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J. Ranger, P. Bonnaud, P. Santenoise, B. Zeller, G. Nourrisson, et al.. Effect of limited compaction on soil solution chemistry in two acidic forest ecosystems: Changes, recovery and impact of liming. Forest Ecology and Management, 2021, 499, pp.119538. 10.1016/j.foreco.2021.119538 . hal-04222494

HAL Id: hal-04222494
https://hal.inrae.fr/hal-04222494v1

Submitted on 22 Jul 2024

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Abstract

Forest practices are rapidly becoming mechanised in France, resulting in unknown consequences for the current and long-term functioning and functions of ecosystems. Degradation of forest soil porosity cannot be remediated artificially, and restoration via natural processes is slow and not likely to include deep soil layers, where tree roots take up large amounts of water and nutrients. In 2007 and 2008, two experimental sites were set up in the Lorraine Plateau (France). The soils are Ruptic Luvisols and are classified as highly sensitive to compaction. We observed multiple parameters and studied weakly bound soil solutions, which are known to react to changes in ecosystem functioning. We hypothesised that (i) soil solution chemistry is a relevant indicator to assess soil changes after compaction and dynamics of soil recovery in the decade following compaction, (ii) restoration is greater at the more fertile site and (iii) soil pH is a relevant parameter to explain the behaviour of soil solutions. Our results showed that soil solution concentrations changed drastically after compaction and that restoration was more effective in the less fertile soil than in the more fertile one. Finally, a soil pH threshold of 4.5 was relevant for explaining the behaviour of nitrate, which is particularly useful for monitoring solution geochemistry in these acidic soils. Liming at the less fertile site increased the pH to more than 4.5, which changed the behaviour of nitrate and reinforced the utility of this threshold for explaining soil biogeochemical functioning. Soil solution is a relevant indicator of current soil functioning after compaction; however, this study demonstrated that additional information is required to understand its meaning accurately. This study highlights that long-term observation is needed to identify the consequences of soil compaction on long-living ecosystems.

Keywords: soil compaction; soil solution; changes; recovery; liming

1 Introduction

The unavoidable mechanisation of forest operations may deform the soil greatly when pressure exerted by machinery exceeds the soil bearing capacity. This phenomenon increases as soil sensitivity to compaction and soil water content increases (Ampoorter et al., 2010). The consequences are difficult to identify in semi-intensively managed ecosystems that had little mechanisation in the past.

Compaction increases soil bulk density, decreases soil macro-porosity (Herbauts, 1996; Page-Dumroese et al., 2006) and increases the frequency of hypoxic or anoxic events in the soil (Stepniewski et al., 1994). Compaction influences the habitat of biological actors that mineralise organic matter (Van der Linden et al., 1989), thus reducing their populations (Battigelli et al., 2004) and activity (Jensen et al., 1996; Lee et al., 2008; Tan et al., 2008). Consequently, compaction changes trends in the soil's physical, chemical, physico-chemical and biological functioning, which alters all cycles, such as those of water (Horton et al., 1994), carbon (C) and nitrogen (N) (Brevik et al., 2002; Silveira et al., 2010; Van der Linden et al., 1989), pH and cations (Saeedifar and Asgari, 2014). The quality of native and/or allochthonous organic matter can change (De Neve and Hofman, 2000). All the soil functions, such as those related to production, biodiversity and the environment could then be altered. The growth of young forest plants could decrease due to an increase in soil physical resistance (von Wilpert, and Schäffer, 2006) and via the physiological effects of changes in gas diffusion in soils, which could result in ethylene accumulation in roots and hormonal responses that restrict growth (Pandey et al., 2021). Climate conditions (Smith, 1977), soil type (Dick et al., 1988) and soil mineralogy (Silva et al., 2011) influence the impact of compaction, but sensitive fine-textured soils are influenced most when they are compacted under wet conditions (Pischedda et al., 2009).

Mechanisation could represent a major risk for the sustainability of forest ecosystems on fine-textured acidic soils with low coarse-material content (Pischedda et al., 2009), such as the soils of the Lorraine Plateau. These soils are acidic (pH of ca. 4.5 in the A horizon), fine-silty textured, not hydromorphic if not compacted and highly sensitive to physical degradation (MEDDE, 2005).

A review of the literature shows that the field of agriculture is the main source of knowledge about the degradation and restoration of soils after compaction. The studies frequently focus on the soil solid phase, often using *ex situ* approaches and/or short-term experiments (De Neve and Hoffman, 2000; Lee et al., 2008; Silva et al., 2011). Information on the medium- to long-term dynamics of soil restoration is rare and, to our knowledge, no study has used soil solutions as an indicator of forest soil degradation-restoration following compaction.

However, soil solutions are known to be much more reactive than the solid phase (Zabowski and Ugolini, 1990; Ranger et al., 2001) and highly sensitive to changes in the ecosystem (Wolt, 1994). Absolute concentrations of elements in solutions and their ratios provide relevant information on forest soil geochemistry and its changes due to environmental conditions (Sverdrup et al., 1992) or forest practices (Cronan and Grigal, 1995), as well as consequences on soil fertility. The soil solution is also the compartment from which vegetation takes up most nutrients, and it is considered one of the most important indicators of nutrient bio-availability (Wolt, 1994; Arocena, 2000; Smethurst, 2000).

The present study used soil solutions collected in porous cup lysimeters at two long-term monitored experimental sites (Azerailles (AZ) and Clermont-en-Argonne (CA)) on the sensitive soils of the Lorraine Plateau (France) to test the influence and duration of physical degradation on forest soil fertility. Previous observations of these sites showed that the soil morphology and the occurrence and geochemistry of the perched water table were not fully restored 10 years after compaction (Bonnaud et al. 2019). While degradation of the soil was rapid, restoration of its porosity was slow, and assessment of restoration seems to depend on the indicator.

As soil solutions are highly reactive, we hypothesised that they are a relevant indicator of soil changes after compaction and of the dynamics of soil recovery in the decade following compaction. We hypothesised that the chemistry of soil solutions that we studied would add valuable information to that obtained from the perched water table at the same sites (Bonnaud et al., 2019). We also hypothesised that, unlike the perched water table indicator, restoration assessed with non-saturated soil solutions would be more advanced in the site with more fertile (AZ) than that with less fertile soil (CA). Finally, we hypothesised that soil pH is a relevant parameter for explaining differences in nitrogen dynamics and associated cations at the two sites, especially the threshold pH of 4.5 which is also known to be an important parameter for Al speciation and soil biogeochemical functioning (Driscoll et al., 1990).

2 Materials and methods

We studied two experimental sites set up in north-eastern France: AZ (54) (48° 30' 1.10" N, 6° 42' 6.89" E), in the “Hauts Bois” estate forest, and the CA (55) (49° 8' 27.59" N, 5° 1' 9.58" E), in the “Grand Pays” estate forest. As these long-term monitored experimental sites have been described in previous articles (Goutal et al., 2013, Bonnaud et al., 2019), we present only general information and/or information specific to soil solutions here.

2.1 Study sites

The mean site elevation is 300 and 270 m a.s.l. at AZ and CA, respectively. The 30-year mean annual rainfall and temperature (data Météo-France) are 920 mm and 8.5°C, respectively, at AZ and 1000 mm and 9°C, respectively, at CA. Before clear-cutting, the stands at AZ consisted of a high forest dominated by *Fagus sylvatica* L. followed by *Quercus petraea* L., while those at CA consisted of a high forest originating from an old coppice with standards, dominated by *Fagus sylvatica* L. and *Quercus petraea* L., followed by *Betula verrucosa* Ehrh., *Acer platanoides* L. and *Populus tremula* L.

Both sites were clear-cut over a 6 ha area. Logs were removed using a cable-harvesting system, and in order to minimize the soil disturbance, all slash was removed manually or using a very low ground pressure machine dedicated to the transport in forest (Ironhorse, Lennartsfors). Each site was divided into three blocks delineated after low-resolution soil mapping. Each treatment was randomly distributed on a 50 × 50 m plot in each block. AZ had four treatments: control (C), trafficked (T), de-compacted by disking (D) and local de-compaction at planting points (P) (Fig. 1). Because its soil was more acidic, two amended treatments were added at CA: control amended (A) and trafficked amended (TA). Liming was applied at CA in September 2008: 2 t ha^{-1} of dolomite enriched in magnesian quicklime (36% CaO, 24% MgO) and 600 kg ha^{-1} of potassium sulphate (50% K2O, 17% S), corresponding to 500 kg ha^{-1} of Ca, 290 kg ha^{-1} of Mg, 250 kg ha^{-1} of K and 100 kg ha^{-1} of S.

Experimental compaction was performed using the same full-loaded forwarder (VALMET 840) driven over the soil for an equivalent of two passes, in May 2007 at AZ and March 2008 at CA. Its 60 cm diameter tyres were inflated to 360 kPa, and its total weight was 23 and 17 t at AZ and CA, respectively, because the CA site was wetter than the AZ site when the forwarder was driven. At the time of driving, the mean volumetric water content of the soil surface (0-10 cm layer) was 0.41 m^3 m^{-3} (range = 0.28-0.53 m^3 m^{-3}) at AZ and 0.47 m^3 m^{-3} (range = 0.25-0.59 m^3 m^{-3}) at CA. Heavy traffic caused ruts that averaged 5 cm deep at both sites, but due to the spatial heterogeneity in soil water content, certain points had deeper ruts than others (which were always avoided during sampling) (Goutal et al., 2013).

In autumn 2007 (AZ) and autumn 2008 (CA), the entire site surface area was planted with sessile oak (Quercus petraea L.) at a density of 1600 seedlings ha^{-1}. Rotation length for sessile oak plantations in these Estate Forests ranges between 180 and 200 years.

2.2 Soil properties

2.2.1 Initial characterisation

Before setting up the experimental designs, soil pits were opened and forest floors and soils were described. Forest floor was classified as a mesomull (Baize and Girard, 1998) at AZ and was more acidic at CA, ranging from dysmull to eumoder types (Baize and Girard, 1998). Soils at both sites are classified as Luvisol (Ruptic) according to the IUSS (2014) and are polygenic, *i.e.* developed from two geologic materials: a continental silt loam layer ca. 50 cm thick that lies on clayey material. At AZ, the fluvial loamy Quaternary layer lies on weathered marls of the Keuper; at CA, the loamy Quaternary material lies on weathered gaize of the Cenomanian. This strong textural discontinuity caused a limited localised and temporary water logging, but did not lead to result in hydromorphic soils. Hydromorphic features were limited at both sites to the very lowest section of the silty layer, at the contact interface with the clay- rich layer. Consequently, these soils are considered highly sensitive to compaction.

The soil sampling, preparation and analysis are described in detail in previous studies (Goutal et al, 2013 and Bedel et al, 2018) and only a summarized description is given here. Selected soil parameters were measured in samples taken from the pits. Bulk density was measured using 250 cm^3 steel cylinders in two replicates collected every 10 cm from all pits. Soil samples were also collected at consistent depths (0-10, 10-20, 20-30, 30-45, 45-60, 60-75, 75-90 and 90-110 cm). After air drying, samples were sieved to separate coarse material from fine earth (< 2 mm) and the following soil determinations were performed: soil moisture (105°C), particle size distribution, pH_{water} and pH_{KCl} (1M), cation exchange capacity (CEC) and exchangeable cations (colbaltihexamine chloride method), total soil organic C (Corg) and N (Norg), total Al-Fe-Mg-Ca-K-Na-Mn (HF digestion), Fe-oxides (Mehra and Jackson, 1960) and soil clay mineralogy (only for the central pit at each site). Initial soil properties are presented in table 1.

2.2.2 Initial similarities and differences between sites

Based on previous studies (Bedel et al., 2016, Bedel et al., 2018, Bonnaud et al., 2019), a summarized description of the similarities and differences between the soils of the two sites is given here.

Even though the sites have the same soil type, they have significant differences in physical, chemical and mineralogical properties (Bedel et al., 2016, Bedel et al., 2018). The clay content in the upper and lower layers is lower at CA (13-15% and 33-34%, respectively) than in those at AZ (22-24% and 45-60%, respectively) (Table 1). At AZ, the clay mineralogy is nearly pure illite in the deep soil layer and a complex admixture of illite, kaolinite, chlorite and vermiculite associated with interstratified and intergrade minerals in the upper soil layers. At CA, the clays in the deep clayey layer consist of an admixture of kaolinite, illite and a swelling clay from the Fe-beidellite group. The same spectrum is found in the upper soil layers, with the swelling Fe-beidellite clay present in both pure and interstratified phases, albeit in lower amounts (Bedel et al., 2018).

Moreover, even if the soil geochemical context indicated acidic soils at both sites (Bedel et al., 2016; Bonnaud et al., 2019), differences in chemical properties should be noticed. At CA, pH_{water} was 4.4 in the upper soil layer (0-10 cm), 4.5-4.6 from 10-50 cm and ca. 5.0 in the deep clayey horizons (below 60 cm). At AZ, the upper organic horizon had a significantly higher pH of ca. 4.8, which decreased to 4.6 in the loamy horizons, then increased to 5.0 in the deep clayey horizons (Table 1). Corg content was the same in the 0-10 cm layer at the two sites, but in the horizons below it, that at CA was ca. half that at AZ. Norg was lower at CA than at AZ. The C:N ratio was higher at CA than at AZ. CEC ranged from 3.5-4.0 at the surface to 16-18 cmol+ kg^{-1} at depth at CA and from 4.0-4.5 at the surface to 12-15 cmol+ kg^{-1} at depth at AZ. The "base" cation saturation rate was nearly twice as high at AZ as at CA for the same depths in upper layers (63% *vs.* 29%, respectively, at 0-10 cm; 24-30% *vs.* 12-15%, respectively, at 10-45 cm), but more similar at both sites in lower layers (50-70% at AZ *vs.* 45-60% at CA).

2.2.3 Monitoring

Changes and recovery in soil physical properties were presented in previous studies (Goutal et al., 2013, Pousse et al, 2021) and only relevant information in the context of our study are summarized hereafter: i) compaction strongly influenced soil bulk density (Goutal et al., 2013), macroporosity (Bonnaud et al., 2019) and physical resistance (Pousse et al., 2021) at both sites; ii) recovery was slow and limited to the upper soil layers (Goutal et al., 2013; Pousse et al, 2021); iii) the liming increased the recovery of physical resistance to undisturbed levels over the study period (Pousse et al., 2021).

Changes in soil chemical properties were also monitored: two soil profiles per treatment (C and T at AZ and CA, and A and TA at CA) were sampled and analysed in 2012 at AZ and in 2014 at CA, using the depths and methods previously described (see section 2.2.1).

No quantification of the forest floor and its evolution over time has been carried out at AZ and CA.

2.3 Meso- and pedo-climates

Rainfall, air temperature and relative humidity were measured every four hours at a weather station located at each site. Soil temperature and soil water content were recorded every four hours using specific data loggers (DL2e Data Logger, Delta-T devices Ltd., UK, for soil temperature, and Trase B.E. by Soil Moisture, Sols Mesures, France, for soil water content). Time-domain reflectometry (TDR) probes and temperature sensors (five replicates per depth × treatment) were inserted at three depths (15, 30 and 50 cm in undisturbed soil and 10, 25 and 45 cm in compacted soil to compensate for changes in bulk density). Only one block was equipped at each site. The TDR measurements were converted into volumetric water content using calibration curves of Heathman *et al.* (2003) and derived from laboratory calibration of TDR data, using undisturbed soil cores from each site.

2.4 Soil solutions

From 2008-2016, weakly bound soil solutions were collected each month in the C, T, A and TA treatments at three depths (4 replicates per depth): 15, 30 and 50 cm in undisturbed soil and 10, 25 and 45 cm in compacted soil to compensate for changes in bulk density. To simplify presentation of the text, we consider thereafter the same depth for all treatments. Only one block was equipped at each site for economic and logistical reasons. Solutions were collected with ceramic tension-cup lysimeters (Oikos) at a constant pressure of 0.7 bar, mainly when the soil was not saturated during the vegetation growth period (*i.e.* 229 days per year at AZ and 287 days per year at CA; Bonnaud et al, 2019). Soil solutions were stored in the dark at 4°C until analysis.

