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## Effect of limited compaction on soil solution chemistry in two acidic forest ecosystems: Changes, recovery and impact of liming

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1 **Effect of limited compaction on soil solution chemistry in two acidic forest ecosystems:**  
2 **changes, recovery and impact of liming**

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7

8 **Abstract**

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

30

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

## 32 **1 Introduction**

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

38 Compaction increases soil bulk density, decreases soil macro-porosity (Herbauts, 1996; Page-  
39 Dumroese et al., 2006) and increases the frequency of hypoxic or anoxic events in the soil  
40 (Stepniewski et al., 1994). Compaction influences the habitat of biological actors that  
41 mineralise organic matter (Van der Linden et al., 1989), thus reducing their populations  
42 (Battigelli et al., 2004) and activity (Jensen et al., 1996; Lee et al., 2008; Tan et al., 2008).  
43 Consequently, compaction changes trends in the soil's physical, chemical, physico-chemical  
44 and biological functioning, which alters all cycles, such as those of water (Horton et al.,  
45 1994), carbon (C) and nitrogen (N) (Brevik et al., 2002; Silveira et al., 2010; Van der Linden  
46 et al., 1989), pH and cations (Saeedifar and Asgari, 2014). The quality of native and/or  
47 allochthonous organic matter can change (De Neve and Hofman, 2000). All the soil functions,  
48 such as those related to production, biodiversity and the environment could then be altered.  
49 The growth of young forest plants could decrease due to an increase in soil physical resistance  
50 (von Wilpert, and Schäffer, 2006) and via the physiological effects of changes in gas diffusion  
51 in soils, which could result in ethylene accumulation in roots and hormonal responses that  
52 restrict growth (Pandey et al., 2021). Climate conditions (Smith, 1977), soil type (Dick et al.,  
53 1988) and soil mineralogy (Silva et al., 2011) influence the impact of compaction, but  
54 sensitive fine-textured soils are influenced most when they are compacted under wet  
55 conditions (Pischedda et al., 2009).

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

61 A review of the literature shows that the field of agriculture is the main source of knowledge  
62 about the degradation and restoration of soils after compaction. The studies frequently focus  
63 on the soil solid phase, often using *ex situ* approaches and/or short-term experiments (De  
64 Neve and Hoffman, 2000; Lee et al., 2008; Silva et al., 2011). Information on the medium- to

65 long-term dynamics of soil restoration is rare and, to our knowledge, no study has used soil  
66 solutions as an indicator of forest soil degradation-restoration following compaction.  
67 However, soil solutions are known to be much more reactive than the solid phase (Zabowski  
68 and Ugolini, 1990; Ranger et al., 2001) and highly sensitive to changes in the ecosystem  
69 (Wolt, 1994). Absolute concentrations of elements in solutions and their ratios provide  
70 relevant information on forest soil geochemistry and its changes due to environmental  
71 conditions (Sverdrup et al., 1992) or forest practices (Cronan and Grigal, 1995), as well as  
72 consequences on soil fertility. The soil solution is also the compartment from which  
73 vegetation takes up most nutrients, and it is considered one of the most important indicators of  
74 nutrient bio-availability (Wolt, 1994; Arocena, 2000; Smethurst, 2000).

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

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

## 93 **2 Materials and methods**

94 We studied two experimental sites set up in north-eastern France: AZ (54) (48° 30' 1.10" N,  
95 6° 42' 6.89" E), in the "Hauts Bois" estate forest, and the CA (55) (49° 8' 27.59" N, 5° 1' 9.58"  
96 E), in the "Grand Pays" estate forest. As these long-term monitored experimental sites have

97 been described in previous articles (Goutal et al., 2013, Bonnaud et al., 2019), we present  
98 only general information and/or information specific to soil solutions here.

## 99 2.1 Study sites

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

107 Both sites were clear-cut over a 6 ha area. Logs were removed using a cable-harvesting  
108 system, and in order to minimize the soil disturbance, all slash was removed manually or  
109 using a very low ground pressure machine dedicated to the transport in forest (Ironhorse,  
110 Lennartsfors). Each site was divided into three blocks delineated after low-resolution soil  
111 mapping. Each treatment was randomly distributed on a 50 × 50 m plot in each block. AZ had  
112 four treatments: control (C), trafficked (T), de-compacted by disking (D) and local de-  
113 compaction at planting points (P) (Fig. 1). Because its soil was more acidic, two amended  
114 treatments were added at CA: control amended (A) and trafficked amended (TA). Liming was  
115 applied at CA in September 2008: 2 t ha<sup>-1</sup> of dolomite enriched in magnesian quicklime (36%  
116 CaO, 24% MgO) and 600 kg ha<sup>-1</sup> of potassium sulphate (50% K<sub>2</sub>O, 17% S), corresponding to  
117 500 kg ha<sup>-1</sup> of Ca, 290 kg ha<sup>-1</sup> of Mg, 250 kg ha<sup>-1</sup> of K and 100 kg ha<sup>-1</sup> of S.

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

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

## 130 2.2 Soil properties

### 131 2.2.1 Initial characterisation

132 Before setting up the experimental designs, soil pits were opened and forest floors and soils  
133 were described. Forest floor was classified as a mesomull (Baize and Girard, 1998) at AZ and  
134 was more acidic at CA, ranging from dysmull to eumoder types (Baize and Girard, 1998).  
135 Soils at both sites are classified as Luvisol (Ruptic) according to the IUSS (2014) and are  
136 polygenic, *i.e.* developed from two geologic materials: a continental silt loam layer ca. 50 cm  
137 thick that lies on clayey material. At AZ, the fluvial loamy Quaternary layer lies on weathered  
138 marls of the Keuper; at CA, the loamy Quaternary material lies on weathered gaise of the  
139 Cenomanian. This strong textural discontinuity caused a limited localised and temporary  
140 water logging, but did not lead to result in hydromorphic soils. Hydromorphic features were  
141 limited at both sites to the very lowest section of the silty layer, at the contact interface with  
142 the clay- rich layer. Consequently, these soils are considered highly sensitive to compaction.  
143 The soil sampling, preparation and analysis are described in detail in previous studies (Goutal  
144 et al, 2013 and Bedel et al, 2018) and only a summarized description is given here. Selected  
145 soil parameters were measured in samples taken from the pits. Bulk density was measured  
146 using 250 cm<sup>3</sup> steel cylinders in two replicates collected every 10 cm from all pits. Soil  
147 samples were also collected at consistent depths (0-10, 10-20, 20-30, 30-45, 45-60, 60-75, 75-  
148 90 and 90-110 cm). After air drying, samples were sieved to separate coarse material from  
149 fine earth (< 2 mm) and the following soil determinations were performed: soil moisture  
150 (105°C), particle size distribution, pH<sub>water</sub> and pH<sub>KCl</sub> (1M), cation exchange capacity  
151 (CEC) and exchangeable cations (colbaltihexamine chloride method), total soil organic C  
152 (Corg) and N (Norg), total Al-Fe-Mg-Ca-K-Na-Mn (HF digestion), Fe-oxides (Mehra and  
153 Jackson, 1960) and soil clay mineralogy (only for the central pit at each site). Initial soil  
154 properties are presented in table 1.

