↗↗↗	↗	↗↗	↗↗	↗↗↗	
	10-20 cm			↗			↗	↗↗		↗↗			↗↗
	20-40 cm					↗↗↗		↗	↘↘				
	0-40 cm					↗↗↗		↗↗		↗↗	0		
Climat continental	0-10 cm	↘	↘↘		↗↗	↗↗		↗↗			0		↗↗↗
	10-20 cm				↘↘	↗↗↗	0	↗		↗			↗↗
	20-40 cm	↗↗	0	0	↘↘	↗↗↗					↗↗		
	0-40 cm	0	↘↘		0	↗↗						↗↗	
Climat montagnard	0-10 cm	0	0		↗↗	↗↗↗		↗↗↗			↗↗		↗↗↗
	10-20 cm				↘↘	↗↗↗	0	↗↗		↗↗			↗↗
	20-40 cm	↗	0	↘	↘↘↘	↗↗↗					↗↗		
	0-40 cm	0	0		↘	↗↗↗						↗↗	
Climat océanique	0-10 cm	↘	↘↘		0	↗↗		↗↗			0		↗↗
	10-20 cm				↘↘	↗↗↗	0	↗		↗			↗↗
	20-40 cm	0	↘	0	↘↘↘	↗↗↗					0		
	0-40 cm	0	↘↘		↘↘	↗↗↗						↗↗	
Toutes placettes	0-10 cm	↘	↘↘	↗↗	↗↗	↗↗	0	↗↗	↗	↗↗	↗	↗↗↗	↗↗↗
	10-20 cm	0	↘	0	↘↘	↗↗↗	0	↗↗	↘	↗↗	↗	↗↗	↗↗
	20-40 cm	↗	0	↘	↘↘↘	↗↗↗	0	↗	↘	0	↗	0	↗
	0-40 cm	0	↘	↗↗	↘	↗↗↗	0	↗↗	↘	↗	0	↗↗	↗↗