The chemistry of individual solution samples was measured as soon as possible, from solutions filtered through 0.45 μm Metriciel® acetate membrane filters. Samples were analysed for pH (Mettler DL 7O ES Titrator), and anions (Cl^-, NO_3^-, $H_2PO_4^-$, NO_2^-, SO_4^{2-}, F^-) were measured by ion chromatography (Dionex ICS2100). NH_4^+ was determined by molecular absorption spectrometry (Skalar San++ System), and total Si, Al, Fe, Mg, Ca, K, Na, P and S were measured by ICP-AES (Agilent Technologies 700 series). Lastly, a Shimadzu apparatus was used to measure total dissolved Corg and Norg.

A general comparison of treatments is helpful, but some processes are difficult to identify because they are not constant over the time of observation (*e.g.* flush response to clear-cutting or compaction). Three periods were defined based on the analysis of soil solution chemistry: an initial period of two years, which corresponded to rapid changes (flushes), a final period of two years, when solution chemistry seemed to have stabilised, and an intermediate period of three years between the two.

Changes in particle size distribution at ca. 50 cm depth at both sites (Table 1) explained the occurrence of a perched water table (Bonnaud et al, 2019) and an accurate hydrological budget could not be calculated. Thus, nutrient fluxes transferred through the soils could not be quantified. Furthermore, atmospheric deposition were not monitored at the study sites but according to Coddeville et al (2016), annual deposition are expected to be less than 10 kg ha^{-1} yr^{-1} for N and 5 kg ha^{-1} yr^{-1} for S at the two sites, with a low variability from year to year.

2.5 Statistics

All statistical calculations of chemistry data on the soil solid/liquid phase were performed using R software (R Core Team, 2020). Analysis of variance (ANOVA) was applied to a linear mixed-effects model to test the significance of one or more fixed effects on (Y) variables of two chemistry datasets. The model fitted using the maximum likelihood method is as follows:

$$Y = \mu + \sum_{j} \boldsymbol{Fef}^{(j)} + Ref + \varepsilon \tag{1}$$

with μ the grand mean, $\boldsymbol{Fef}^{(j)}$ the set of fixed effects composed of individual factors ($j = 1$) or the interaction of j (> 1) factors, Ref the random effect normally distributed with mean 0 and variance $\sigma_R^2.Id$ and ε the residual term also normally distributed with mean 0 and variance $\sigma^2.Id$. Ref is used in model (1) to consider the spatial variability in the experimental design.

For the solid phase, one ANOVA was performed per depth class (5 levels: every 10 cm from 0-40 cm) at CA to test the significance of the unique factor $\boldsymbol{Fef}^{(1)} = Treatment$ (4 levels: C, T, A and TA) on a total of 12 Y variables. Ref is designated by a factor that combines the information of $Block$ and $Treatment$ factors (12 levels: 3 blocks × 4 treatments). When $\boldsymbol{Fef}^{(1)}$ was declared significant ($p \leq 0.05$), a Tukey's multiple comparison of means (Hothorn *et al.* 2008, Bretz *et al.* 2011) was applied to model (1) to identify for which pair of treatments the Y variable distribution was significantly different.

For the liquid phase, one ANOVA was performed for the combination of depth class (3 levels: 10-15, 25-30 and 45-50 cm), year class (3 levels: 2009-2010, 2011-2013 and 2015-2016) and pair of treatments (C vs. T, A vs. C, A vs. TA and T vs. TA) at each site to test the significance of a set of fixed effects $\sum_{j=1,2} \boldsymbol{Fef}^{(j)}$ (described below) on a total of 19 Y variables

$$\begin{cases} \boldsymbol{Fef}^{(1)} = Treatment + Year + Season \\ \boldsymbol{Fef}^{(2)} = Treatment{:}Year + Treatment{:}Season \end{cases} \quad (2)$$

The period of the $Year$ factor was adjusted for the four seasons (winter to fall) and $Ref = Captor$, which corresponded to replicate measurements. As measurements in 2009 for A and TA treatments in CA were reduced to a single month and did not represent all depth classes, the first year class correspond only to 2010 in ANOVA models, in which one of the two treatments was included, and the fixed effects $Year$ and $Treatment{:}Year$ were removed from the set in model (2).

In addition, principal component analysis (PCA) was applied to the correlation matrix composed of the 19 Y variables per depth class and pair of treatments to identify groups of individuals/variables that contributed the most to the total variance, and to observe the position of the centroid and 95% confidence ellipsoid of categorical variables on the projected plane of PCA dimensions 1 to 3.

3 Results

3.1 Impact of soil compaction on chemical soil solid-phase properties

Compaction did not influence soil chemistry significantly, regardless of the depth or treatment considered (C *vs.* T at AZ; C vs. T and A *vs.* TA at CA) (data not shown for AZ; data for CA in 2014 shown in Table 2). Liming at CA had a positive impact in 2014, but only in the upper 20 cm of soil: pH_{KCl}; exchangeable Ca, Mg, H and Al; “base cation” saturation and effective CEC increased significantly in the 0-10 cm layer in A compared to C, while pH_{water} and exchangeable Mg and K increased significantly in the 0-20 cm layer. Comparison of T and TA indicates that the main differences were due to liming (Table 2).

The accuracy of estimates of the residual portion of the liming products in 2014 was limited by the high spatial variability and the physical changes in the soil (*i.e.* de-compaction, albeit limited). When considering only the layers that experienced significant changes, ca. 90% of the Ca applied, 80% of the Mg applied and 30% of the K applied were retained in the CEC. The budget of each must also consider the portion fixed by vegetation, which usually returned to the soil rapidly. At CA, the amounts fixed were ca. 30 kg ha^{-1} each for Ca and K and ca. 10 kg ha^{-1} for Mg (database of the experimental site).

3.2 Impact of soil compaction on soil solution chemistry at Azerailles

3.2.1 Behaviour of the control

At AZ, in treatment C, the ionic strength of the soil solution (IS) increased as soil depth increased, and the relative contribution of anions to IS was generally as follows: SO_4^{2-} (35-70%) > Cl^- (20-45%) > NO_3^- (2-30%) (Table 3). The anion composition in C was dominated mainly by SO_4^{2-} (1.5-6.5 mg.L^{-1}), followed by Cl^- (1-3.5 mg.L^{-1}) and NO_3^- (0.2-2.0 mg.L^{-1}), regardless of the layer or the time scale (Table 4). For the cations, their relative contribution to IS in C were as follows: $Ca^{2+} >> Mg^{2+} >> K^+ = Al^{3+} = NH_4^+$ for all layers and dates. Ca remained constant with depth, Mg increased with depth, while Al and K decreased at 50 cm regardless of the period (Table 4). For each layer observed, changes over time were limited in C (Table 4).

3.2.2 Effect of soil compaction

Compaction increased in IS regardless of the soil layer or period, from 145 µeq.L^{-1} in C to 245 µeq.L^{-1} in treatment T (Table 3, general mean). The relative contribution of anions to IS also changed after compaction, especially during the initial period: while SO_4^{2-} generally remained dominant, followed by Cl^-, in T, NO_3^- became dominant during the initial period (at 30 and 50 cm depths) and co-dominant during the final period (at 15 and 30 cm depths) (Table 4) (Figures 2, 3 and 4 for NO_3^-, SO_4^{2-} and DOC, respectively). The increase in IS in T did not change the relative contribution of cations during the initial period: IS doubled, but only K changed significantly (+10% at 15 cm depth) (Mn increased by 36% at 30 cm depth, but not significantly so). IS increased moderately (10-30%) during the intermediate period and even more (20-80%) during the final period, with the largest increase for K at 15 cm depth (10% and 14% for the intermediate and final periods, respectively). Changes over time were greater in T than in C, especially in the medium and deep layers, where flushes of anions and cations were observed (Table 3, Figures 2 to 4, Supplementary material 1 and 2) in T, while they were not clearly evident in the upper soil layer, probably due to the delay between the treatment (2007) and when monitoring of soil solutions began (2009).

Compaction influenced the soil solution composition strongly, especially in the upper soil layers (Table 4). In the upper soil layer during the initial period, the concentrations of 11 of the 19 elements studied changed significantly, while fewer elements changed in the 30 and 50 cm depths; however, nitrate concentrations were high (> 10 mg.L^{-1}) in T at these depths. During the intermediate period, soil solution concentrations continued to be influenced significantly, especially at 15 and 30 cm depths, except for nitrate, which decreased strongly and thus differed little between C and T. During the final period, soil solution chemistry was always influenced strongly in the upper soil layer (significant changes for 10 elements, usually the same ones as in the initial period). Impact decreased with depth, but seven elements differed significantly in T compared to C at 30 cm depth. At 50 cm, Cl and K, followed by Si and Mg (10% confidence), remained significantly influenced. Besides the compaction effect, year and season effects were strongly significant regardless of the soil layer or period.

3.3 Impact of soil compaction on soil solution chemistry at Clermont-en-Argonne

3.3.1 Behaviour of the control

At CA, in C, the IS did not vary greatly with soil depth, except during the initial period at 15 cm (Table 3). However, IS changed over periods, being higher during the initial and final periods (usually > 400 µeq.L^{-1}) than during the intermediate period (ca. 200 µeq.L^{-1}). The relative contribution of anions to IS in C was generally as follows: NO_3^- (40-70%) > SO_4^{2-} (25-50%) > Cl^- (8-20%). The concentration of NO_3^- was much higher than that of SO_4^{2-} in C, especially in the intermediate period (13-17 vs. 3-4 mg.L^{-1}, respectively), but less so during the final period, especially in the deep layer (4-5 vs. 2-45 mg.L^{-1}, respectively).

3.3.2 Effect of soil compaction

Compaction significantly decreased the IS regardless of the soil layer or period, from 344 µeq.L^{-1} in C to 183 µeq.L^{-1} in T (Table 3, general mean). For all depths, the decrease was 40-65% during the initial and intermediate periods, but only ca. 10-25% during the final period. The relative contribution of anions to IS also changed after compaction: SO_4^{2-} (30-70%) > Cl^- (10-30%) > NO_3^- (5-40%) (Table 3). The concentrations of anions in the soil solution changed drastically: NO_3^- decreased strongly (*i.e.* -81%, -93% and -61% as the mean of all layers, during the initial, intermediate and final periods, respectively), while SO_4^{2-} tended to increase regardless of the period or soil layer (i.e. +14%, +36% and +9% as the mean of all layers during the initial, intermediate and final periods, respectively). Cl^- decreased in the initial period (-33%) but increased during the intermediate (+35%) and final (+101%) periods (Table 5 and Figures 5, 6 and 7 for NO_3^-, SO_4^{2-} and DOC, respectively) Compaction had much less influence on cations, whose mean relative contribution to the IS (Ca >> Mg ≥ Al > K) did not change (data not shown). Nevertheless, for all depths and periods, mean absolute concentrations of Ca, Mg and K decreased by ca. 30%, 47% and 74%, respectively (Table 5 and Supplementary material 3, 4, 5, 6 for Ca, Mg, K and Al, respectively).

Compaction influenced mainly the solutions in the upper soil layers during the initial and intermediate periods, when the concentrations of 7-12 elements changed (Table 4). Only three elements differed significantly between C and T during the final period: Cl, Na (decreased in all layers) and Si (increased at 15 cm but decreased at 25 and 45 cm). The year and season effects remained significant for most elements (12-15 elements of the 19 studied).

3.3.3 Effect of liming without soil compaction

Liming increased the IS of soil solutions collected from all soil depths by 35-80% compared to those in C during the initial period (from a mean of 380 to ca. 600 µeq.L^{-1}), but it decreased IS for all depths during the intermediate and final periods (from a mean of 330 to 145 µeq.L^{-1}), except in the deepest layer, where no or few changes were observed. Liming also changed the relative percentages of NO_3^- and SO_4^{2-} drastically compared those in C: NO_3^- decreased strongly to contribute 1-16% to the IS for all layers and periods, while SO_4^{2-} became dominant (contribution of ca. 80% to the IS for all layers and periods); Cl^- changed much less and did so mainly during the initial period (Table 3). Nitrate concentrations decreased from extreme values of 4-17 mg.L^{-1} in C to 0.2-3.0 mg.L^{-1} in A throughout the entire observation period. Conversely, SO_4^{2-} concentrations increased from 4 mg.L^{-1} in C to 20-30 mg.L^{-1} in A during the initial period. Differences were smaller during the intermediate and final periods, except in the deepest layer.

Liming also changed the contribution of cations to the IS. Their relative contribution to IS in A was K > Ca> Al> Mg during the initial period at 15 and 30 cm and then a co-dominance of Ca, Mg and K at 15 and 30 cm during the intermediate and final periods. Ca, followed by Mg, strongly dominated at 50 cm depth in A regardless of the period (Table 3). The largest changes related to liming were for K and Ca. K concentrations at 15 and 30 cm depths ranged from 0.7-1.3 mg.L^{-1} in C and 1.1-8.0 mg.L^{-1} in A, with a continuous decrease in concentration over time. Ca concentrations changed the most at 50 cm depth, increasing from 1.8-3.4 mg.L^{-1} in C to 2.9-5.2 mg.L^{-1} in A (Table 6).

3.3.4 Effects of liming and soil compaction

Compared to T, TA increased IS in all layers during the initial and intermediate periods (from a mean of 190 to ca. 300 µeq.L^{-1}) and in the deep layer during the final period (+54%), while it decreased IS in the upper layer during the final period (-42%). The mean relative contribution of anions to the IS changed little between these treatments and was as follows: SO_4^{2-} >> Cl^- > NO_3^- in all soil layers during all periods, except during the initial (at 15 and 25 cm) and intermediate periods, when NO_3^- tended to be higher than Cl^-. Compared to T, TA changed the mean cation distribution, which was as follows: Ca ≥ Mg ≥ Al = K, except at 50 cm, where Mg >> Al (Table 3). Mg increased in the upper and medium layers in TA during the intermediate and final periods, while Ca and K increased for all dates in the deep and upper layers, respectively (Table 7). TA and T differed mainly due to the elements contained in the product applied (*i.e.* SO_4^{2-}, Mg, Ca and K), and those resulting from the liming effect (*i.e.* NO_3^-, Al, TN). Eight years after liming, the interaction of liming with compaction remained significant in all layers, especially at 50 cm depth for F^-, SO_4^{2-}, Si, Mn, Al, Ca, Na, DOC, Norg and H^+.

4 Discussion

Due to the experimental design, changes observed in the soil solution chemistry may have resulted from multiple processes:

- clear-cutting, for all treatments at both sites; however, part of its initial effect was not observed, as sampling of soil solutions began two years after cutting at AZ and one year after cutting at CA
- soil compaction, observed in T at both sites and in TA at CA
- liming, observed in A and TA at CA
- changes in vegetation over time, for all treatments at both sites for young plantations, but differentially when compaction induced strong changes in tree growth and understorey vegetation
- restoration of soil porosity, observed in T at both sites and in TA at CA
- inter-annual climate variations, for all treatments at both sites

It was thus difficult to distinguish the influence of each process clearly, especially during the initial period but the comparison between treatments allow us discussing the dominant processes that are likely to cause the observed changes.

4.1 Drastic changes in the first years following disturbances

4.1.1 Impact of clear-cutting and planting

At AZ, the impact of clear-cutting in C appeared to be relatively weak and limited to certain elements, due in part to the delay of ca. 2.5 years between clear-cutting and the first observations of soil solutions. Nitrate contents were extremely low, and no signal, even delayed, was observed in the deeper soil layers. These observations may have be due to the relatively low soil damage during the stand tree harvesting (Nykvist et al., 1994; Ranger et al. 2007), to the entire tree-harvesting process, including litter raking on reactive soils (McColl, 1978), or to the system's ability to immobilise all nitrate production (Stark and Hart, 1997). Ten years after clear-cutting, the impact of harvest, planting and new stand development seems to stabilise, again without any signal in NO_3^- concentration in soil solutions. Soil reactivity and development of dense understorey vegetation could facilitate nitrate immobilisation in the ecosystem (Katzensteiner, 2003).