### 155 2.2.2 Initial similarities and differences between sites

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

159 Even though the sites have the same soil type, they have significant differences in physical,  
160 chemical and mineralogical properties (Bedel et al., 2016, Bedel et al., 2018). The clay  
161 content in the upper and lower layers is lower at CA (13-15% and 33-34%, respectively) than  
162 in those at AZ (22-24% and 45-60%, respectively) (Table 1). At AZ, the clay mineralogy is

163 nearly pure illite in the deep soil layer and a complex admixture of illite, kaolinite, chlorite  
164 and vermiculite associated with interstratified and intergrade minerals in the upper soil layers.  
165 At CA, the clays in the deep clayey layer consist of an admixture of kaolinite, illite and a  
166 swelling clay from the Fe-beidellite group. The same spectrum is found in the upper soil  
167 layers, with the swelling Fe-beidellite clay present in both pure and interstratified phases,  
168 albeit in lower amounts (Bedel et al., 2018).  
169 Moreover, even if the soil geochemical context indicated acidic soils at both sites (Bedel et  
170 al., 2016; Bonnaud et al., 2019), differences in chemical properties should be noticed. At CA,  
171  $\text{pH}_{\text{water}}$  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  
172 deep clayey horizons (below 60 cm). At AZ, the upper organic horizon had a significantly  
173 higher pH of ca. 4.8, which decreased to 4.6 in the loamy horizons, then increased to 5.0 in  
174 the deep clayey horizons (Table 1). Corg content was the same in the 0-10 cm layer at the two  
175 sites, but in the horizons below it, that at CA was ca. half that at AZ. Norg was lower at CA  
176 than at AZ. The C:N ratio was higher at CA than at AZ. CEC ranged from 3.5-4.0 at the  
177 surface to 16-18  $\text{cmol}^+ \text{kg}^{-1}$  at depth at CA and from 4.0-4.5 at the surface to 12-15  $\text{cmol}^+ \text{kg}^{-1}$   
178 at depth at AZ. The “base” cation saturation rate was nearly twice as high at AZ as at CA for  
179 the same depths in upper layers (63% vs. 29%, respectively, at 0-10 cm; 24-30% vs. 12-15%,  
180 respectively, at 10-45 cm), but more similar at both sites in lower layers (50-70% at AZ vs.  
181 45-60% at CA).

### 182 **2.2.3 Monitoring**

183 Changes and recovery in soil physical properties were presented in previous studies (Goutal et  
184 al., 2013, Pousse et al, 2021) and only relevant information in the context of our study are  
185 summarized hereafter: i) compaction strongly influenced soil bulk density (Goutal et al.,  
186 2013), macroporosity (Bonnaud et al., 2019) and physical resistance (Pousse et al., 2021) at  
187 both sites; ii) recovery was slow and limited to the upper soil layers (Goutal et al., 2013;  
188 Pousse et al, 2021); iii) the liming increased the recovery of physical resistance to undisturbed  
189 levels over the study period (Pousse et al., 2021).

190 Changes in soil chemical properties were also monitored: two soil profiles per treatment (C  
191 and T at AZ and CA, and A and TA at CA) were sampled and analysed in 2012 at AZ and in  
192 2014 at CA, using the depths and methods previously described (see section 2.2.1).

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

### 195 **2.3 Meso- and pedo-climates**

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

### 206 **2.4 Soil solutions**

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

216 The chemistry of individual solution samples was measured as soon as possible, from  
217 solutions filtered through 0.45 µm Metriciel® acetate membrane filters. Samples were  
218 analysed for pH (Mettler DL 70 ES Titrator), and anions (Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, H<sub>2</sub>PO<sub>4</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, F<sup>-</sup>)  
219 were measured by ion chromatography (Dionex ICS2100). NH<sub>4</sub><sup>+</sup> was determined by  
220 molecular absorption spectrometry (Skalar San++ System), and total Si, Al, Fe, Mg, Ca, K,  
221 Na, P and S were measured by ICP-AES (Agilent Technologies 700 series). Lastly, a  
222 Shimadzu apparatus was used to measure total dissolved Corg and Norg.

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



227 two years, when solution chemistry seemed to have stabilised, and an intermediate period of  
228 three years between the two.

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

## 235 2.5 Statistics

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

$$Y = \mu + \sum_j \mathbf{Fef}^{(j)} + Ref + \varepsilon \quad (1)$$

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

246 For the solid phase, one ANOVA was performed per depth class (5 levels: every 10 cm from  
247 0-40 cm) at CA to test the significance of the unique factor  $\mathbf{Fef}^{(1)} = Treatment$  (4 levels:  
248 C, T, A and TA) on a total of 12 *Y* variables. *Ref* is designated by a factor that combines the  
249 information of *Block* and *Treatment* factors (12 levels: 3 blocks  $\times$  4 treatments). When  
250  $\mathbf{Fef}^{(1)}$  was declared significant ( $p \leq 0.05$ ), a Tukey's multiple comparison of means  
251 (Hothorn et al. 2008, Bretz et al. 2011) was applied to model (1) to identify for which pair of  
252 treatments the *Y* variable distribution was significantly different.

253 For the liquid phase, one ANOVA was performed for the combination of depth class (3  
254 levels: 10-15, 25-30 and 45-50 cm), year class (3 levels: 2009-2010, 2011-2013 and 2015-  
255 2016) and pair of treatments (C vs. T, A vs. C, A vs. TA and T vs. TA) at each site to test the  
256 significance of a set of fixed effects  $\sum_{j=1,2} \mathbf{Fef}^{(j)}$  (described below) on a total of 19 *Y*  
257 variables

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

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

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

## 269 **3 Results**

### 270 **3.1 Impact of soil compaction on chemical soil solid-phase properties**

271 Compaction did not influence soil chemistry significantly, regardless of the depth or treatment  
 272 considered (C vs. T at AZ; C vs. T and A vs. TA at CA) (data not shown for AZ; data for CA  
 273 in 2014 shown in Table 2). Liming at CA had a positive impact in 2014, but only in the upper  
 274 20 cm of soil: pH<sub>KCl</sub>; exchangeable Ca, Mg, H and Al; “base cation” saturation and effective  
 275 CEC increased significantly in the 0-10 cm layer in A compared to C, while pH<sub>water</sub> and  
 276 exchangeable Mg and K increased significantly in the 0-20 cm layer. Comparison of T and  
 277 TA indicates that the main differences were due to liming (Table 2).

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

### 285 **3.2 Impact of soil compaction on soil solution chemistry at Azerailles**

#### 286 **3.2.1 Behaviour of the control**

287 At AZ, in treatment C, the ionic strength of the soil solution (IS) increased as soil depth  
288 increased, and the relative contribution of anions to IS was generally as follows:  $\text{SO}_4^{2-}$  (35-  
289 70%) >  $\text{Cl}^-$  (20-45%) >  $\text{NO}_3^-$  (2-30%) (Table 3). The anion composition in C was dominated  
290 mainly by  $\text{SO}_4^{2-}$  (1.5-6.5  $\text{mg.L}^{-1}$ ), followed by  $\text{Cl}^-$  (1-3.5  $\text{mg.L}^{-1}$ ) and  $\text{NO}_3^-$  (0.2-2.0  $\text{mg.L}^{-1}$ ),  
291 regardless of the layer or the time scale (Table 4). For the cations, their relative contribution  
292 to IS in C were as follows:  $\text{Ca}^{2+} \gg \text{Mg}^{2+} \gg \text{K}^+ = \text{Al}^{3+} = \text{NH}_4^+$  for all layers and dates. Ca  
293 remained constant with depth, Mg increased with depth, while Al and K decreased at 50 cm  
294 regardless of the period (Table 4). For each layer observed, changes over time were limited in  
295 C (Table 4).

### 296 3.2.2 *Effect of soil compaction*

297 Compaction increased in IS regardless of the soil layer or period, from 145  $\mu\text{eq.L}^{-1}$  in C to  
298 245  $\mu\text{eq.L}^{-1}$  in treatment T (Table 3, general mean). The relative contribution of anions to IS  
299 also changed after compaction, especially during the initial period: while  $\text{SO}_4^{2-}$  generally  
300 remained dominant, followed by  $\text{Cl}^-$ , in T,  $\text{NO}_3^-$  became dominant during the initial period (at  
301 30 and 50 cm depths) and co-dominant during the final period (at 15 and 30 cm depths)  
302 (Table 4) (Figures 2, 3 and 4 for  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$  and DOC, respectively). The increase in IS in T  
303 did not change the relative contribution of cations during the initial period: IS doubled, but  
304 only K changed significantly (+10% at 15 cm depth) (Mn increased by 36% at 30 cm depth,  
305 but not significantly so). IS increased moderately (10-30%) during the intermediate period  
306 and even more (20-80%) during the final period, with the largest increase for K at 15 cm  
307 depth (10% and 14% for the intermediate and final periods, respectively). Changes over time  
308 were greater in T than in C, especially in the medium and deep layers, where flushes of anions  
309 and cations were observed (Table 3, Figures 2 to 4, Supplementary material 1 and 2) in T,  
310 while they were not clearly evident in the upper soil layer, probably due to the delay between  
311 the treatment (2007) and when monitoring of soil solutions began (2009).

312 Compaction influenced the soil solution composition strongly, especially in the upper soil  
313 layers (Table 4). In the upper soil layer during the initial period, the concentrations of 11 of  
314 the 19 elements studied changed significantly, while fewer elements changed in the 30 and 50  
315 cm depths; however, nitrate concentrations were high (> 10  $\text{mg.L}^{-1}$ ) in T at these depths.  
316 During the intermediate period, soil solution concentrations continued to be influenced  
317 significantly, especially at 15 and 30 cm depths, except for nitrate, which decreased strongly  
318 and thus differed little between C and T. During the final period, soil solution chemistry was  
319 always influenced strongly in the upper soil layer (significant changes for 10 elements,

320 usually the same ones as in the initial period). Impact decreased with depth, but seven  
321 elements differed significantly in T compared to C at 30 cm depth. At 50 cm, Cl and K,  
322 followed by Si and Mg (10% confidence), remained significantly influenced. Besides the  
323 compaction effect, year and season effects were strongly significant regardless of the soil  
324 layer or period.

### 325 **3.3 Impact of soil compaction on soil solution chemistry at Clermont-en-Argonne**

#### 326 **3.3.1 Behaviour of the control**

327 At CA, in C, the IS did not vary greatly with soil depth, except during the initial period at 15  
328 cm (Table 3). However, IS changed over periods, being higher during the initial and final  
329 periods (usually  $> 400 \mu\text{eq.L}^{-1}$ ) than during the intermediate period (ca.  $200 \mu\text{eq.L}^{-1}$ ). The  
330 relative contribution of anions to IS in C was generally as follows:  $\text{NO}_3^-$  (40-70%)  $>$   $\text{SO}_4^{2-}$   
331 (25-50%)  $>$   $\text{Cl}^-$  (8-20%). The concentration of  $\text{NO}_3^-$  was much higher than that of  $\text{SO}_4^{2-}$  in C,  
332 especially in the intermediate period (13-17 vs. 3-4  $\text{mg.L}^{-1}$ , respectively), but less so during  
333 the final period, especially in the deep layer (4-5 vs. 2-45  $\text{mg.L}^{-1}$ , respectively).

#### 334 **3.3.2 Effect of soil compaction**

335 Compaction significantly decreased the IS regardless of the soil layer or period, from 344  
336  $\mu\text{eq.L}^{-1}$  in C to 183  $\mu\text{eq.L}^{-1}$  in T (Table 3, general mean). For all depths, the decrease was 40-  
337 65% during the initial and intermediate periods, but only ca. 10-25% during the final period.  
338 The relative contribution of anions to IS also changed after compaction:  $\text{SO}_4^{2-}$  (30-70%)  $>$   $\text{Cl}^-$   
339 (10-30%)  $>$   $\text{NO}_3^-$  (5-40%) (Table 3). The concentrations of anions in the soil solution changed  
340 drastically:  $\text{NO}_3^-$  decreased strongly (*i.e.* -81%, -93% and -61% as the mean of all layers,  
341 during the initial, intermediate and final periods, respectively), while  $\text{SO}_4^{2-}$  tended to increase  
342 regardless of the period or soil layer (*i.e.* +14%, +36% and +9% as the mean of all layers  
343 during the initial, intermediate and final periods, respectively).  $\text{Cl}^-$  decreased in the initial  
344 period (-33%) but increased during the intermediate (+35%) and final (+101%) periods (Table  
345 5 and Figures 5, 6 and 7 for  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$  and DOC, respectively) Compaction had much less  
346 influence on cations, whose mean relative contribution to the IS ( $\text{Ca} \gg \text{Mg} \geq \text{Al} > \text{K}$ ) did not  
347 change (data not shown). Nevertheless, for all depths and periods, mean absolute  
348 concentrations of Ca, Mg and K decreased by ca. 30%, 47% and 74%, respectively (Table 5  
349 and Supplementary material 3, 4, 5, 6 for Ca, Mg, K and Al, respectively).