At CA, where the delay was only ca. two years between clear-cutting and the first observation of soil solutions, clear-cutting in C had a stronger effect than at AZ, which influenced DOC, as well as major anions and cations (except in the upper soil layer). Nitrate increased after clear-cutting, even when cable harvesting of logs limited the disturbance to the forest floor. The sylvicultural practices related to harvest and planting were very similar between sites, which suggests that the less fertile soil cannot immobilise NO_3^-, as reported in many other studies (Brown et al., 1973; Hart et al., 1981; Dahlgren and Driscoll, 1994; Jerabkova et al, 2011). A large delayed increase in NO_3^- in soil solutions was also observed in all soil layers in C five to eight years after the clear-cut, suggesting that the entire biological system (i.e. soil microbes, understorey vegetation and young stand) cannot immobilise this additional flux, which could be related to an as-yet-unidentified process of stand development.

4.1.2 Impact of soil compaction

Soil compaction increased concentrations of nearly all elements greatly at the more fertile site (AZ), but the high spatial variability limits the significance of this result. This initial impact dominated in the upper soil layer, and DOC and NO_3^- were the anions that drove the changes in cations. Soil compaction is known to influence the rate of organic matter decomposition and mineralisation in the soil (Kalbitz et al., 2004), and the ability of microorganisms to immobilise NO_3^- seemed to be exceeded at AZ after compaction. At the less fertile site (CA), compaction resulted in opposite behaviour, which was a quasi-general decrease in the concentration of nearly all elements, especially NO_3^-. Compaction decreased soil porosity (macroporosity decreased by 70% at AZ and 56% at CA) and increased waterlogging at both sites (Bonnaud et al., 2019). These changes may have reduced the nitrification rate, decreased microbial immobilisation and increased the de-nitrification rate (Philippot et al., 2007). The effect of compaction on these processes and on nitrate concentrations in soil solutions were thus different between sites.

Our results are in accordance with the Norg mineralisation and nitrification rates measured at the sites using the method of Raison et al. (1987) (Supplementary material 7). They showed that (i) nitrifying microbes are present and functional at both sites, (ii) the mineralisation rate was higher at AZ than at CA, but the nitrification rate was higher at CA; (iii) the mineralisation rate increased after clear-cutting at both sites, but far more at CA; and (iv) compaction increased the mineralisation rate slightly at AZ but decreased it at CA compared to that in C; the nitrification rate was ca. 60% in both treatments.

4.2 Contrasting restoration between sites after compaction

For the more fertile soil at AZ, clear-cutting and the planting of a new stand seems to have had little impact nine years after planting (i.e. 10 years after cutting) in C, in which the concentrations of most elements in the soil solutions decreased and were quite stable. In T, however, concentrations did not stabilise. This is not completely surprising, as compaction increased young oak mortality (plants were replenished in 2008 and 2009), and the herbaceous understorey vegetation (rushes and *Glyceria* spp.) competed strongly, which delayed canopy closure of the stand (database of the experimental site). Consequently, the chemistry of many elements in soil solutions in T continued to differ significantly from those in C nine years after planting, with higher concentrations in the upper layers (0-30 cm depth) for DOC, mineral-N, Fe, Mn, Ca, Al, K, Na and H. The difference was smaller at 50 cm depth, where only four elements still differed (Table 4). These observations suggest that geochemical functioning was not restored well at AZ nine years after compaction.

For the less fertile soil at CA, clear-cutting and the planting of the new stand also seemed to have little impact eight years after planting (i.e. 10 years after cutting) for most elements in C. The chemistry of a few elements in soil solutions in T continued to differ significantly from those in C eight years after compaction, usually in the upper layers (0-30 cm depth): DOC, Na, Cl and Si (Table 5). Young oak trees had low initial mortality at CA, and compaction did not induce drastic changes in the understorey vegetation, with no development of invasive species (*i.e.* bramble and woody-plant competition was high but similar among treatments). These observations suggest the idea of relatively advanced restoration of geochemical functioning at CA eight years after compaction.

PCA based on soil solution chemistry (Supplementary material 8 and 9, for AZ and CA respectively) illustrated satisfactorily the restoration state at the two sites eight years after compaction according to the centroids of individual observations in the C and T treatments. These treatments converged for the less fertile soil at CA but not for the more fertile soil at AZ (Supplementary material 8 and 9). This unexpected result was previously observed at the same sites using another indicator: the chemistry of the perched water table (Bonnaud et al., 2019). This confirms the idea that the porosity disturbed in the poorly structured soil at CA recovers relatively quickly, mainly via physical processes (*e.g.* desiccation-wetting cycles, freeze-thaw cycles, root penetration), as no anecic earthworms are present (Bottinelli et al., 2014). At AZ, the same degree of compaction resulted in a relatively larger and longer-lasting disturbance of the soil that drastically changed the biological system, which remained disturbed 10 years later. Four years after compaction at AZ, Bottinelli et al. (2014) found that the habitat quality was not satisfactory for re-colonisation by anecic earthworms. This situation continued six years after compaction, when colonisation by anecic earthworms was low and limited to the topsoil at AZ (Capowiez et al., 2015).

4.3 Impact of liming at CA

Liming changed the soil solutions drastically via (i) direct input of elements and (ii) the result of changes in major C, N and S cycles, which influence cations the most. Some of the powdery dolomite associated with Mg-quicklime and K-sulphate probably dissolved during the winter after application on the soil surface. An approximate budget calculated six years after liming indicates that a large amount of the Ca, Mg and K remained in the soil as part of the exchangeable pool, which indicates a small initial flush of Ca, Mg and K leached in solutions. This is typical for short-term observations after liming and is consistent with previous studies (Löfgren et al., 2009, Court et al., 2018).

In treatment A compared to C, a small but significant amount of Ca was rapidly transferred into deeper soil layers, which resulted in a rapid and long-lasting (eight years, +60%) increase in the Ca concentration in solutions at these depths. In the upper soil layers, Ca concentrations decreased much more rapidly in A than in C, which suggests high Ca efficiency of the soil-plant system and/or high retention due to a strong affinity for organic matter (Curtin et al., 1998). Even if Magnesium does not have such affinity for organic matter, it behaved similar to Ca, except that its concentrations increased in the upper soil layers in the last three years of observation: it may be due to active uptake and recycling of Mg by the vegetation (Edmeades and Judd, 1980) combined with its moderate affinity for both organic matter and the mineral phase. These processes may explain in part why Mg concentration did not increase in the deeper soil. Ca and Mg were vertically transferred more rapidly in the soil than K and it may be due to the latter's strong affinity for the soil solid phase. Strong K-adsorption on clay exchangeable sites (Sawhney, 1970) could have limited its transfer through the soil profile at 30/40 cm, without significant enrichment of the deep soil layer.

In this environment, liming immediately accelerated organic matter mineralisation, which increased DOC and drastically decreased NO_3^- concentrations in the soil solutions (from 7-17 mg $NO_3^-.L^{-1}$ in C to 0.2-2.0 mg $NO_3^-.L^{-1}$ in A). The likely rapid dissolution of K-sulphate released a large flux of SO_4^{2-} that became the main driver of cations transferred in the soil profile, which replaced NO_3^-. Many studies showed that nitrification increased after liming under natural or controlled conditions, regardless of the environment (Nyborg and Hoyt, 1978; Arnold et al., 1994; Zhao et al., 2017), except in raw humus with high C:N ratios, due to low soil pH (acidity) and harsh climate in Nordic countries (Nömmik, 1979; Derome, 1990). At CA, liming increased the soil pH by ca. 0.5 in the upper soil layer and the pH is known to regulate the nitrification rate: Nugroho (2006) reported that a low nitrification rate in acidic soils, despite the presence of nitrifiers, was due to several pH-related factors. At CA, nitrate concentrations decreased strongly in soil solutions after liming. In reference to Nugroho et al. (2006), we hypothesise that liming improved overall microbial activity, which was then able to immobilise most nitrate produced and thus decrease leaching and soil acidification.

Soil solutions in TA were relatively similar to those in T but differed from those in C for elements released from liming products or influenced indirectly by liming (Table 8). These effects are highly relevant for tree growth, as indicated by the current height increment of young oaks, which have the same height in treatments TA and C (Ranger et al., 2021). We thus hypothesise that liming limits the negative impact of soil compaction on tree growth. Liming may improve tree nutrition directly (Court et al, 2018), but Ca and Mg (and perhaps K) could also influence root system development greatly, especially by improving soil structure (Flores Fernández et al., 2019) during certain strategic periods.

4.4 Do the two sites have different biogeochemical functioning?

As previously described, the C cycle was modified at both sites after compaction, as indicated by the increase in DOC concentrations, especially in the upper soil layer. The S cycle was also modified, which increased sulphate concentrations, which remain in equilibrium in this moderately reductive environment (White, 1998). However, nitrogen cycle is the most affected by compaction and it seems to react in an opposite manner at the two sites, especially nitrate concentrations in soil solutions, which increased after compaction at AZ but decreased at CA. Previous studies (Bedel et al, 2018; Bonnaud et al, 2019) showed that the sites have many similarities (acidic and desaturated soils, similar initial forests and harvesting techniques, no nitrification-stimulating tree species as defined by Zeller et al. , 2007), but also significant differences (surface soil pH, clay content and mineralogy, aggregate stability in the upper soil layers), that influence and determine soil biogeochemical functioning and soil solution chemistry.

At AZ, the relatively fertile surface soil, with moderately stable aggregation and pH > 4.5, seems able to immobilise nitrate, even that produced after clear-cutting, as no NO_3^- signal appeared in the soil solution (nevertheless, a rapid flush cannot be excluded). Compaction drastically and immediately disturbed the soil, in which hydromorphic traits appeared after a few months (Bonnaud et al., 2019). Understorey vegetation changed from brambles in C to rushes in T (Goutal et al., 2013). The soil seems to have lost its ability to immobilise nitrate after compaction, but the activity of nitrifying microbes was not suppressed. Due to the new pedoclimatic conditions, denitrification may have increased (Philippot et al., 2007), but our results suggest that it was not sufficient to eliminate all of the NO_3^- produced. Interestingly, the variability in NO_3^- concentration among individual lysimeters was large and much higher than that of all other anions or cations. This could indicate that specific niches exist for nitrification, and probably for denitrification, as observed by Parkin (1987) for sites rich in particulate organic matter. Compaction of buried holorganic layers creates patches and ultimately greater soil heterogeneity. Consequently, residual nitrate-H could migrate downward in the soil profile, with known consequences on the cation exchange process (Reuss and Johnson, 1986).

At CA, the large amount of NO_3^- produced after clear-cutting seems to have exceeded the ability of the less fertile soil (pH < 4.5 in the topsoil) and the growing trees and understorey vegetation to immobilise it. Compaction changed the environment drastically, causing hydromorphic traits, the collapse of structures in wet conditions and induration when dry (i.e. hard-setting behaviour (Bedel et al., 2018)), characterized by a rapid increase in soluble Fe^{2+} and Mn^{2+} in the perched water table (Bonnaud et al., 2019). These changes in soil properties significantly decreased NO_3^- in the soil solution, which may be explained by a decrease in nitrifying activity and a possible increase in denitrification during rewetting events or periods.

The liming treatment provides valuable information on the impact of nutrient limitations on organic matter mineralisation and soil solution chemistry. Applied six months after soil compaction, liming immediately changed the soil solution chemistry due to the release of Ca, Mg, K and SO_4^- from liming products, but also indirectly through interactions with the C and N cycles. Unlike clear-cutting, which increased NO_3^- concentration in the soil solution in C, liming resulted in a drastic, immediate and long-lasting decrease in NO_3^- concentration (by a factor of 3.5-26.0, depending on the soil layer and time). Liming increased the soil pH by ca. 0.5 in the upper soil layer and increased NO_3^- immobilisation in the soil and vegetation. It is unlikely that liming stops nitrate production in such an environment (Nyborg and Hoyt, 1978; Formanek and Vranova, 2003; Nugroho et al., 2006). Our results suggest that liming increases microbial biomass and activity, N mineralisation and plant growth factors that sustain a more conservative N cycle.

Considering these facts, it appears that soil pH had a great influence on the observed changes, and the threshold pH of 4.5 seems to be an important parameter for soil biogeochemical functioning in the present conditions, as for Al chemical speciation in solutions (Driscoll et al., 1990). These two ecosystems did not react in an opposite manner, but rather in accordance with their specific N cycle (and C cycle), which seems strongly influenced by soil pH. At CA, soil acidity limits the mineralisation rate, which increased strongly after clear-cutting but could not immobilise all of the nitrate produced. Liming improved this ability. At AZ, microbes and vegetation immobilised the larger amount of nitrate produced. Compaction disturbed the two ecosystems deeply by rapidly increasing hydromorphological processes, modifying both nitrate production and denitrification (Hilton et al., 1994; Philippot et al., 2007), which decreased nitrate in the solution at CA but increased it at AZ (Figure 8).

5 Conclusions

1. Monitoring of soil solutions over 10 years at two experimental sites set up on soils sensitive to physical degradation in eastern France demonstrates the relevance of this indicator. The limited controlled compaction of two Ruptic Luvisols resulted in immediate and drastic changes in their soil biogeochemistry. This supported our first hypothesis that soil solutions can detect and explain the impact of soil compaction on soil functioning.
2. The soil type, often used as an input for assessment, did not adequately explain the dynamics of restoration. The pH threshold of 4.5 in the upper soil layers is highly relevant for characterizing the observed changes. The liming treatment applied to the less fertile soil shifted the pH above this threshold and supports this conclusion. Our results show that soil type, which is used worldwide to characterise the environment, is not relevant to explain the differences in soil solution behaviour observed at the two sites studied. Thus, all available information (e.g. local climate, precise geology, vegetation, land-use history, available soil analysis) must be used to identify soil sub-types with more homogeneous biogeochemical functioning and behaviour.
3. Positive recovery dynamics were observed at both sites, but more especially in the less fertile soil at CA, according to the soil solution indicator. Thus, this indicator does not support our hypothesis that chemical fertility has a positive influence on recovery.

Bonnaud et al. (2019) studied the perched water table indicator at the same sites and came to the same conclusion.

4. Soil solution chemistry is a relevant indicator, but for it to become operational for management, a large network of sites must be observed. This is necessary to build a reference database that can be used to predict the behaviour of unknown sites accurately.
5. The medium term (ca. 10 years) is a relevant time step, but for long-living forest ecosystems, the long term requires particular study, which is much more difficult. Limited disturbance had a significant impact on the sensitive soils, and determining long-term recovery requires using multiple indicators. We observed that soil compaction modified the root structure of young oak trees and understorey vegetation (unpublished data). Soil colonisation by roots was limited more to upper soil layers after compaction. It is difficult to estimate what the consequences will be as the trees age, especially when considering additional physical constraints and climatic stresses.

6 Acknowledgments

Financial support since 2006 was provided by (i) the DST project of the French Ministry of Ecology and Sustainable Development (MEDD – Gessol); (ii) the French Ministry of Agriculture and Fisheries (MAP); (iii) the French National Research Agency (ANR) via the DST project (ANR- 05-PADD-013), LABEX Arbre, the French Investissements d'Avenir Program (ANR-11-LABX-0002-01) and the infrastructure ANAEE France (ANR-11-INBS-0001); (iv) the European Union through FEDER (12000266); (v) the French National Office of Forestry (ONF); (vi) the Lorraine Region and (vii) the GIP Ecofor (Allenvi-Soere). We thank the ONF agents in charge of the Azerailles and Clermont-en-Argonne estate forests for their continuous cooperation during the monitoring. We thank Michelle and Michael Corson for revising the English.