350 Compaction influenced mainly the solutions in the upper soil layers during the initial and  
351 intermediate periods, when the concentrations of 7-12 elements changed (Table 4). Only three

352 elements differed significantly between C and T during the final period: Cl, Na (decreased in  
353 all layers) and Si (increased at 15 cm but decreased at 25 and 45 cm). The year and season  
354 effects remained significant for most elements (12-15 elements of the 19 studied).

### 355 **3.3.3 Effect of liming without soil compaction**

356 Liming increased the IS of soil solutions collected from all soil depths by 35-80% compared  
357 to those in C during the initial period (from a mean of 380 to ca. 600  $\mu\text{eq.L}^{-1}$ ), but it decreased  
358 IS for all depths during the intermediate and final periods (from a mean of 330 to 145  
359  $\mu\text{eq.L}^{-1}$ ), except in the deepest layer, where no or few changes were observed. Liming also  
360 changed the relative percentages of  $\text{NO}_3^-$  and  $\text{SO}_4^{2-}$  drastically compared those in C:  $\text{NO}_3^-$   
361 decreased strongly to contribute 1-16% to the IS for all layers and periods, while  $\text{SO}_4^{2-}$   
362 became dominant (contribution of ca. 80% to the IS for all layers and periods);  $\text{Cl}^-$  changed  
363 much less and did so mainly during the initial period (Table 3). Nitrate concentrations  
364 decreased from extreme values of 4-17  $\text{mg.L}^{-1}$  in C to 0.2-3.0  $\text{mg.L}^{-1}$  in A throughout the  
365 entire observation period. Conversely,  $\text{SO}_4^{2-}$  concentrations increased from 4  $\text{mg.L}^{-1}$  in C to  
366 20-30  $\text{mg.L}^{-1}$  in A during the initial period. Differences were smaller during the intermediate  
367 and final periods, except in the deepest layer.

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

### 376 **3.3.4 Effects of liming and soil compaction**

377 Compared to T, TA increased IS in all layers during the initial and intermediate periods (from  
378 a mean of 190 to ca. 300  $\mu\text{eq.L}^{-1}$ ) and in the deep layer during the final period (+54%), while  
379 it decreased IS in the upper layer during the final period (-42%). The mean relative  
380 contribution of anions to the IS changed little between these treatments and was as follows:  
381  $\text{SO}_4^{2-} \gg \text{Cl}^- > \text{NO}_3^-$  in all soil layers during all periods, except during the initial (at 15 and 25  
382 cm) and intermediate periods, when  $\text{NO}_3^-$  tended to be higher than  $\text{Cl}^-$ . Compared to T, TA  
383 changed the mean cation distribution, which was as follows:  $\text{Ca} \geq \text{Mg} \geq \text{Al} = \text{K}$ , except at 50  
384 cm, where  $\text{Mg} \gg \text{Al}$  (Table 3). Mg increased in the upper and medium layers in TA during

385 the intermediate and final periods, while Ca and K increased for all dates in the deep and  
386 upper layers, respectively (Table 7). TA and T differed mainly due to the elements contained  
387 in the product applied (*i.e.*  $\text{SO}_4^{2-}$ , Mg, Ca and K), and those resulting from the liming effect  
388 (*i.e.*  $\text{NO}_3^-$ , Al, TN). Eight years after liming, the interaction of liming with compaction  
389 remained significant in all layers, especially at 50 cm depth for F<sup>-</sup>,  $\text{SO}_4^{2-}$ , Si, Mn, Al, Ca, Na,  
390 DOC, Norg and H<sup>+</sup>.

## 391 **4 Discussion**

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

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

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

### 407 **4.1 Drastic changes in the first years following disturbances**

#### 408 **4.1.1 Impact of clear-cutting and planting**

409 At AZ, the impact of clear-cutting in C appeared to be relatively weak and limited to certain  
410 elements, due in part to the delay of ca. 2.5 years between clear-cutting and the first  
411 observations of soil solutions. Nitrate contents were extremely low, and no signal, even  
412 delayed, was observed in the deeper soil layers. These observations may have be due to the  
413 relatively low soil damage during the stand tree harvesting (Nykvist et al., 1994; Ranger et al.  
414 2007), to the entire tree-harvesting process, including litter raking on reactive soils (McColl,  
415 1978), or to the system's ability to immobilise all nitrate production (Stark and Hart, 1997).  
416 Ten years after clear-cutting, the impact of harvest, planting and new stand development

417 seems to stabilise, again without any signal in  $\text{NO}_3^-$  concentration in soil solutions. Soil  
418 reactivity and development of dense understorey vegetation could facilitate nitrate  
419 immobilisation in the ecosystem (Katzensteiner, 2003).

420 At CA, where the delay was only ca. two years between clear-cutting and the first observation  
421 of soil solutions, clear-cutting in C had a stronger effect than at AZ, which influenced DOC,  
422 as well as major anions and cations (except in the upper soil layer). Nitrate increased after  
423 clear-cutting, even when cable harvesting of logs limited the disturbance to the forest floor.  
424 The silvicultural practices related to harvest and planting were very similar between sites,  
425 which suggests that the less fertile soil cannot immobilise  $\text{NO}_3^-$ , as reported in many other  
426 studies (Brown et al., 1973; Hart et al., 1981; Dahlgren and Driscoll, 1994; Jerabkova et al.,  
427 2011). A large delayed increase in  $\text{NO}_3^-$  in soil solutions was also observed in all soil layers in  
428 C five to eight years after the clear-cut, suggesting that the entire biological system (i.e. soil  
429 microbes, understorey vegetation and young stand) cannot immobilise this additional flux,  
430 which could be related to an as-yet-unidentified process of stand development.

#### 431 *4.1.2 Impact of soil compaction*

432 Soil compaction increased concentrations of nearly all elements greatly at the more fertile site  
433 (AZ), but the high spatial variability limits the significance of this result. This initial impact  
434 dominated in the upper soil layer, and DOC and  $\text{NO}_3^-$  were the anions that drove the changes  
435 in cations. Soil compaction is known to influence the rate of organic matter decomposition  
436 and mineralisation in the soil (Kalbitz et al., 2004), and the ability of microorganisms to  
437 immobilise  $\text{NO}_3^-$  seemed to be exceeded at AZ after compaction. At the less fertile site (CA),  
438 compaction resulted in opposite behaviour, which was a quasi-general decrease in the  
439 concentration of nearly all elements, especially  $\text{NO}_3^-$ . Compaction decreased soil porosity  
440 (macroporosity decreased by 70% at AZ and 56% at CA) and increased waterlogging at both  
441 sites (Bonnaud et al., 2019). These changes may have reduced the nitrification rate, decreased  
442 microbial immobilisation and increased the de-nitrification rate (Philippot et al., 2007). The  
443 effect of compaction on these processes and on nitrate concentrations in soil solutions were  
444 thus different between sites.

445 Our results are in accordance with the Norg mineralisation and nitrification rates measured at  
446 the sites using the method of Raison et al. (1987) (Supplementary material 7). They showed  
447 that (i) nitrifying microbes are present and functional at both sites, (ii) the mineralisation rate  
448 was higher at AZ than at CA, but the nitrification rate was higher at CA; (iii) the  
449 mineralisation rate increased after clear-cutting at both sites, but far more at CA; and (iv)

450 compaction increased the mineralisation rate slightly at AZ but decreased it at CA compared  
451 to that in C; the nitrification rate was ca. 60% in both treatments.

## 452 **4.2 Contrasting restoration between sites after compaction**

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

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

474 PCA based on soil solution chemistry (Supplementary material 8 and 9, for AZ and CA  
475 respectively) illustrated satisfactorily the restoration state at the two sites eight years after  
476 compaction according to the centroids of individual observations in the C and T treatments.  
477 These treatments converged for the less fertile soil at CA but not for the more fertile soil at  
478 AZ (Supplementary material 8 and 9). This unexpected result was previously observed at the  
479 same sites using another indicator: the chemistry of the perched water table (Bonnaud et al.,  
480 2019). This confirms the idea that the porosity disturbed in the poorly structured soil at CA  
481 recovers relatively quickly, mainly via physical processes (e.g. desiccation-wetting cycles,  
482 freeze-thaw cycles, root penetration), as no anecic earthworms are present (Bottinelli et al.,



483 2014). At AZ, the same degree of compaction resulted in a relatively larger and longer-lasting  
484 disturbance of the soil that drastically changed the biological system, which remained  
485 disturbed 10 years later. Four years after compaction at AZ, Bottinelli et al. (2014) found that  
486 the habitat quality was not satisfactory for re-colonisation by anecic earthworms. This  
487 situation continued six years after compaction, when colonisation by anecic earthworms was  
488 low and limited to the topsoil at AZ (Capowiez et al., 2015).

### 489 **4.3 Impact of liming at CA**

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

498 In treatment A compared to C, a small but significant amount of Ca was rapidly transferred  
499 into deeper soil layers, which resulted in a rapid and long-lasting (eight years, +60%) increase  
500 in the Ca concentration in solutions at these depths. In the upper soil layers, Ca concentrations  
501 decreased much more rapidly in A than in C, which suggests high Ca efficiency of the soil-  
502 plant system and/or high retention due to a strong affinity for organic matter (Curtin et al.,  
503 1998). Even if Magnesium does not have such affinity for organic matter, it behaved similar  
504 to Ca, except that its concentrations increased in the upper soil layers in the last three years of  
505 observation: it may be due to active uptake and recycling of Mg by the vegetation (Edmeades  
506 and Judd, 1980) combined with its moderate affinity for both organic matter and the mineral  
507 phase. These processes may explain in part why Mg concentration did not increase in the  
508 deeper soil. Ca and Mg were vertically transferred more rapidly in the soil than K and it may  
509 be due to the latter's strong affinity for the soil solid phase. Strong K-adsorption on clay  
510 exchangeable sites (Sawhney, 1970) could have limited its transfer through the soil profile at  
511 30/40 cm, without significant enrichment of the deep soil layer.

512 In this environment, liming immediately accelerated organic matter mineralisation, which  
513 increased DOC and drastically decreased  $\text{NO}_3^-$  concentrations in the soil solutions (from 7-17  
514  $\text{mg NO}_3^- \cdot \text{L}^{-1}$  in C to 0.2-2.0  $\text{mg NO}_3^- \cdot \text{L}^{-1}$  in A). The likely rapid dissolution of K-sulphate  
515 released a large flux of  $\text{SO}_4^{2-}$  that became the main driver of cations transferred in the soil

516 profile, which replaced  $\text{NO}_3^-$ . Many studies showed that nitrification increased after liming  
517 under natural or controlled conditions, regardless of the environment (Nyborg and Hoyt,  
518 1978; Arnold et al., 1994; Zhao et al., 2017), except in raw humus with high C:N ratios, due  
519 to low soil pH (acidity) and harsh climate in Nordic countries (Nömmik, 1979; Derome,  
520 1990). At CA, liming increased the soil pH by ca. 0.5 in the upper soil layer and the pH is  
521 known to regulate the nitrification rate: Nugroho (2006) reported that a low nitrification rate  
522 in acidic soils, despite the presence of nitrifiers, was due to several pH-related factors. At CA,  
523 nitrate concentrations decreased strongly in soil solutions after liming. In reference to  
524 Nugroho et al. (2006), we hypothesise that liming improved overall microbial activity, which  
525 was then able to immobilise most nitrate produced and thus decrease leaching and soil  
526 acidification.

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

#### 535 **4.4 Do the two sites have different biogeochemical functioning?**

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

548 At AZ, the relatively fertile surface soil, with moderately stable aggregation and  $\text{pH} > 4.5$ ,  
549 seems able to immobilise nitrate, even that produced after clear-cutting, as no  $\text{NO}_3^-$  signal  
550 appeared in the soil solution (nevertheless, a rapid flush cannot be excluded). Compaction  
551 drastically and immediately disturbed the soil, in which hydromorphic traits appeared after a  
552 few months (Bonnaud et al., 2019). Understorey vegetation changed from brambles in C to  
553 rushes in T (Goutal et al., 2013). The soil seems to have lost its ability to immobilise nitrate  
554 after compaction, but the activity of nitrifying microbes was not suppressed. Due to the new  
555 pedoclimatic conditions, denitrification may have increased (Philippot et al., 2007), but our  
556 results suggest that it was not sufficient to eliminate all of the  $\text{NO}_3^-$  produced. Interestingly,  
557 the variability in  $\text{NO}_3^-$  concentration among individual lysimeters was large and much higher  
558 than that of all other anions or cations. This could indicate that specific niches exist for  
559 nitrification, and probably for denitrification, as observed by Parkin (1987) for sites rich in  
560 particulate organic matter. Compaction of buried holorganic layers creates patches and  
561 ultimately greater soil heterogeneity. Consequently, residual nitrate-H could migrate  
562 downward in the soil profile, with known consequences on the cation exchange process  
563 (Reuss and Johnson, 1986).