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Figure list

Figure 1. Aerial view of the Azerailles (54) experimental site in 2012 (control (C), compacted (T), de-compacted (D), and 'potets' (P) (i.e. locally de-compacted at the planting point) treatments). Note the changes in understory vegetation with rushes (light green), which invaded all compacted zones, and brambles (dark green), which dominated in the controls (photograph: C. Bailly, INRAE).

Figure 2. Nitrate (N-NO_3) concentrations in the soil solutions of the control (C) and compacted (T) treatment at Azerailles. A, B and C indicate the initial, intermediate and final period, respectively.

Figure 3. Sulphate concentrations in the soil solutions of the control (C) and compacted (T) treatment at Azerailles. A, B and C indicate the initial, intermediate and final period, respectively.

Figure 4. Dissolved organic carbon (TC) concentrations in the soil solutions of the control (C) and compacted (T) treatment at Azerailles. A, B and C indicate the initial, intermediate and final period, respectively.

Figure 5. Nitrate (N-NO_3) concentrations in the soil solutions of the control (C), compacted (T), limed (A) and compacted and limed (TA) treatments at Clermont-en-Argonne. A, B and C indicate the initial, intermediate and final period, respectively.

Figure 6. Sulphate (SO_4) concentrations in the soil solutions of the control (C), compacted (T), limed (A) and compacted and limed (TA) treatments at Clermont-en-Argonne. A, B and C indicate the initial, intermediate and final period, respectively.

Figure 7. Dissolved organic carbon (TC) concentrations in the soil solutions of the control (C), compacted (T), limed (A) and compacted and limed (TA) treatments at Clermont-en-Argonne. A, B and C indicate the initial, intermediate and final period, respectively.

Figure 8. Summary of the pH, soil fertility and nitrate behaviour at the Azerailles and Clermont-en-Argonne experimental sites. (-) very low; (+) low; (++) medium; (+++) high.

Table list

Table 1. Initial mean soil characteristics at the two experimental sites in 2007. CEC: cationic exchange capacity; Fe $_{DCB}$ and Al$_{DCB}$: Fe and Al oxides (Mehra and Jackson, 1960).

Table 2. Mean soil characteristics at the Clermont-en-Argonne site in 2014; statistics concern the post-hoc test (see Materials and Methods for definitions) of the treatment effect. ** p>0.01; * 0.01<p<0.05; ~ 0.05<p<0.10; NS non significant. Exch: exchangeable (colbaltihexamine chloride extraction); T(CEC): effective cationic exchange capacity; S:T: base saturation; S-SO$_4$: adsorbed sulphate (NaH$_2$PO$_4$ extraction).

Table 3. **a)** Mean soil solutions concentrations for major anions and cations, related to the site, the treatment and the period. Ionic strength (IS) of soil solutions at both sites computed as the sum of major anions is also presented. **b)** Comparison between treatments for the ionic strength (IS), by site and soil layer; the treatment X is indicated in subscript letter IS$_X$. C: control; T: compacted; A: limed; TA: compacted and limed.

Table 4. Mean soil solution concentrations based on time and soil depth in the control (C) and compacted (T) treatment at Azerailles. ** p>0.01; * 0.01<p<0.05; ~ 0.05<p<0.10.

Table 5. Mean soil solution concentrations based on time and soil depth in the control (C) and compacted (T) treatment at Clermont-en-Argonne. ** p>0.01; * 0.01<p<0.05; ~ 0.05<p<0.10.

Table 6. Mean soil solution concentrations based on time and soil depth in the control (C) and limed (A) treatment at Clermont-en-Argonne. ** p>0.01; * 0.01<p<0.05; ~ 0.05<p<0.10.

Table 7. Mean soil solution concentrations based on time and soil depth in the limed (A) and compacted and limed (TA) treatment at Clermont-en-Argonne. ** p>0.01; * 0.01<p<0.05; ~ 0.05<p<0.10.

Table 8. Mean soil solution concentrations based on time and soil depth in the compacted (T) and compacted and limed (TA) treatment at Clermont-en-Argonne. ** p>0.01; * 0.01<p<0.05; ~ 0.05<p<0.10.

Supplementary material

Supplementary material 1. Calcium (Ca) concentrations in the soil solutions of the control (C) and compacted (T) treatment at Azerailles. A, B and C indicate the initial, intermediate and final period, respectively.

Supplementary material 2. Aluminium (Al) concentrations in the soil solutions of the control (C) and compacted (T) treatment at Azerailles. A, B and C indicate the initial, intermediate and final period, respectively.

Supplementary material 3. Calcium (Ca) concentrations in the soil solutions of the control (C), compacted (T), limed (A) and compacted and limed (TA) treatments at Clermont-en-Argonne. A, B and C indicate the initial, intermediate and final period, respectively.

Supplementary material 4. Magnesium (Mg) concentrations in the soil solutions of the control (C), compacted (T), limed (A) and compacted and limed (TA) treatments at Clermont-en-Argonne. A, B and C indicate the initial, intermediate and final period, respectively.

Supplementary material 5. Potassium (K) concentrations in the soil solutions of the control (C), compacted (T), limed (A) and compacted and limed (TA) treatments at Clermont-en-Argonne. A, B and C indicate the initial, intermediate and final period, respectively.

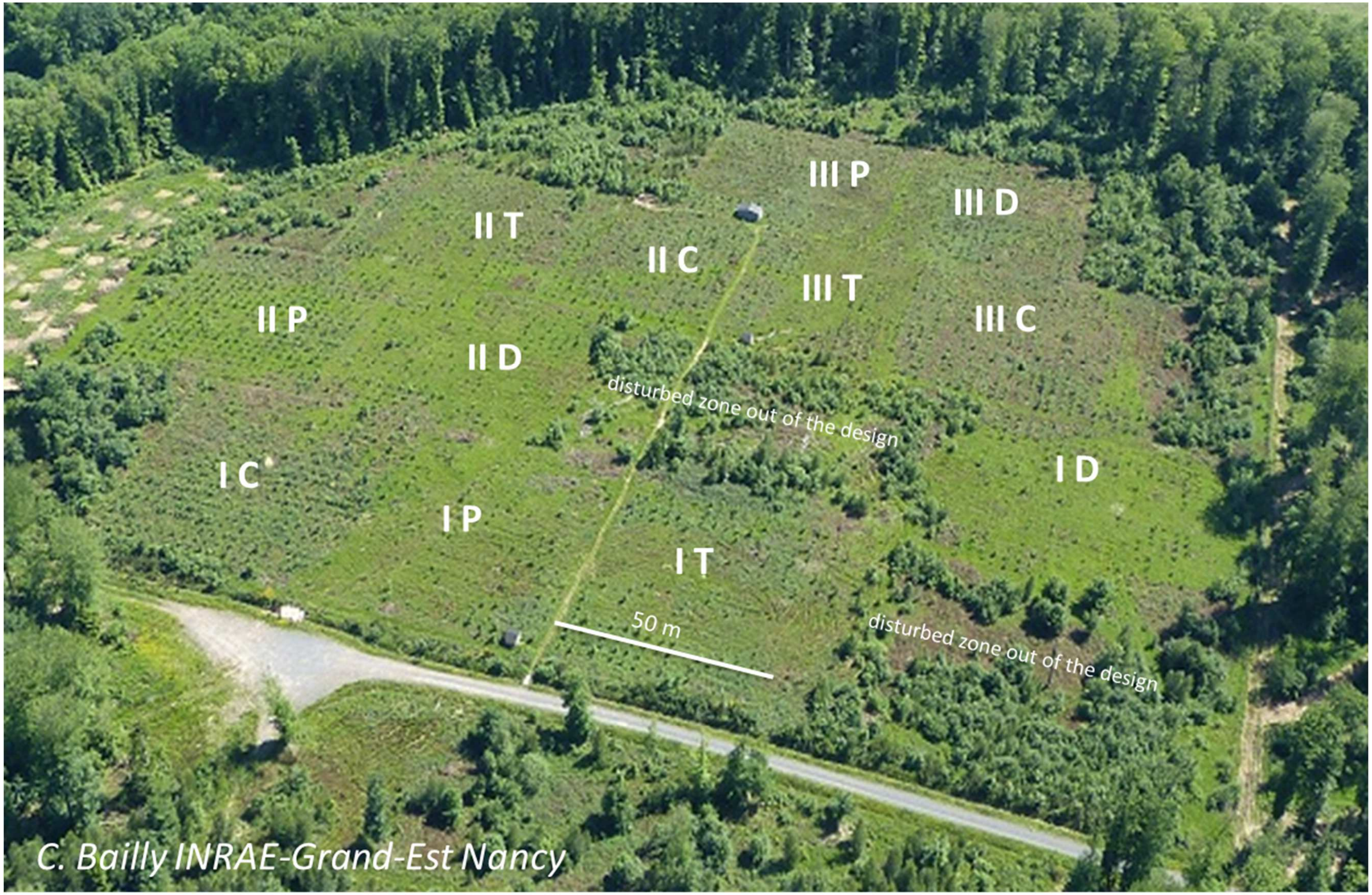
Supplementary material 6. Aluminium (Al) concentrations in the soil solutions of the control (C), compacted (T), limed (A) and compacted and limed (TA) treatments at Clermont-en-Argonne. A, B and C indicate the initial, intermediate and final period, respectively.

Supplementary material 7 (B. Zeller, unpublished data). Mineralisation and nitrification rates at Azerailles and Clermont-en-Argonne in 2011-2012. Measurements performed using the Raison et al. (1987) in situ incubation method (five replicates of the 0-15 cm layer in mature forest, and five replicates in each of the three blocks for control (C) and compacted (T) treatments). Observations were made monthly.

Supplementary material 8. PCA illustrating the effect of compaction at Azerailles, for the initial (2009-2010), intermediate (2011-2013) and final (2014-2016) periods (C control; T compacted).

Supplementary material 9. PCA illustrating the effect of compaction at Clermont-en-Argonne, for the initial (2009-2010), intermediate (2011-2013) and final (2014-2016) periods (C control; T compacted).

Figure 1


III P
III D
II T
II C
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III C
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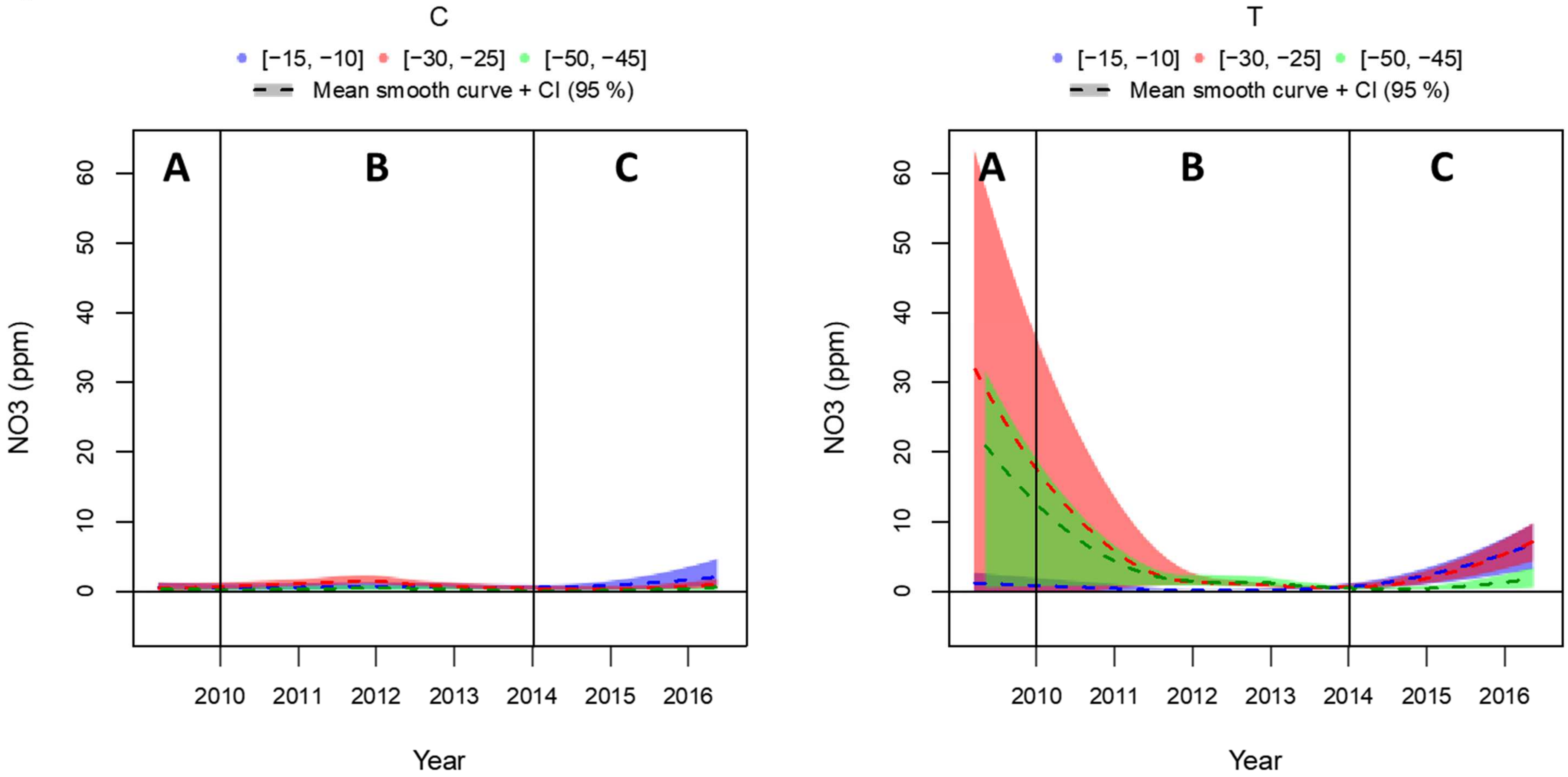
disturbed zone out of the design
I C
I D
I P
I T
50 m
disturbed zone out of the design
C. Bailly INRAE-Grand-Est Nancy

Figure 2


C
[−15, −10]
[−30, −25]
[−50, −45]
Mean smooth curve + CI (95 %)
A
B
C
NO3 (ppm)
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10
20
30
40
50
60
2010
2011
2012
2013
2014
2015
2016
Year
T
[−15, −10]
[−30, −25]
[−50, −45]
Mean smooth curve + CI (95 %)
A
B
C
NO3 (ppm)
0
10
20
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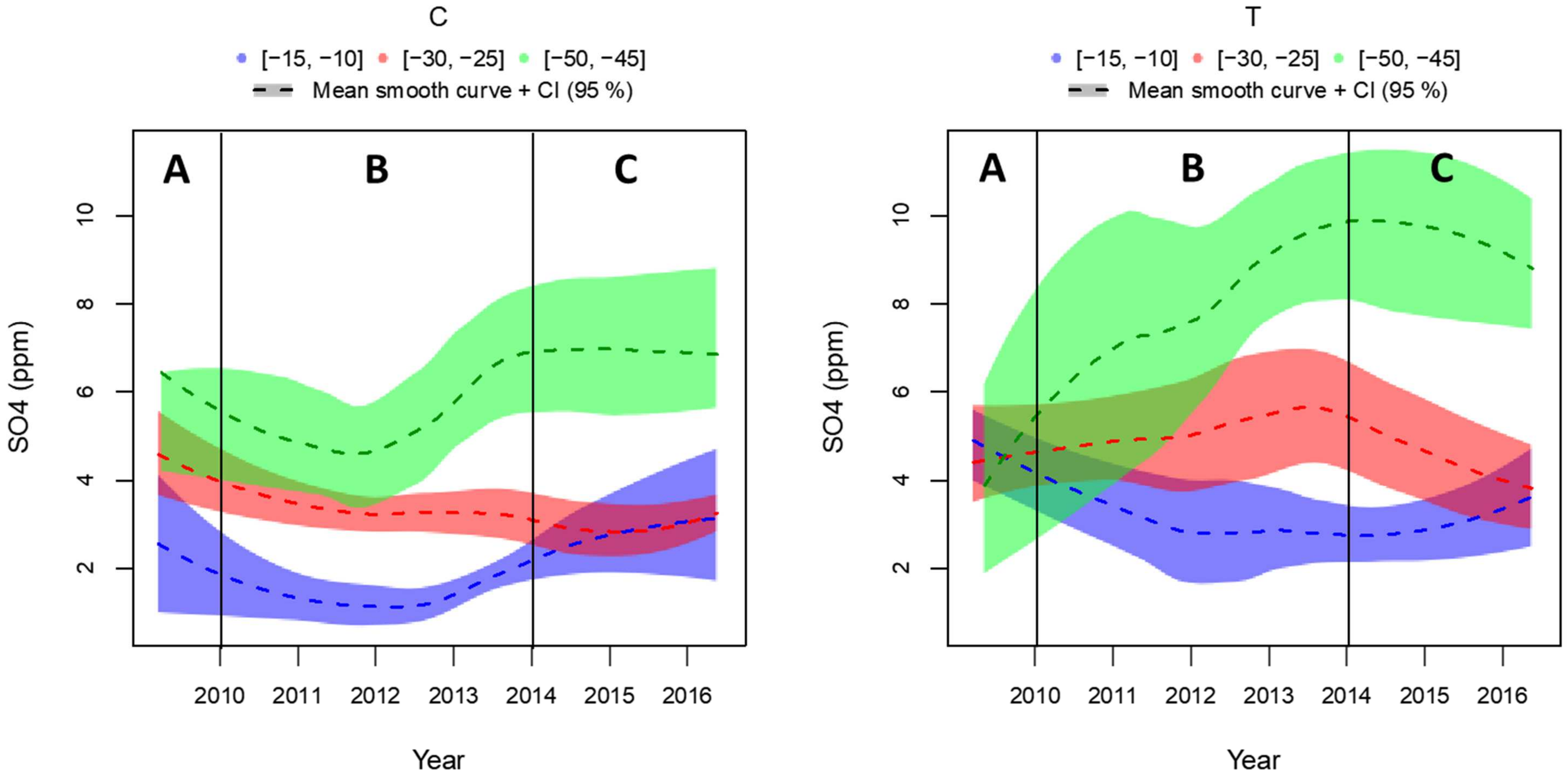
40
50
60
2010
2011
2012
2013
2014
2015
2016
Year

Figure 3


C
[−15, −10]
[−30, −25]
[−50, −45]
Mean smooth curve + CI (95 %)
A
B
C
SO4 (ppm)
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6
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2010
2011
2012
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2015
2016
Year
T
[−15, −10]
[−30, −25]
[−50, −45]
Mean smooth curve + CI (95 %)
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B
C
SO4 (ppm)
2
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2011
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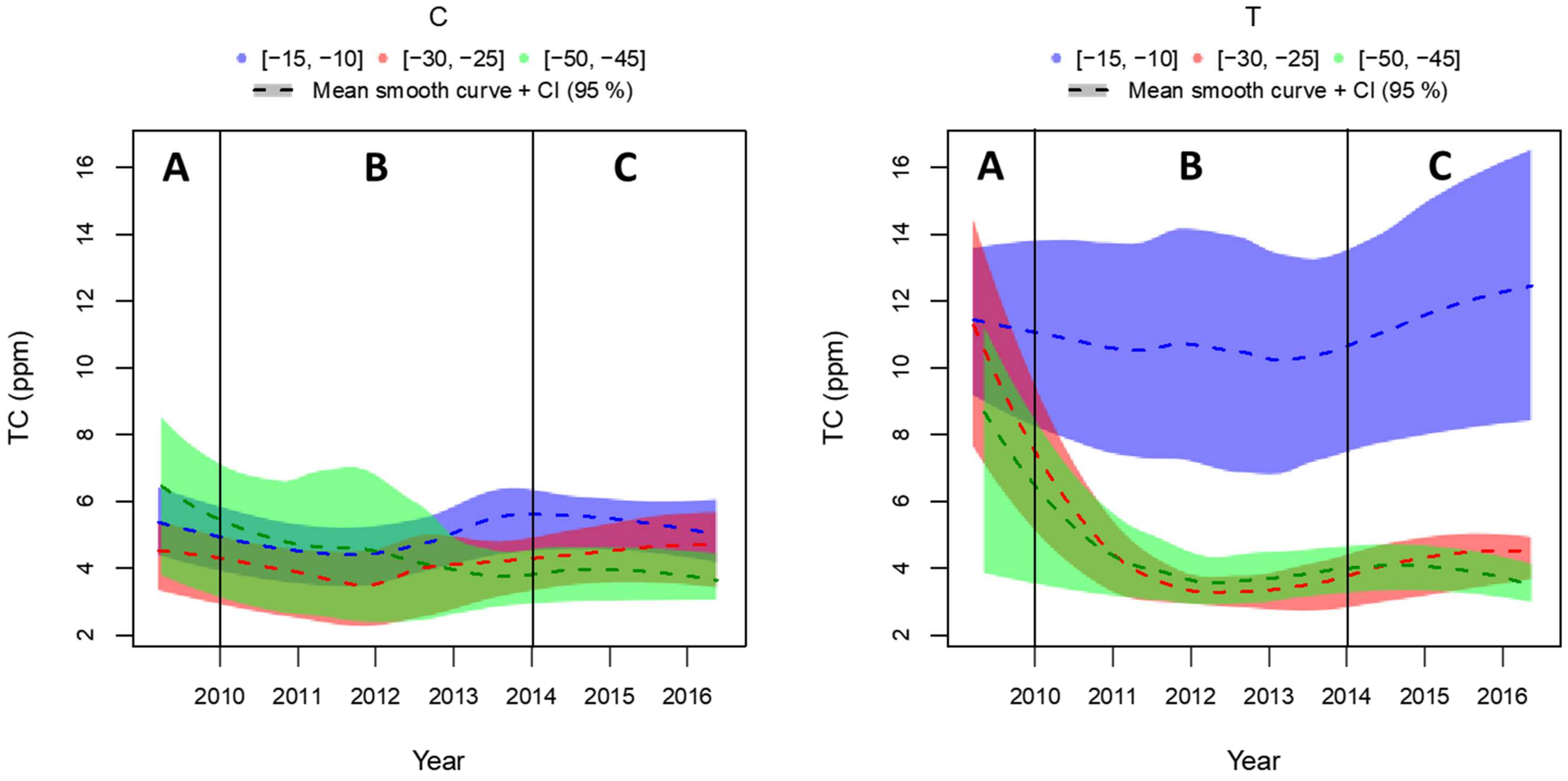
2015
2016
Year

Figure 4


C
[−15, −10]
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Mean smooth curve + CI (95 %)
A
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TC (ppm)
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[−15, −10]
[−30, −25]
[−50, −45]
Mean smooth curve + CI (95 %)
A
B
C
TC (ppm)
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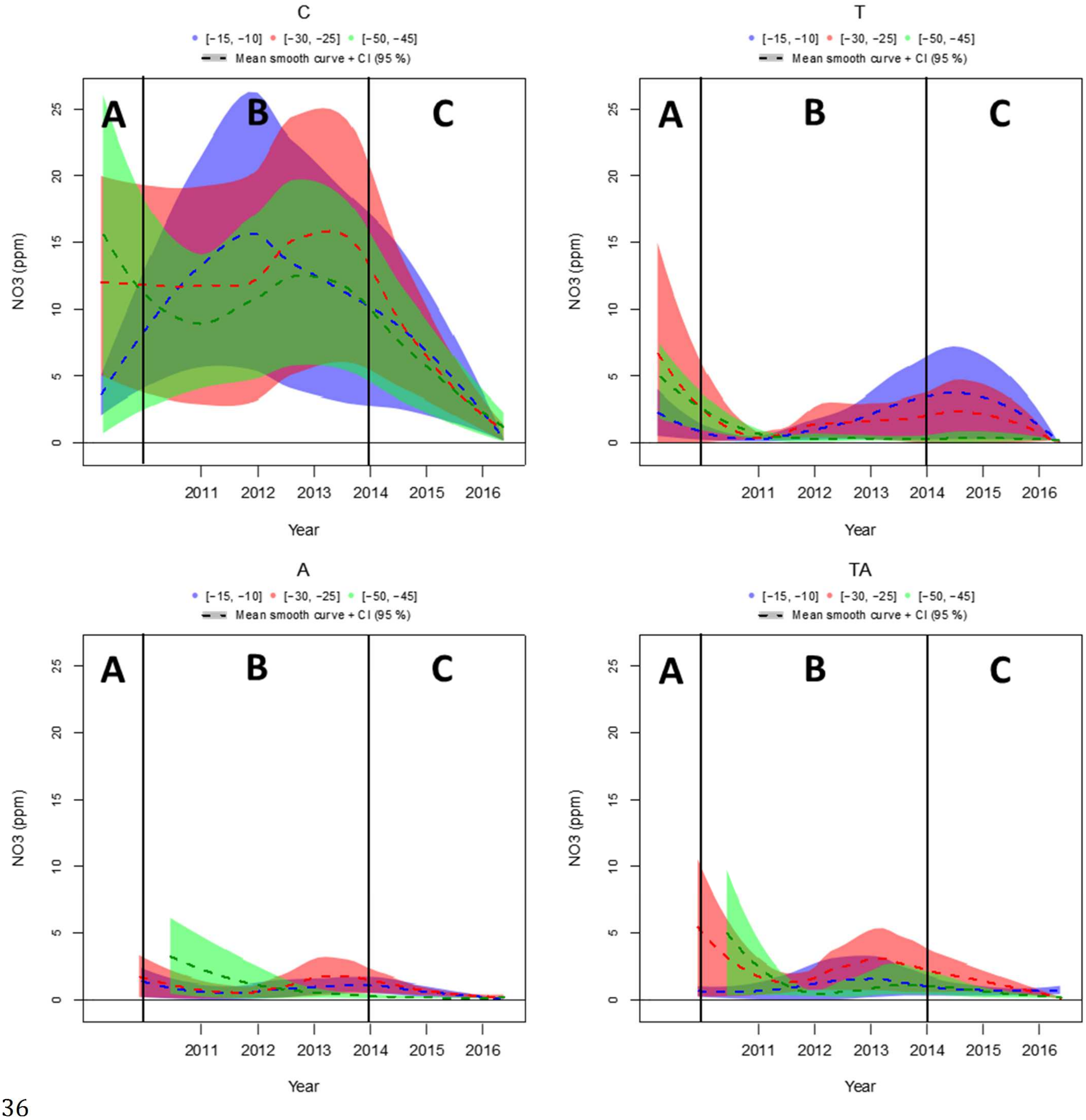
2016
Year

Figure 5


C
T
A
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● [−15, −10] ● [−30, −25] ● [−50, −45]
Mean smooth curve + CI (95 %)
A
B
C
NO3 (ppm)
0
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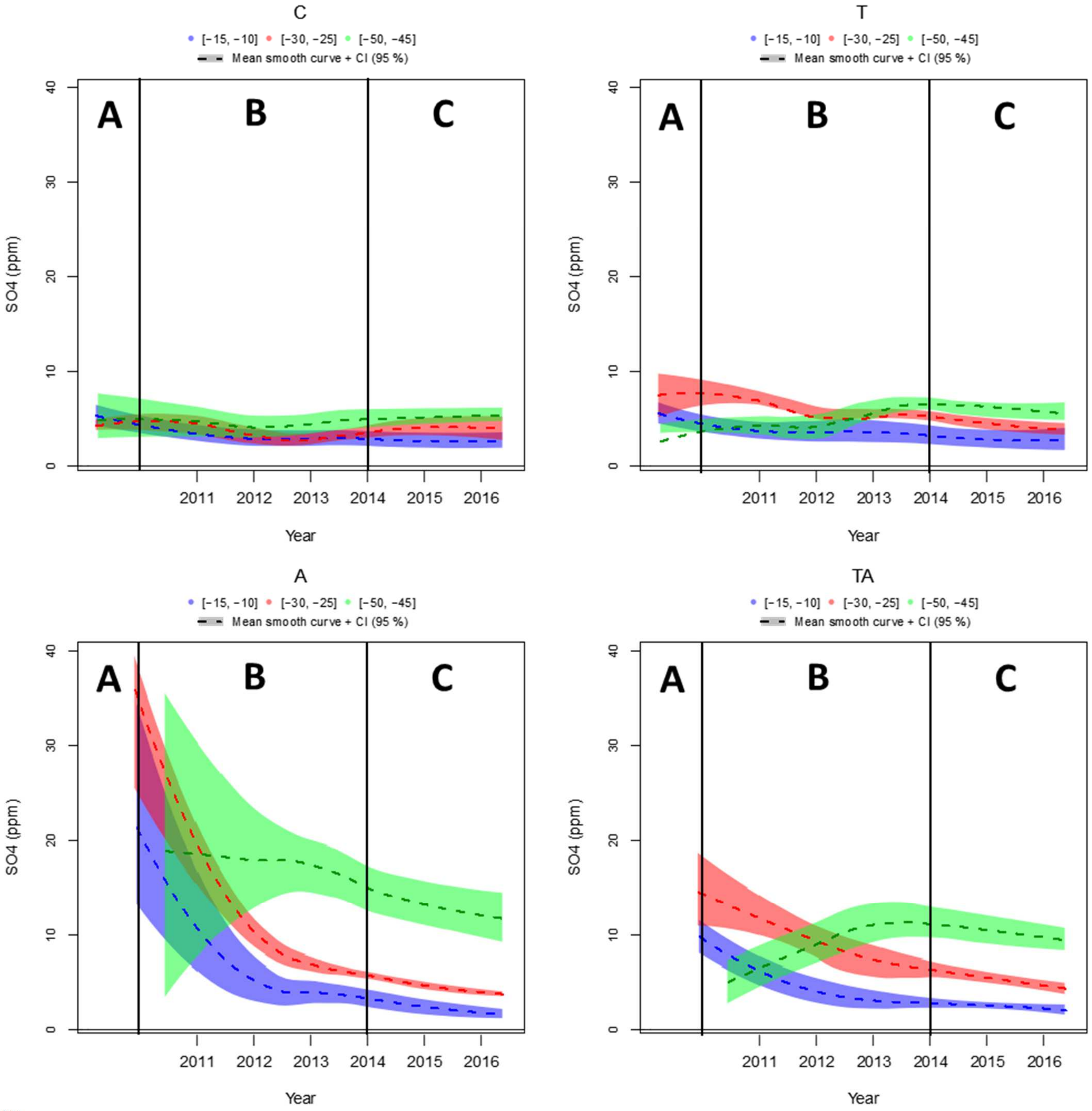
2015
2016
Year