564 At CA, the large amount of  $\text{NO}_3^-$  produced after clear-cutting seems to have exceeded the  
565 ability of the less fertile soil ( $\text{pH} < 4.5$  in the topsoil) and the growing trees and understorey  
566 vegetation to immobilise it. Compaction changed the environment drastically, causing  
567 hydromorphic traits, the collapse of structures in wet conditions and induration when dry (i.e.  
568 hard-setting behaviour (Bedel et al., 2018)), characterized by a rapid increase in soluble  $\text{Fe}^{2+}$   
569 and  $\text{Mn}^{2+}$  in the perched water table (Bonnaud et al., 2019). These changes in soil properties  
570 significantly decreased  $\text{NO}_3^-$  in the soil solution, which may be explained by a decrease in  
571 nitrifying activity and a possible increase in denitrification during rewetting events or periods.  
572 The liming treatment provides valuable information on the impact of nutrient limitations on  
573 organic matter mineralisation and soil solution chemistry. Applied six months after soil  
574 compaction, liming immediately changed the soil solution chemistry due to the release of Ca,  
575 Mg, K and  $\text{SO}_4^-$  from liming products, but also indirectly through interactions with the C and  
576 N cycles. Unlike clear-cutting, which increased  $\text{NO}_3^-$  concentration in the soil solution in C,  
577 liming resulted in a drastic, immediate and long-lasting decrease in  $\text{NO}_3^-$  concentration (by a  
578 factor of 3.5-26.0, depending on the soil layer and time). Liming increased the soil pH by ca.  
579 0.5 in the upper soil layer and increased  $\text{NO}_3^-$  immobilisation in the soil and vegetation. It is  
580 unlikely that liming stops nitrate production in such an environment (Nyborg and Hoyt, 1978;  
581 Formanek and Vranova, 2003; Nugroho et al., 2006). Our results suggest that liming increases

582 microbial biomass and activity, N mineralisation and plant growth factors that sustain a more  
583 conservative N cycle.

584 Considering these facts, it appears that soil pH had a great influence on the observed changes,  
585 and the threshold pH of 4.5 seems to be an important parameter for soil biogeochemical  
586 functioning in the present conditions, as for Al chemical speciation in solutions (Driscoll et  
587 al., 1990). These two ecosystems did not react in an opposite manner, but rather in accordance  
588 with their specific N cycle (and C cycle), which seems strongly influenced by soil pH. At CA,  
589 soil acidity limits the mineralisation rate, which increased strongly after clear-cutting but  
590 could not immobilise all of the nitrate produced. Liming improved this ability. At AZ,  
591 microbes and vegetation immobilised the larger amount of nitrate produced. Compaction  
592 disturbed the two ecosystems deeply by rapidly increasing hydromorphological processes,  
593 modifying both nitrate production and denitrification (Hilton et al., 1994; Philippot et al.,  
594 2007), which decreased nitrate in the solution at CA but increased it at AZ (Figure 8).

## 595 **5 Conclusions**

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

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

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

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## 638 **Literature cited**

- 639 Ampoorter, E., Van Nevel, L., De Vos, B., Hermy, M. & Verheyen, K., 2010. Assessing the  
640 effects of initial soil characteristics, machine mass and traffic intensity on forest soil  
641 compaction. *Forest Ecology and Management*. 260, 1664-1676.
- 642 Arnold, G., van Beusichem, M.L., van Diest, A., 1994. Nitrogen mineralization and H<sup>+</sup>  
643 transfers in a Scots pine (*Pinus sylvestris* L.) forest soil as affected by liming. *Plant and*  
644 *Soil*. 161, 209-218.

645 Arocena, J.M., 2000. Cations in solution from forest soils subjected to forest-floor removal  
646 and compaction treatments. *Forest Ecology and Management*. 133, 71-80.

647 Baize, D., Girard, M.C., 1998. A Sound Reference Base for Soils: The "Référentiel  
648 Pédologique". Translation by Hodgson, J.M., Eskenazi, N.R. and Baize, D. INRA, Paris.

649 Battigelli, J.P., Spence, J.R., Langor, D.W., Berch, S.M., 2004. Short-term impact of forest  
650 soil compaction and organic matter removal on soil mesofauna density and oribatid mite  
651 diversity. *Canadian Journal of Forest Research*. 34, 1136-1149

652 Bedel, L., Poszwa, A., Van Der Heijden G, Legout, A., Aquilina, L., Ranger, J., 2016.  
653 Unexpected calcium sources in deep soil layers in low-fertility forest soils identified by  
654 strontium isotopes (Lorraine plateau, eastern France). *Geoderma*. 264, 103-116.

655 Bedel, L., Legout, A., Poszwa, A., Van Den Heijden, G., Court, M., Goutal-Pousse, N.,  
656 Montarges-Pelletier, E., Bonnaud, P., Ranger, J., 2018. Soil aggregation is a relevant  
657 indicator of soil mineral fertility: the case study of soils in the plateau lorrain. *Annals of*  
658 *Forest Science*. 4, 75-103.

659 Bonnaud, P, Santenoise, P, Tisserand, D., Nourrisson, G, Ranger, J., 2019. Impact of  
660 compaction on two sensitive forest soils in Lorraine (France) assessed by the changes  
661 occurring in the perched water table. *Forest Ecology and Management*. 437, 380-395.

662 Bottinelli, N., Capowiez, Y., Ranger, J., 2014. Slow recovery of earthworm populations after  
663 heavy traffic in two forest soils in Northern France. *Soil Ecology*. 73, 130-133.

664 Brevik, E., Fenton, T., Moran, L., 2002. Effect of soil compaction on organic carbon amounts  
665 and distribution, South Central Iowa. *Environmental Pollution*. 116, 137-141.

666 Bretz, F., Hothorn, T., Westfall, P., 2011. *Multiple Comparisons Using R*. New York:  
667 Chapman and Hall/CRC.

668 Brown, G.W., Galher, A.R., Marston, R.B., 1973. Nutrient losses after clear-cut logging and  
669 slash burning in the Oregon Coast Range. *Water Resources Research*. 9, 5, 1450-1453.