Figure 6


C
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● [−15, −10] ● [−30, −25] ● [−50, −45]
Mean smooth curve + CI (95 %)
A
B
C
SO4 (ppm)
0
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2011
2012
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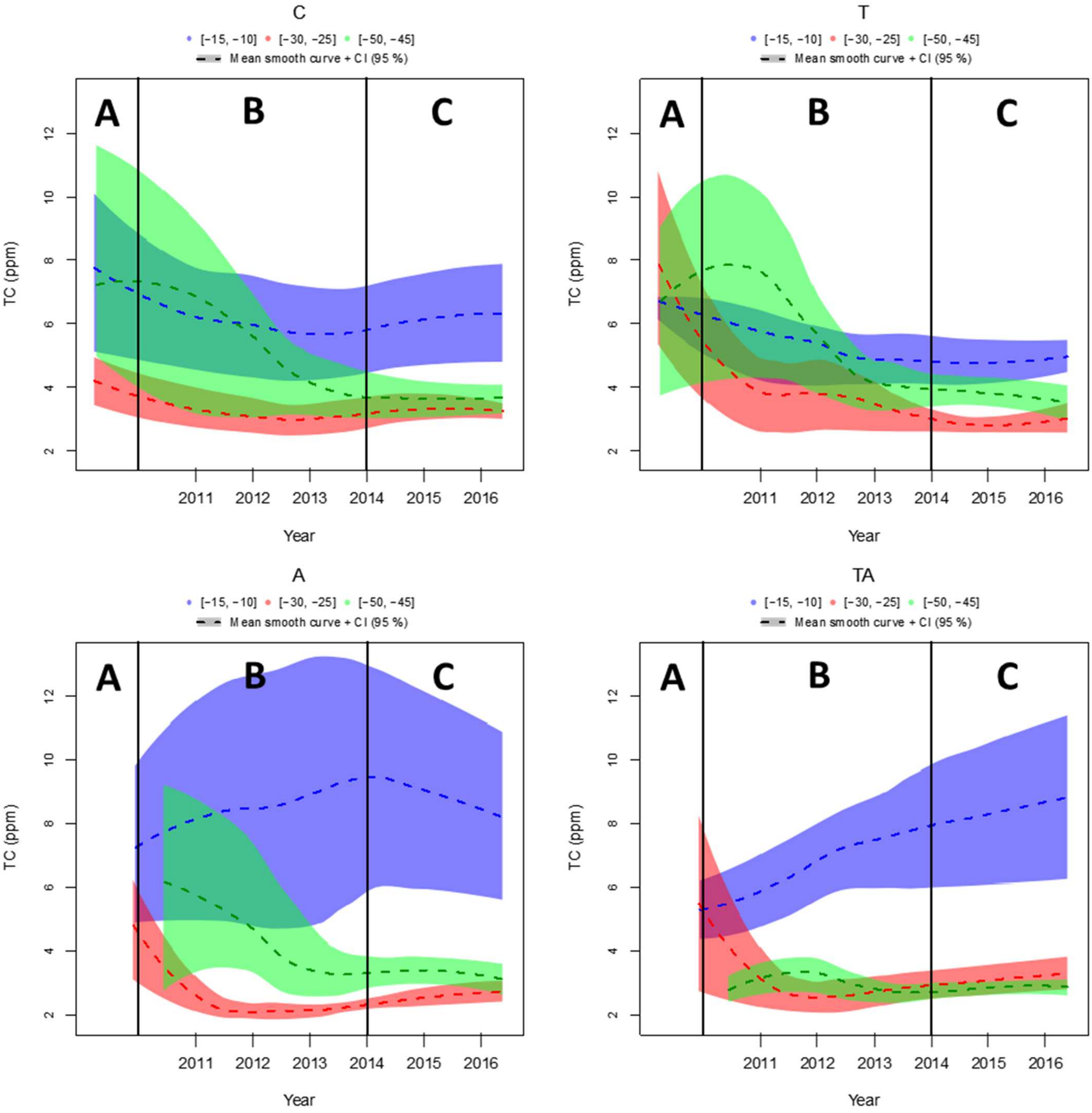
2014
2015
2016
Year

Figure 7


C
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Mean smooth curve + CI (95 %)
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TC (ppm)
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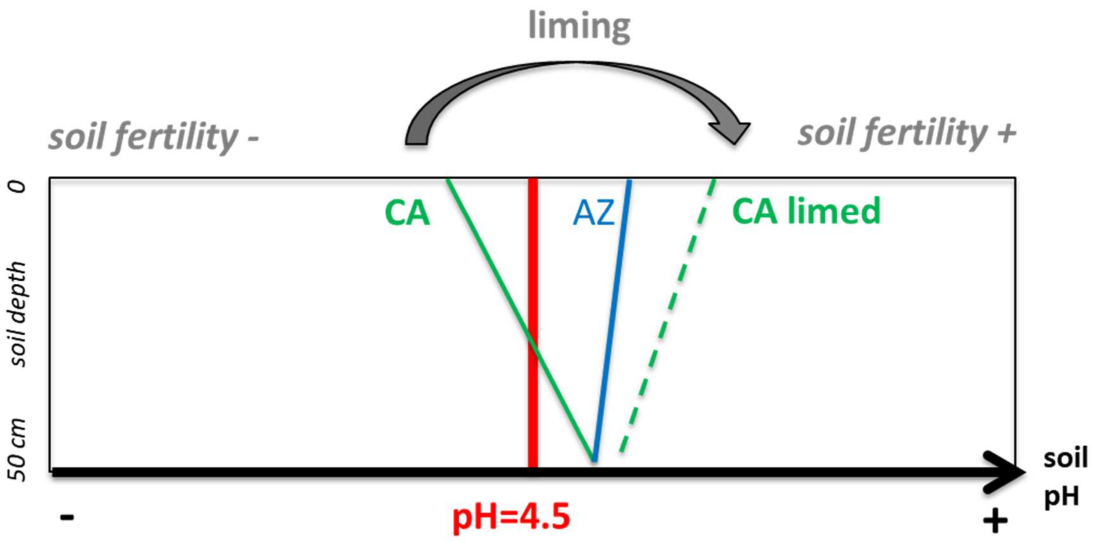
943 **Figure 8**



	CLERMONT en ARGONNE	AZERAILLES
N mineralization rate	++	+++
Nitrification rate	++	+
Nitrate immobilisation rate	+	+++
Nitrate in solution after clear-cut	+++	-
Nitrate in solution after compaction	-	++
Nitrate in solution after liming	-	not tested

944

Table 1

						Particle size distibution											Total elements			
	Depth	pH_{H2O}	pH_{KCl}	C org	N org	Clay	Fine Silt	Coarse Silt	Fine Sands	Coarse Sands	CEC $^{(1)}$	Ca $_{exch}$	[Ca+Mg+K +Na] saturation	Fe $_{DCB}$	Al $_{DCB}$	CEC clays $^{(2)}$	Ca	Mg	Fe	Al
	cm			$g.kg^{-1}$	$g.kg^{-1}$	$g.kg^{-1}$	$g.kg^{-1}$	$g.kg^{-1}$	$g.kg^{-1}$	$g.kg^{-1}$	$cmol+. kg^{-1}$	$cmol+. kg^{-1}$	%	%	%	$cmol+. kg^{-1}$	%	%	%	%
Azerailles (AZ)	0-10	4.8	3.9	26.7	1.8	222	356	201	58	165	5.7	2.2	63	1.8	0.3	24.0	0.13	0.27	2.49	4.00
	10-20	4.6	3.7	15.0	1.0	216	363	208	59	154	4.3	0.45	24	1.9	0.3	22.0	0.14	0.27	2.57	4.03
	20-30	4.6	3.7	10.8	0.8	235	363	204	59	140	4.5	0.46	24	1.5	0.3	18.0	0.13	0.30	2.60	4.28
	30-45	4.6	3.7	5.5	0.5	323	328	173	47	129	7.0	1.23	29	2.2	0.4	20.0	0.13	0.44	3.27	5.34
	45-60	4.7	3.7	3.6	0.4	455	289	139	33	84	12.0	3.38	43	2.7	0.5	25.0	0.15	0.66	4.21	6.94
	60-80	4.9	3.6	2.0	0.3	501	273	137	30	58	15.3	4.07	47	2.3	0.5	29.0	0.16	0.64	4.08	7.28
	80-100	5.2	3.5	1.5	0.3	590	233	93	26	59	14.2	5.95	70	2.4	0.4	27.0	0.16	0.77	4.38	8.14
	> 100	5.1	3.4	1.5	0.3	631	240	77	17	35	17.9	5.56	54	2.5	0.4	26.0	0.16	0.88	4.47	8.43
Clermont en Argonne (CA)	0-10	4.4	3.5	26.1	1.4	128	357	365	140	10	4.3	0.65	29	0.6	0.2	31.0	0.17	0.14	1.11	2.63
	10-20	4.5	3.8	9.6	0.5	128	357	362	141	13	3.4	0.19	16	0.6	0.2	23.0	0.16	0.16	1.19	2.84
	20-30	4.5	3.8	4.5	0.3	155	345	348	134	18	4.5	0.20	12	0.7	0.2	24.0	0.16	0.21	1.49	3.26
	30-45	4.6	3.7	2.6	0.3	212	328	321	124	15	7.3	0.39	12	0.8	0.3	27.0	0.14	0.30	1.94	3.91
	45-60	4.8	3.5	10.6	0.3	285	305	284	113	13	12.7	1.73	26	1.0	0.3	35.0	0.15	0.42	2.60	4.65
	60-75	5.0	3.4	13.4	0.3	330	277	251	124	18	16.7	4.00	42	1.0	0.3	41.0	0.18	0.48	2.98	4.94
	75-90	5.0	3.4	1.4	0.3	336	297	241	120	6	16.9	5.38	53	1.0	0.3	44.0	0.21	0.48	2.99	4.88
	90-110	5.1	3.3	1.2	0.2	334	281	287	89	10	17.8	6.30	55	1.0	0.3	46.0	0.26	0.48	2.98	4.83
	> 110	5.1	3.3	1.2	0.2	329	264	246	137	24	19.5	7.77	60	1.0	0.2	51.0	0.27	0.47	2.90	4.78

All data refered to soil fine earth dried at 105°C except CECclays refering to the clay fraction itself

(1) CEC of the fine earth

(2) CEC of clays calculated from fine earth CEC fully attributed to the clay fraction

Table 2

Treatment	Horizon	pH$_{water}$	pH$_{KCl}$	Ca$_{exch}$	Mg$_{exch}$	Mn$_{exch}$	K$_{exch}$	H$^+$	Al^{3+} titrated	acidity	T (CEC)	S:T	S-(SO$_4$)
	cm	UpH		cmolc.kg^{-1}									mg.kg^{-1}
Control C	00-10	4.52	3.69	0.68	0.15	0.59	0.27	0.36	2.48	2.84	4.58	0.38	0.99
	10-20	4.66	3.88	0.13	0.04	0.29	0.07	0.22	2.70	2.92	3.48	0.16	0.92
	20-30	4.65	3.88	0.11	0.04	0.22	0.05	0.17	3.40	3.58	4.02	0.11	1.37
	30-40	4.56	3.69	0.17	0.08	0.10	0.13	0.19	5.75	5.94	6.44	0.08	1.62
	40-50	4.64	3.53	0.69	0.38	0.05	0.27	0.22	9.42	9.64	11.07	0.13	1.24
mean		**4.61**	**3.74**	**0.36**	**0.14**	**0.25**	**0.16**	**0.23**	**4.75**	**4.99**	**5.92**	**0.17**	**1.23**
Compacted T	00-10	4.63	3.78	1.08	0.18	0.69	0.29	0.27	2.26	2.54	4.81	0.47	1.24
	10-20	4.72	3.93	0.23	0.05	0.28	0.09	0.16	2.81	2.97	3.63	0.18	1.24
	20-30	4.65	3.82	0.20	0.07	0.20	0.09	0.17	4.06	4.23	4.80	0.12	2.12
	30-40	4.64	3.62	0.41	0.18	0.12	0.21	0.19	7.74	7.93	8.88	0.11	1.95
	40-50	4.74	3.49	1.48	0.79	0.08	0.35	0.20	10.49	10.70	13.43	0.21	1.19
mean		**4.67**	**3.73**	**0.68**	**0.25**	**0.27**	**0.21**	**0.20**	**5.47**	**5.67**	**7.11**	**0.22**	**1.55**
Limed A	00-10	5.16	4.22	3.00	1.62	0.67	0.42	0.09	0.79	0.89	6.62	0.85	1.23
	10-20	4.81	3.91	0.50	0.27	0.40	0.26	0.18	2.92	3.10	4.53	0.32	0.99
	20-30	4.78	3.84	0.44	0.22	0.31	0.28	0.17	5.13	5.30	6.56	0.23	1.47
	30-40	4.66	3.69	0.90	0.49	0.16	0.40	0.19	7.56	7.75	9.71	0.17	2.02
	40-50	4.73	3.63	1.78	1.00	0.12	0.37	0.20	8.70	8.89	12.19	0.21	2.49
mean		**4.83**	**3.86**	**1.32**	**0.72**	**0.33**	**0.35**	**0.17**	**5.02**	**5.19**	**7.92**	**0.36**	**1.64**
Compacted and limed TA	00-10	5.00	4.10	2.46	1.27	0.56	0.42	0.13	1.23	1.36	6.10	0.75	1.21
	10-20	4.84	3.96	0.36	0.24	0.36	0.24	0.15	2.36	2.51	3.73	0.31	1.11
	20-30	4.69	3.88	0.19	0.14	0.29	0.23	0.16	3.76	3.92	4.77	0.18	2.49
	30-40	4.63	3.70	0.53	0.32	0.15	0.28	0.20	6.29	6.49	7.79	0.15	2.61
	40-50	4.74	3.54	1.62	0.97	0.07	0.38	0.20	8.75	8.95	12.02	0.24	1.87
mean		**4.78**	**3.83**	**1.03**	**0.59**	**0.29**	**0.31**	**0.17**	**4.48**	**4.65**	**6.88**	**0.33**	**1.86**
post-hoc test C vs T	*0 - 10 cm*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
	10 - 20 cm	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
post-hoc test A vs TA	*0 - 10 cm*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
	10 - 20 cm	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
post-hoc test C vs A	*0 - 10 cm*	**	**	**	**	*NS*	*NS*	**	**	**	**	**	*NS*
	10 - 20 cm	**	*NS*	*NS*	**	*NS*	**	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
post-hoc test T vs TA	*0 - 10 cm*	*	*	*	**	*NS*	*NS*	~	**	**	~	**	*NS*
	10 - 20 cm	~	*NS*	*NS*	**	*NS*	*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

Table 3

a)

			C				T				C					T				
			Cl^-	NO_3^-	SO_4^{2-}	IS_C	Cl^-	NO_3^-	SO_4^{2-}	IS_T	Mg^{2+}	Al^{3+}	Ca^{2+}	K^+	NH_4^+	Mg^{2+}	Al^{3+}	Ca^{2+}	K^+	NH_4^+
AZERAILLES		**depth (cm)**	µeq.L^{-1}				µeq.L^{-1}				µeq.L^{-1}					µeq.L^{-1}				
	Initial period [2009-2010]	-15	44	9	41	**94**	33	12	54	**148**	14	6	35	5	10	12	7	38	16	7
		-30	28	8	62	**134**	8	70	21	**442**	14	5	33	9	7	11	4	21	6	4
		-50	44	2	53	**210**	20	52	26	**465**	20	2	39	2	5	25	1	41	5	3
	Intermediate period [2011-2013]	-15	36	28	35	**90**	36	7	56	**115**	12	7	39	7	9	9	9	38.049	17	7
		-30	23	29	46	**148**	13	15	71	**160**	14	8	36	7	8	16	1	39	6	6
		-50	28	8	62	**188**	10	11	78	**221**	20	1	39	2	11	23	1	41	5	7
	Final period [2014-2016]	-15	29	24	46	**130**	34	32	33	**188**	10	10	43	6	1	9	11	42	20	1
		-30	35	11	53	**117**	25	29	45	**214**	12	10	36	6	2	15	6	43	5	2
		-50	26	3	69	**214**	16	7	76	**259**	21	4	43	2	1	23	2	43	4	1