670 Capowiez, Y, Boizard, H., Bottinelli, N., Ranger J., 2015. Capacity of earthworms to  
671 restructure compacted soils. *Colloque Regeneration of compacted forest soils, Osnabrück,*  
672 *(Germany)*. 29 October 2015.

673 Carignan, J., Hild, P., Mevelle, G., Morel, J., Yeghicheyan, D., 2001. Routine analyses of  
674 trace elements in geological samples using flow injection and low pressure on-line liquid  
675 chromatography coupled to ICP-MS: A study of geochemical reference materials BR, DR-  
676 N, UB-N, AN-G and GH. *Geostandards Newsletter*. 25, 2-3, 187-198.

677 Ciesielski, H., Sterckeman, T., Santerne, M., Willery, J.P., 1997. Determination of cation  
678 exchange capacity and exchangeable cations in soils by means of cobalt hexamine  
679 trichloride. Effects of experimental conditions, 17. EDP Sciences, Les Ulis, France.

680 Coddeville, P., Pascaud, A., Sauvage, S., Nicolas, M., Mathias, E., Probst, A., 2016. Changes  
681 in atmospheric emissions, air quality and deposition in rural areas, especially in forests.  
682 Pollution Atmosphérique numéro special, 43-63.

683 Court, M., van der Heijden, G, Didier, S., Nys, C., Richter, C., Pousse, N., Saint-André, L.,  
684 Legout, A., 2018. Long-term effects of forest liming on mineral soil, organic layer and  
685 foliage chemistry: Insights from multiple beech experimental sites in Northern France.  
686 Forest Ecology and Management. 409, 872-889

687 Cronan, C.S., and Grigal, D.F., 1995. Use of calcium/aluminium ratios as indicators of stress  
688 in forest ecosystems. Journal of Environmental Quality. 24, 209-226

689 Curtin, D., Selles, F., Steppuhn, H., 1998. Estimating calcium-magnesium selectivity in  
690 smectitic soils from organic matter and texture. Soil Science Society of America Journal.  
691 62, 5, 1280-1285.

692 Dahlgren, R.A., Driscoll, C.T., 1994. The effects of whole-tree clear-cutting on soil processes  
693 at the Hubbard Brook experimental forest, New Hampshire, USA. Plant and Soil. 158,  
694 239-262.

695 De Neve, S., Hofman, G., 2000. Influence of soil compaction on carbon and nitrogen  
696 mineralisation of soil organic matter and crop residues. Biology and Fertility of Soils. 30,  
697 544-549.

698 Derome, J., 1990 Effects of liming on the nutrient status of podzolic soils in Finland. Water,  
699 Air and Soil Pollution. 54, 337-350.

700 Dick, R.P., Myrold, D.D., Kerle, E.A., 1988. Microbial biomass and soil enzyme activities in  
701 compacted and rehabilitated skid trail soils. Soil Science Society of America Journal. 52,  
702 512-516.

703 Driscoll, C.T., Schecher, W.D., 1990. The chemistry of aluminum in the environment.  
704 Environmental Geochemistry and Health 12.

705 Flores Fernández, J.L., Rubin, L., Hartmann, P., Puhlmann, P., von Wilpert, K., 2019. Initial  
706 recovery of soil structure of a compacted forest soil can be enhanced by technical  
707 treatments and planting. Forest Ecology and Management. 431, 54-62.

708 Formanek, P. and Vranova, V. 2003. A contribution to the effect of liming on forest soils:  
709 review of literature. Journal of Soil Science. 49, 4, 182-190.

710 Goutal, N., Keller, T., Defossez, P., Ranger, J., 2013. Soil compaction due to heavy forest  
711 traffic: measurements and simulations using an analytical soil compaction model. *Annals*  
712 *of Forest Science*. 70, 545-556.

713 Hart, G.E., Debyle, N.V., Hennes, R.W., 1981. Slash treatment after clearcutting Lodgepole  
714 pine affects nutrients in soil water. *Journal of Forestry*. 446-450.

715 Heathman, G.C., Starks, P.J. & Brown, M.A., 2003. Time Domain Reflectometry Field  
716 Calibration in the Little Washita River Experimental Watershed. *Soil Science Society of*  
717 *America Journal*. 67, 52-61.

718 Herbauts, J., El Bayad, J. and W. Gruber, W. 1996. Influence of logging traffic on the  
719 hydromorphic degradation of acid forest soils developed on loessic loam in middle  
720 Belgium. *Forest Ecology and Management*. 87, 193–207.

721 Hilton, B.R., Fixen, P.E., Woodard, H.J., 1994. Effects of tillage, nitrogen placement, and  
722 wheel compaction on denitrification rates in the corn cycle of a corn-oats rotation. *Journal*  
723 *of Plant Nutrition*. 17, 8, 1341-1357.

724 Horton, R., Ankeny, M.D., Allmaras, R.R., 1994. Effect of compaction on soil hydraulic  
725 properties. In Stone B.D. and van Ouwerkerk C. (eds) *Soil compaction and crop*  
726 *production*. Chapter 7, 141-166.

727 Hothorn, T., Bretz, F., Westfall, P., 2008. Simultaneous inference in general parametric  
728 models. *Biom J*. 50, 3, 346-363.

729 Jensen, L.S., McQueen, D.J., Ross, D.J., Tate, K.R., 1996. Effects of soil compaction on N-  
730 mineralisation and microbial-C and -N. II laboratory simulation. *Soil & Tillage Research*.  
731 38, 189-202.

732 Jerabkova, L., Prescott, C.E., Titus, B.D., Hope, G.D., Walters, M.B., 2011. A meta-analysis  
733 of the effects of clear-cut and variable-retention harvesting on soil nitrogen fluxes in boreal  
734 and temperate forests. *Canadian Journal of Forest Research*. 41, 1852-1870.

735 Kalbitz, K., Glaser, B., Bol, R., 2004. Clear-cutting of a Norway spruce stand: implications  
736 for controls on the dynamics of dissolved organic matter in the forest floor. *European*  
737 *Journal of Soil Science*. 55, 401-413.

738 Katzensteiner, K., 2003. Effects of harvesting on nutrient leaching in a Norway spruce  
739 ecosystem on a lithic leptosol in the Northern Limestone Alps. *Plant and Soil*. 250, 59-73.

740 Lee, W.J., Wood, C.W., Reeves, D.W., Entry, J.A., Raper, R.L., 2008. Interactive effects of  
741 wheel-traffic and tillage system on soil carbon and nitrogen. *Communications in Soil*  
742 *Science and Plant Analysis*. 27, 3027-3043.