			C				T				C					T				
			Cl^-	NO_3^-	SO_4^{2-}	IS_C	Cl^-	NO_3^-	SO_4^{2-}	IS_T	Mg^{2+}	Al^{3+}	Ca^{2+}	K^+	NH_4^+	Mg^{2+}	Al^{3+}	Ca^{2+}	K^+	NH_4^+
CLERMONT en ARGONNE		**depth (cm)**	µeq.L^{-1}				µeq.L^{-1}				µeq.L^{-1}					µeq.L^{-1}				
	Initial period [2009-2010]	-15	22	47	30	**314**	23	10	64	**145**	10	16	35	8	4	11	13	31	5	5
		-30	14	59	26	**404**	13	19	67	**244**	11	14	40	11	3	15	10	33	4	3
		-50	20	54	25	**420**	28	26	46	**213**	10	1	39	8	3	28	1	35	5	4
	Intermediate period [2011-2013]	-15	7	79	14	**460**	33	19	47	**161**	9	24	39	9	2	10	18	33	4	4
		-30	8	76	16	**448**	26	15	58	**199**	10	20	41	8	4	12	11	35	3	5
		-50	9	67	23	**411**	23	5	71	**167**	32	1	41	7	3	28	1	35	4	4
	Final period [2014-2016]	-15	9	63	28	**195**	23	43	34	**174**	10	16	43	9	1	7	23	29	9	1
		-30	9	50	41	**210**	22	24	54	**169**	10	11	44	10	1	11	11	37	4	1
		-50	9	42	48	**231**	21	6	73	**175**	29	3	37	9	1	27	3	35	4	1
			A				**TA**				**A**					**TA**				
			Cl^-	NO_3^-	SO_4^{2-}	IS_A	Cl^-	NO_3^-	SO_4^{2-}	IS_{TA}	Mg^{2+}	Al^{3+}	Ca^{2+}	K^+	NH_4^+	Mg^{2+}	Al^{3+}	Ca^{2+}	K^+	NH_4^+
		depth (cm)	µeq.L^{-1}				µeq.L^{-1}				µeq.L^{-1}					µeq.L^{-1}				
	Initial period [2009-2010]	-15	8	11	81	**487**	34	7	58	**289**	8	12	22	44	2	17	12	38	9	3
		-30	11	2	86	**735**	13	16	70	**420**	8	19	26	29	1	14	13	33	16	2
		-50	13	10	76	**569**	15	33	51	**310**	26	5	49	4	1	27	1	45	3	2
	Intermediate period [2011-2013]	-15	12	11	76	**137**	25	27	48	**162**	33	13	25	15	1	28	13	29	10	4
		-30	10	12	78	**247**	15	25	60	**300**	15	7	21	34	1	19	13	31	18	2
		-50	6	6	87	**420**	14	13	72	**296**	29	2	46	7	1	27	1	44	3	2
	Final period [2014-2016]	-15	14	16	69	**78**	32	16	52	**93**	33	12	25	15	1	33	15	28	6	1
		-30	17	10	73	**128**	18	15	66	**167**	14	7	21	34	1	25	7	34	14	1
		-50	5	1	93	**296**	15	4	77	**271**	29	2	46	7	1	26	3	45	3	1

b)

		AZERAILLES	**CLERMONT en ARGONNE**			
		(IS_T-IS_C) / IS_C	**(IS_T-IS_C) / IS_C**	**(IS_A-IS_C) / IS_C**	**$(IS_{TA}-IS_A)$ / IS_A**	**$(IS_{TA}-IS_T)$ / IS_T**
	depth (cm)	%	%	%	%	%
Initial period [2009-2010]	-15	57	-54	55	-41	99
	-30	230	-40	82	-43	72
	-50	121	-49	35	-46	46
Intermediate period [2011-2013]	-15	28	-65	-70	18	1
	-30	8	-56	-45	21	51
	-50	18	-59	2	-30	77
Final period [2014-2016]	-15	45	-11	-60	19	-47
	-30	83	-20	-39	30	-1
	-50	21	-24	28	-8	55

Table 4

Class of depth (cm)	observations	pH	F	Cl	NO3	SO4	S	P	Fe	Si	Mn	Mg	Al	Ca	Na	K	N-NH4	TC	TN	N org	H
AZERAILLES (C and T treatments)																					
												ppm									
Initial period [2009-2010]																					
C [-15; -10]	93	5.57	0.03	1.49	0.44	1.95	0.69	0.03	0.01	5.78	0.09	0.19	0.06	0.79	0.56	0.22	0.19	5.18	0.50	0.21	0.01
T [-15; -10]	177	5.75	0.03	1.75	0.84	3.84	1.37	0.00	0.02	4.66	0.17	0.31	0.14	1.71	0.78	1.33	0.27	11.32	1.03	0.60	0.01
treatment						*	**			**		*		**	**	~	*	**	**	**	
year						~	**	**	**	**	**	**	**			**		~			**
season			**	**		**	**			**	~		**		**	~	**	**			**
C [-30; -25]	66	5.40	0.04	1.36	0.53	3.98	1.22	0.00	0.00	5.91	0.07	0.24	0.06	0.88	0.73	0.47	0.16	4.70	0.51	0.23	0.01
T [-30; -25]	132	5.94	0.06	1.25	12.79	4.56	1.65	0.01	0.00	6.31	3.57	0.48	0.11	1.52	1.12	0.79	0.27	8.15	3.77	0.73	0.00
treatment							*			~				~	~			**		**	
year			**	**	**	*				**	**	**	**	**	**	**	**	**	**		
season				**		**	**	**		**		*		**	**		*	~		*	
C [-50; -45]	67	5.74	0.06	3.37	0.22	5.49	1.74	0.00	0.00	6.72	0.08	0.52	0.03	1.70	1.35	0.21	0.28	6.72	0.60	0.28	0.01
T [-50; -45]	61	6.09	0.10	3.40	10.85	5.86	1.94	0.01	0.00	6.41	0.58	1.25	0.05	3.47	1.77	0.74	0.27	5.84	2.85	0.24	0.00
treatment					*			~				**		**	*	**			*		
year			*	**	**	**	**	**	**	**	**	**	**	**	**	**		**	**		**
season				**	**		**	**	**	**		**		**			*	**			**
Intermediate period [2011-2013]																					
C [-15; -10]	142	5.94	0.02	1.01	0.87	1.48	0.56	0.00	0.01	5.25	0.05	0.18	0.08	0.97	0.65	0.36	0.20	5.06	0.67	0.28	0.00
T [-15; -10]	123	6.19	0.02	1.32	0.29	3.21	1.29	0.00	0.06	3.85	0.12	0.26	0.19	1.80	0.86	1.50	0.31	9.94	0.80	0.43	0.00
treatment						**	**			**	*		~	**	**	**	*	*		~	
year			**		**	**		**	**	**	*	**	**	**	**	**	**		**	**	**
season			**		**	**	**	**	**	**	**	**	**	**	**	**	**	**		**	**
C [-30; -25]	110	5.72	0.04	1.18	1.95	3.22	1.08	0.00	0.01	5.54	0.07	0.27	0.11	1.13	0.83	0.43	0.34	4.08	1.06	0.30	0.00
T [-30; -25]	119	6.29	0.04	0.79	1.70	5.37	1.75	0.00	0.00	5.15	0.16	0.37	0.02	1.55	1.25	0.49	0.43	4.52	0.98	0.18	0.00
treatment				**	~	*	*		**		*		**			**			*		**
year			**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
season				**	**	**	**	**	**	**	**	**	*	**	*	**	**	**	**		**
C [-50; -45]	133	6.16	0.05	1.92	0.64	5.40	1.88	0.00	0.00	6.21	0.06	0.57	0.03	1.82	1.36	0.20	0.77	4.45	1.23	0.32	0.00
T [-50; -45]	128	6.54	0.06	0.73	1.33	8.20	2.76	0.00	0.00	5.57	0.17	0.81	0.01	2.42	1.40	0.62	0.48	4.22	0.91	0.18	0.00
treatment				**						*						*					
year				~	**	**	**	**	**		**	**	**	**	**	**	**	**	**	~	**
season			**	**	*	**	**	**	**	**	**	**	**	**	**	**	**	**	**		**
Final period [2014-2016]																					
C [-15; -10]	95	5.53	0.03	1.35	1.23	2.78	0.96	0.00	0.04	5.10	0.06	0.19	0.14	1.27	0.75	0.40	0.03	5.55	0.48	0.18	0.01
T [-15; -10]	89	5.78	0.02	2.39	2.35	3.11	1.16	0.00	0.13	3.96	0.08	0.31	0.29	2.43	0.84	2.16	0.06	11.95	0.94	0.35	0.00
treatment									**			~	*	*		**	**	*	~	~	~
year			**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
season			**	**	**			**	**	**	**	**	**	**	**	**	**	**	**	**	
C [-30; -25]	82	5.53	0.03	1.46	0.60	2.80	0.97	0.00	0.04	5.11	0.06	0.21	0.12	1.00	0.83	0.35	0.04	4.55	0.31	0.15	0.01
T [-30; -25]	101	5.73	0.05	1.88	2.59	4.39	1.49	0.00	0.03	5.34	0.12	0.40	0.12	1.85	1.24	0.47	0.08	4.55	0.75	0.12	0.00
treatment				**	**						*	**		**	*				**		
year			**	**	**	~	**	**	**	**	**	**	**	**	**	**		**	**	**	**
season			**	**		**	**	**	**	**	**	**		**	**	**	**	**		**	
C [-50; -45]	93	5.80	0.05	1.85	0.25	6.50	2.08	0.00	0.03	6.50	0.06	0.51	0.08	1.75	1.33	0.19	0.05	3.82	0.21	0.11	0.00
T [-50, -45]	95	6.08	0.06	1.37	0.79	9.54	3.05	0.00	0.03	5.81	0.18	0.80	0.06	2.48	1.59	0.48	0.08	3.93	0.34	0.08	0.00
treatment				*						~		~				*					
year			**	**	**		**	**	**	**	**	**			*	**		**	**	**	**
season						**			~	**	**	**	**	**	**	**	**	**			***

Table 5

CLERMONT en ARGONNE (C and T treatments)

Class of depth (cm)	observations	pH	F	Cl	NO3	SO4	S	P	Fe	Si	Mn	Mg	Al	Ca	Na	K	N-NH4	TC	TN	N org	H
												ppm									
Initial period [2009-2010]																					
C [-15; -10]	88	4.87	0.03	2.39	6.82	4.54	1.48	0.00	0.01	5.16	0.28	0.34	0.42	2.00	1.06	0.93	0.16	6.87	2.11	0.48	0.02
T [-15; -10]	90	5.26	0.02	1.29	0.73	4.48	1.41	0.00	0.01	4.09	0.23	0.21	0.19	0.99	0.87	0.32	0.15	6.61	0.59	0.28	0.01
treatment				**	*								~	*		~			*		*
year					**	**	**			**	**		**	**	**			**	**		
season			**	**	~	*				**	**		**	**	**	**		**			**
C [-30; -25]	75	5.18	0.04	2.00	11.21	4.92	1.56	0.00	0.01	5.64	0.29	0.46	0.38	2.68	1.01	1.32	0.17	4.91	2.86	0.37	0.02
T [-30; -25]	75	5.40	0.05	1.01	2.07	7.86	2.40	0.00	0.01	4.58	0.84	0.40	0.19	1.51	0.95	0.37	0.13	5.54	0.82	0.25	0.01
treatment				**	~	**	**			~							~		~		
year						~				**	**				**	~		**			~
season			~	**	**		**			**	**				**	~	**	**			**
C [-50; -45]	60	5.87	0.03	2.50	9.13	5.00	1.56	0.00	0.00	7.98	0.07	1.16	0.04	2.39	1.42	1.01	0.19	6.22	2.35	0.18	0.00
T [-50; -45]	57	6.48	0.02	2.29	2.39	4.13	1.28	0.00	0.00	7.69	0.03	0.81	0.01	1.67	1.60	0.40	0.18	7.16	1.08	0.39	0.00
treatment					~				*			~	*								~
year			**	**	**	**	**			**	**	**		**	**	**			**		
season				**		**	**		**	**					~	**	**			*	
Intermediate period [2011-2013]																					
C [-15; -10]	141	4.91	0.02	1.07	16.66	2.99	1.24	0.00	0.02	4.72	0.35	0.53	1.02	3.74	1.10	1.67	0.20	5.79	5.13	1.27	0.02
T [-15; -10]	109	5.37	0.01	1.71	1.38	3.62	1.31	0.00	0.02	3.72	0.11	0.21	0.31	1.24	1.18	0.25	0.13	5.35	0.64	0.21	0.01
treatment			~		**					~	~	~	~	*		*	**		**	*	*
year			**				**	**	**	**	**	*	*	**	**	**	**	**	**	**	**
season			**	**	**					**	*	**	**	**	**	**	*	**	**		**
C [-30; -25]	137	5.18	0.04	1.22	16.69	3.28	1.24	0.00	0.01	5.38	0.37	0.57	0.87	3.90	1.28	1.50	0.19	3.38	4.96	1.11	0.02
T [-30; -25]	131	5.60	0.03	1.83	1.39	5.33	1.87	0.00	0.01	4.35	0.17	0.32	0.19	1.53	1.47	0.22	0.25	3.74	0.74	0.20	0.00
treatment					**	**	**			**				~	~	~			*	~	*
year			**	**	**	**	**	**	**	**	**	**	**	**	**	**	**		**	**	**
season				**	**	**	**	**	**	**		**		**	~	**		**	**		**
C [-50; -45]	129	6.00	0.04	1.34	12.72	4.31	1.63	0.00	0.00	7.10	0.11	1.67	0.04	3.42	1.48	1.16	0.34	5.12	3.87	0.80	0.00
T [-50; -45]	125	6.44	0.02	1.39	0.36	5.52	1.98	0.00	0.00	6.69	0.03	0.87	0.01	1.78	1.52	0.43	0.20	5.35	0.45	0.18	0.00
treatment					*							*							*		~
year				**		**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	*
season			**		**	**	**	*	**	**		**	**	**	**	**	**	~	**		
Final period [2014-2016]																					
C [-15; -10]	124	5.13	0.01	0.61	5.25	2.71	0.98	0.00	0.05	3.95	0.11	0.25	0.32	1.92	0.64	0.76	0.04	6.08	1.37	0.19	0.01
T [-15; -10]	92	5.09	0.01	1.40	3.31	2.84	1.01	0.00	0.06	4.77	0.12	0.15	0.39	1.12	0.98	0.67	0.03	4.66	0.84	0.12	0.01
treatment				*						~					*						
year			**	*	**			**			**	**	**	**		**		**	**	**	
season			**	**	**	**	**	**	*	**		**	**	**		~		**	**		**
C [-30; -25]	126	5.26	0.02	0.66	4.72	4.05	1.38	0.00	0.03	4.93	0.14	0.25	0.21	1.89	0.75	0.82	0.03	3.33	1.08	0.07	0.01
T [-30; -25]	126	5.34	0.02	1.34	1.84	4.27	1.44	0.00	0.03	4.37	0.12	0.24	0.16	1.29	1.13	0.24	0.03	2.82	0.46	0.06	0.01
treatment				**						~					**			~			
year			**	**	**		**	**	**	**	**	**	**	**	**	**	**	*	**	**	
season			**	**	**	**		**	**	**	**	**	**	**				**	**		**
C [-50; -45]	123	6.14	0.03	0.76	4.45	5.26	1.75	0.00	0.03	7.51	0.06	0.85	0.04	1.82	1.11	0.84	0.06	3.66	1.06	0.06	0.00
T [-50; -45]	121	6.46	0.02	1.33	0.49	6.01	1.97	0.00	0.03	7.28	0.03	0.77	0.03	1.64	1.64	0.37	0.05	3.68	0.23	0.08	0.00
treatment				**											**					~	
year			**	**	**	**		**	**	~	**	**	**	**	**	**			**	**	**
season			**	**		**	**	**	**	**	**	**	**	**			~	**	**	~	**

Table 6

CLERMONT en ARGONNE (A and C treatments)																			
Class of depth (cm)	observations	pH	F	Cl	NO3	SO4	Fe	Si	Mn	Mg	Al	Ca	Na	K	N-NH4	TC	TN	N org	H
			ppm																
Initial period [2009-2010]																			
A [-15; -10]	49	4.94	0.02	1.42	2.07	19.58	0.01	5.62	0.24	0.42	0.49	2.00	0.89	8.04	0.16	7.71	0.84	0.25	0.02
C [-15; -10]	88	4.87	0.03	2.39	6.82	4.54	0.01	5.16	0.28	0.34	0.42	2.00	1.06	0.93	0.16	6.87	2.11	0.48	0.02
treatment				**		*							**	**			~		~
year																			
season				*		**		**		*	~		**	**		**			**
A [-30; -25]	34	4.67	0.07	2.25	1.07	27.50	0.01	5.07	0.48	0.59	0.92	2.81	0.96	7.49	0.16	3.54	0.43	0.04	0.03
C [-30; -25]	75	5.18	0.04	2.00	11.21	4.92	0.01	5.64	0.29	0.46	0.38	2.68	1.01	1.32	0.17	4.91	2.86	0.37	0.02
treatment					~	**		~					**	**			~		
year																			
season				**		**		**						**	**				**
A [-50; -45]	28	6.00	0.15	2.83	2.62	19.44	0.01	8.65	0.26	1.73	0.24	5.15	1.51	0.89	0.16	5.96	0.89	0.19	0.00
C [-50; -45]	60	5.87	0.03	2.50	9.13	5.00	0.00	7.98	0.07	1.16	0.04	2.39	1.42	1.01	0.19	6.22	2.35	0.18	0.00
treatment																			
year																			
season																			
Intermediate period [2011-2013]																			
A [-15; -10]	125	5.88	0.01	0.57	0.71	5.23	0.03	4.10	0.06	0.43	0.24	0.88	0.55	3.43	0.17	8.86	0.67	0.34	0.00
C [-15; -10]	141	4.91	0.02	1.07	16.66	2.99	0.02	4.72	0.35	0.53	1.02	3.74	1.10	1.67	0.20	5.79	5.13	1.27	0.02
treatment			**	~	**				*		*	**	**	*			**		**
year			**	**		**	**	**	**	**	**	**	**	**	**		**	**	**
season			**	**	**	**			**	**	**	**	**	**	**	**	**		**
A [-30; -25]	142	5.27	0.02	0.95	1.51	9.35	0.01	4.00	0.13	0.29	0.25	1.02	0.66	3.61	0.13	2.49	0.46	0.05	0.01
C [-30; -25]	142	5.18	0.04	1.22	16.69	3.28	0.01	5.38	0.37	0.57	0.87	3.90	1.28	1.50	0.19	3.38	4.96	1.11	0.02
treatment					**	**		**				*	**	*	~	*	*	*	~
year			**	**	**	**	**	**	**	**	**	**	**	**	**		**	**	**
season				**	**	**	**	**		**		**	*	**			**		**
A [-50; -45]	135	6.00	0.08	1.00	1.19	17.03	0.01	6.41	0.19	1.66	0.17	4.85	1.29	0.86	0.17	4.04	0.53	0.13	0.00
C [-50; -45]	129	6.00	0.04	1.34	12.72	4.31	0.00	7.10	0.11	1.67	0.04	3.42	1.48	1.16	0.34	5.12	3.87	0.80	0.00
treatment				~	*	**									~		*	~	
year			**	**			**	**	**	**	*	*	**	**	**	**	**	**	*
season			**	~	**	**	**	**	*	**	**	**	**	**	**	**	**		**
Final period [2014-2016]																			
A [-15; -10]	122	6.15	0.01	0.40	0.54	2.57	0.06	3.25	0.03	0.76	0.21	0.95	0.46	1.10	0.04	8.83	0.44	0.28	0.00
C [-15; -10]	124	5.13	0.01	0.61	5.25	2.71	0.05	3.95	0.11	0.25	0.32	1.92	0.64	0.76	0.04	6.08	1.37	0.19	0.01
treatment									~	~			~						**
year				**	**	~	**	**	**	**	**	**	~	**		**	**	**	
season				**	**	**		**		**	**	**		**	**	**	**	~	**
A [-30; -25]	126	5.45	0.01	0.80	0.57	4.40	0.02	3.27	0.06	0.23	0.07	0.54	0.51	1.72	0.03	2.53	0.19	0.04	0.00
C [-30; -25]	126	5.26	0.02	0.66	4.72	4.05	0.03	4.93	0.14	0.25	0.21	1.89	0.75	0.82	0.03	3.33	1.08	0.07	0.01
treatment					~		~	**				*	**	~		**	~		~
year			**		**	**	**	**	**	**	**	**	**	**		**	**	**	
season			**	**	**	**	**	**	**	**	**	**		**		**	**		**
A [-50; -45]	121	6.16	0.04	0.51	0.17	13.11	0.03	6.15	0.07	1.11	0.06	2.92	1.00	0.86	0.06	3.26	0.18	0.09	0.00
C [-50; -45]	123	6.14	0.03	0.76	4.45	5.26	0.03	7.51	0.06	0.85	0.04	1.82	1.11	0.84	0.06	3.66	1.06	0.06	0.00
treatment						**		~				~						*	
year			**	~	*	**	**	**	**	**	**	**	**	**			**	**	
season			**	*	**	**	**	**	**	**	**	**		*	**	**	**		**

Table 7

CLERMONT en ARGONNE (A and TA treatments)

Class of depth (cm)	observations	pH	F	Cl	NO3	SO4	Fe	Si	Mn	Mg	Al	Ca	Na	K	N-NH4	TC	TN	N org	H
											ppm								
Initial period [2009-2010]																			
A [-15; -10]	49	4.94	0.02	1.42	2.07	19.58	0.01	5.62	0.24	0.42	0.49	2.00	0.89	8.04	0.16	7.71	0.84	0.25	0.02
TA [-15; -10]	49	4.98	0.02	3.94	0.79	8.00	0.01	3.97	0.15	0.64	0.32	2.35	1.07	1.07	0.16	5.62	0.46	0.14	0.02
treatment				**		~		~		**			**	**					
year			**	**	**	**	**	**		**	**	**	**	**	**	**	*	**	**
season				**	*	**			*0.10*	**		*		**		*	*		
A [-25; -30]	34	4.67	0.07	2.25	1.07	27.50	0.01	5.07	0.48	0.59	0.92	2.81	0.96	7.49	0.16	3.54	0.43	0.04	0.03
TA [-25; -30]	34	4.94	0.04	1.92	2.84	13.95	0.01	5.16	0.31	0.63	0.41	2.46	1.02	2.46	0.17	4.47	0.80	0.05	0.02
treatment						**				*	*			**		~			**
year				**	~			**	**	**	**	**		**	**	**	*	**	**
season						**								**					
A [-45; -50]	28	6.00	0.15	2.83	2.62	19.44	0.01	8.65	0.26	1.73	0.24	5.15	1.51	0.89	0.16	5.96	0.89	0.19	0.00
TA [-45; -50]	28	6.18	0.09	1.77	5.09	7.20	0.00	7.32	0.13	0.93	0.02	2.61	1.27	0.33	0.12	2.79	1.16	0.03	0.00
treatment							~	*		*			~						
year			*	**	*	**		**		**	**	**	*		**				
season											*								
Intermediate period [2011-2013]																			
A [-15; -10]	125	5.88	0.01	0.57	0.71	5.23	0.03	4.10	0.06	0.43	0.24	0.88	0.55	3.43	0.17	8.86	0.67	0.34	0.00
TA [-15; -10]	123	5.74	0.01	1.43	2.01	3.85	0.02	4.39	0.08	0.82	0.26	1.46	0.82	1.04	0.21	6.87	0.84	0.24	0.00
treatment				**								**	**	**					
year			**	**	**	**	**	**	**	**			**	**	**		**		**
season			**	**	**	**	**	*	**	**	**	**	**	**	**	**	**		**
A [-25; -30]	142	5.27	0.02	0.95	1.51	9.35	0.01	4.00	0.13	0.29	0.25	1.02	0.66	3.61	0.13	2.49	0.46	0.05	0.01
TA [-25; -30]	134	5.20	0.02	1.65	3.50	8.62	0.01	4.41	0.15	0.68	0.35	1.87	0.92	2.20	0.11	2.69	0.95	0.10	0.01
treatment				**						*			**	~				*	
year			**	**	**	**	**	**	**	**	**	*	**	**	**	~	**	**	**
season			**	**	**	**	**	**	*	**	**	**	**	~	**	**	**	~	**
A [-45; -50]	135	6.00	0.08	1.00	1.19	17.03	0.01	6.41	0.19	1.66	0.17	4.85	1.29	0.86	0.17	4.04	0.53	0.13	0.00
TA [-45; -50]	137	6.23	0.08	1.64	1.76	10.07	0.00	6.20	0.14	1.06	0.03	2.86	1.64	0.37	0.15	3.26	0.59	0.09	0.00
treatment				*		**				**		**	~						
year			**	**	**		**	**	**	**	**	**	**	**	**	**	~	**	*
season				~	**	**	**	**	**	**	**	**	*	**	**	**	**		**
Final period [2014-2016]																			
A [-15; -10]	122	6.15	0.01	0.40	0.54	2.57	0.06	3.25	0.03	0.76	0.21	0.95	0.46	1.10	0.04	8.83	0.44	0.28	0.00
TA [-15; -10]	121	5.90	0.01	1.16	0.76	2.49	0.94	4.03	0.05	0.81	0.27	1.11	0.64	0.43	0.03	8.28	0.45	0.25	0.00
treatment				**					*				**	**					
year			**	**	**	**	**	**	**	**	**	**	**	**		**	**	**	**
season			*		**	*	**	**	**	**	**	**	**	**	~	**	**	**	**
A [-25; -30]	126	5.45	0.01	0.80	0.57	4.40	0.02	3.27	0.06	0.23	0.07	0.54	0.51	1.72	0.03	2.53	0.19	0.04	0.00
TA [-25; -30]	126	5.56	0.01	1.11	1.13	5.22	1.73	3.89	0.08	0.54	0.11	1.16	0.61	0.91	0.03	3.04	0.32	0.06	0.00
treatment			**			~			*	**		**	**	*					
year			**	**	**	**	**	**	**	**	**	**	**	**		**	**	**	**
season			*		**	**	**	**	**	**	**	**	**	**	~	**	**	*	**
A [-45; -50]	121	6.16	0.04	0.51	0.17	13.11	0.03	6.15	0.07	1.11	0.06	2.92	1.00	0.86	0.06	3.26	0.18	0.09	0.00
TA [-45; -50]	125	6.07	0.08	1.42	0.53	10.28	0.03	6.19	0.12	0.90	0.07	2.51	1.26	0.33	0.05	2.87	0.21	0.06	0.00
treatment			*	**					~				~					*	
year			**	**	**	**	**	**	**	**	**	**	**	**		*	**	**	
season			**		**	**	**	**	**	**	**	**	**	**	**	**	**		

Table 8

CLERMONT en ARGONNE (TA and T treatments)

Class of depth (cm)	observations	pH	F	Cl	NO3	SO4	Fe	Si	Mn	Mg	Al	Ca	Na	K	N-NH4	TC	TN	N org	H
											ppm								
Initial period [2009-2010]																			
TA [-15; -10]	49	4.98	0.02	3.94	0.79	8.00	0.01	3.97	0.15	0.64	0.32	2.35	1.07	1.07	0.16	5.62	0.46	0.14	0.02
T [-15; -10]	90	5.26	0.02	1.29	0.73	4.48	0.01	4.09	0.23	0.21	0.19	0.99	0.87	0.32	0.15	6.61	0.59	0.28	0.01
treatment				**		*				**	**	**		**					
year																			
season			**	**	**	**	**	**	~			**	**	**	**	**	*	**	**
TA [-30; -25]	34	4.94	0.04	1.92	2.84	13.95	0.01	5.16	0.31	0.63	0.41	2.46	1.02	2.46	0.17	4.47	0.80	0.05	0.02
T [-30; -25]	75	5.40	0.05	1.01	2.07	7.86	0.01	4.58	0.84	0.40	0.19	1.51	0.95	0.37	0.13	5.54	0.82	0.25	0.01
treatment					**	**				**		~		**	*		~		
year																			
season			**			**		**	**	**	**	**	**	**	**			~	**
TA [-50; -45]	28	6.18	0.09	1.77	5.09	7.20	0.00	7.32	0.13	0.93	0.02	2.61	1.27	0.33	0.12	2.79	1.16	0.03	0.00
T [-50; -45]	57	6.48	0.02	2.29	2.39	4.13	0.00	7.69	0.03	0.81	0.01	1.67	1.60	0.40	0.18	7.16	1.08	0.39	0.00
treatment																			
year																			
season																			
Intermediate period [2011-2013]																			
TA [-15; -10]	123	5.74	0.01	1.43	2.01	3.85	0.02	4.39	0.08	0.82	0.26	1.46	0.82	1.04	0.21	6.87	0.84	0.24	0.00
T [-15; -10]	109	5.37	0.01	1.71	1.38	3.62	0.02	3.72	0.11	0.21	0.31	1.24	1.18	0.25	0.13	5.35	0.64	0.21	0.01
treatment								**		**				**	~				~
year			**	~	**	**	**	**	**	**	**	**	**	**	**		**	**	**
season			**	**	**		**	**	**	**	**	**	**	**	~	**	**		**
TA [-30; -25]	134	5.20	0.02	1.65	3.50	8.62	0.01	4.41	0.15	0.68	0.35	1.87	0.92	2.20	0.11	2.69	0.95	0.10	0.01
T [-30; -25]	131	5.60	0.03	1.83	1.39	5.33	0.01	4.35	0.17	0.32	0.19	1.53	1.47	0.22	0.25	3.74	0.74	0.20	0.00
treatment						**				~			**	**	**	~		~	~
year			**	**	**	**	**	**	**	**		**	**	**	**		**	**	**
season			~	**	**	*	**	**	**	**	**	**	**	**		**	**	~	**
TA [-50; -45]	137	6.23	0.08	1.64	1.76	10.07	0.00	6.20	0.14	1.06	0.03	2.86	1.64	0.37	0.15	3.26	0.59	0.09	0.00
T [-50; -45]	125	6.44	0.02	1.39	0.36	5.52	0.00	6.69	0.03	0.87	0.01	1.78	1.52	0.43	0.20	5.35	0.45	0.18	0.00
treatment			**		~	**			**			**			*	*		~	
year				**	**	**	**	**	**	**	**	**	**		**	**	**	**	**
season				*	**	**	**	**	**	**	**	**		**	**	~	**		**
Final period [2014-2016]																			
TA [-15; -10]		5.90	0.01	1.16	0.76	2.49	0.00	4.03	0.05	0.81	0.27	1.11	0.64	0.43	0.03	8.28	0.45	0.25	0.00
T [-15; -10]	92	5.09	0.01	1.40	3.31	2.84	0.06	4.77	0.12	0.15	0.39	1.12	0.98	0.67	0.03	4.66	0.84	0.12	0.01
treatment								*	~	**			*			~		~	~
year				~	**		~		**	**	**	**				**	**	**	
season			**	**	**	**	~	**	**	**	**	**	**			**	**	*	
TA [-30; -25]		5.56	0.01	1.11	1.13	5.22	0.00	3.89	0.08	0.54	0.11	1.16	0.61	0.91	0.03	3.04	0.32	0.06	0.00
T [-30; -25]	126	5.34	0.02	1.34	1.84	4.27	0.03	4.37	0.12	0.24	0.16	1.29	1.13	0.24	0.03	2.82	0.46	0.06	0.01
treatment						~				**			**	*					
year			**	**	**	**	**	**	**	**	**	**	**	**		**	**	**	~
season			**	**	**	**	**	**	~	**	**	**	**	*		**	**		**
TA [-50; -45]	125	6.07	0.08	1.42	0.53	10.28	0.03	6.19	0.12	0.90	0.07	2.51	1.26	0.33	0.05	2.87	0.21	0.06	0.00
T [-50; -45]	121	6.46	0.02	1.33	0.49	6.01	0.03	7.28	0.03	0.77	0.03	1.64	1.64	0.37	0.05	3.68	0.23	0.08	0.00
treatment			**			**		**	**		**	*	**			**		**	**
year			**	**	**	*	**	*	**	**	**	**	**	**	**		**	**	**
season			**		**	*	**	**	**	**	~	**	~	**	**	**	**	*	**