743 Löfgren, S., Cory, N., Zetterberg, T., Larsson, P.-E., Kronnäs, V., 2009. The long-term effects  
744 of catchment liming and reduced sulphur deposition on forest soils and runoff chemistry in  
745 southwest Sweden. *Forest Ecology and Management*. 258, 567–578.

746 McColl, J.G., 1978. Ionic composition of forest soil solutions and effects of clearcutting. *Soil*  
747 *Science Society of America Journal*. 42, 2, 358-363.

748 MEDDE, 2005. *Repères Sols et Environnement Chiffres Clés*. 102 pages  
749 [www.statistiques.developpement-durable.gouv.fr](http://www.statistiques.developpement-durable.gouv.fr)

750 Mehra, O.P., Jackson, M.L., 1960. Iron oxide removal from soils and clays by a dithionite-  
751 citrate system buffered with sodium bicarbonate. *Clays and Clay Minerals*. 7, 317-327.

752 Nömmik, H. 1979. The future role of liming in forestry. -Skogs –o Lantbr. –akad. Tidskr.  
753 Suppl. 13, 31-37.

754 Nugroho, R.A., 2006. Nitrification in acid coniferous forests: some soils do, some soils don't.  
755 PhD thesis Institute of Ecological Science. Vrije University, Amsterdam, The Netherlands.

756 Nyborg, M., Hoyt, P.B., 1978. Effect of soil acidity and liming on mineralization of soil  
757 nitrogen. *Canadian Journal of Soil Science*. 58, 331-338.

758 Nykvist, N., Grip, H., Liang Sim, B., Malmer, A., Khiong Wong, F., 1994. Nutrient losses in  
759 forest plantation in Sabah, Malaysia. *Ambio*. 23, 3, 210-215.

760 Page-Dumroese, D. S., Jurgensen, M. F., Tiarks, A. E., Ponder, F., Sanchez, F. G., Fleming,  
761 R. L., Kranabetter, J. M., Powers, R. F., Stone, D. M., Elioff, J. D. & Scott, D. A., 2006.  
762 Soil physical property changes at the North American Long-Term Soil Productivity study  
763 sites: 1 and 5 years after compaction. *Canadian Journal of Forest Research*. 36, 551-564.

764 Pandey, B.K., Huang, G., Bhosale, R. Hartman, S., Sturrock, C.J., Jose, L., Martin, O.C.,  
765 Karady, M., Voeselek, L.A.C.J., Ljung, K., Lynch, J.P., Brown, K.M., Whalley, W.R.,  
766 Mooney, S.J., Zhang, D., Bennett, M.J., 2021. Plant roots sense soil compaction through  
767 restricted ethylene diffusion. *Science* 371, 276-280.

768 Parkin, T.B., 1987. Soil microsites as a source of denitrification variability. *Soil Science*  
769 *Society of America Journal* . 51, 1194-1199.

770 Philippot, L., Hallin, S., Schloter, M., 2007. Ecology of denitrifying prokaryotes in  
771 agricultural soil *Advances in Agronomy*. Chapter V, 250-283.

772 Pischedda D. (coordinateur), 2009. Pour une exploitation forestière respectueuse des sols et  
773 de la forêt. PROSOL. Guide technique. Office national des Forêts/FCBA. 110p.

774 Pousse, N., Bonnaud, P., Legout, A., Darboux, F., Ranger, J., 2021. Forest soil penetration  
775 resistance following heavy traffic: A ten-year field study. *Soil Use and Management*. 00,  
776 1-21.

777 Raison R.J., Connell M.J., Khanna P.K., 1987. Methodology for studying fluxes of soil  
778 mineral-N in situ. *Soil Biochemistry*. 19, 521-530.

779 Ranger, J., Marques, R., Jussy, J.-H., 2001. Forest soil dynamics during stand development  
780 assessed by lysimeter and centrifuge solutions. *Forest Ecology and Management*. 144, 129-  
781 145.

782 Ranger, J., Loyer, S., Gelhaye, D., Pollier, B., Bonnaud, P. 2007. Effects of the clear-cutting  
783 of a Douglas-fir plantation (*Pseudotsuga menziesii* F.) on the chemical composition of soil  
784 solutions and on the leaching of DOC and ions in drainage waters. *Annals of Forest  
785 Science*. 64, 2, 183-200.

786 Ranger, J., Legout, A., Bonnaud, P., Arrouays, D., Nourrisson, G., Gelhaye, D., Pousse, N.,  
787 2020. Interactions entre les effets du tassement par les engins d'exploitation et la fertilité  
788 chimique des sols forestiers. *Revue forestière française, AgroParisTech*, 72 (3), pp.191-  
789 213.

790 R Core Team, 2020. R: A language and environment for statistical computing. R Foundation  
791 for Statistical Computing, Vienna, Austria. <http://www.r-project.org/index.html>.

792 Reuss, J.O., Johnson, D.W., 1986. Acid Deposition and the Acidification of Soils and Waters.  
793 Springer-Verlag, New York.

794 Robert, M., Tessier, D., 1974. Méthode de préparation des argiles des sols pour les études  
795 minéralogiques. *Annales Agronomiques*. 25, 6, 859-882.

796 Saeedifar, Z., Asgari, H.R., 2014. Effect of soil compaction on soil carbon and nitrogen  
797 sequestration and some physico-chemical features (case study: NorthofAqQala).  
798 *Ecopersia*, 2, 4, 743-755.

799 Sawhney, B.L., 1970. Potassium and Cesium ion selectivity in relation to clay mineral  
800 structure. *Clays and Clay Minerals*. 18, 47-52.

801 Silva, S.R., Ribeiro da Siva, I., de Barros, N.F., de Sa Mendonça, E., 2011. Effect of soil  
802 compaction on microbial activity and carbon and nitrogen transformations in two oxisols  
803 with different mineralogy. *Revista Brasileira de Ciência do Solo*. 35, 1141-1149.

804 Silveira, M.L., Comerford, N.B., Reddy, K.R., Trenger, J., DeBusk, W.F., 2010. Influence of  
805 military land uses on soil carbon dynamics in forest ecosystems of georgia, USA.  
806 *Ecological Indicators*. 10, 905-909.

807 Smethurst, P., 2000. Soil solution and other soil analysis as indicators of nutrient supply: a  
808 review. *Forest Ecology and Management*. 138, 397-411.

809 Smith, K.A., 1977. Soil aeration. *Soil Science*. 123, 284-291.

810 Stark, J., Hart, S., 1997. High rates of nitrification and nitrate turnover in undisturbed  
811 coniferous forests. *Nature*. 385, 61-64.

812 Stepniewski, W., Glinski, J., Ball, B.C., 1994. Effects of compaction on soil aeration  
813 properties. In Stone B.D. and van Ouerkerk C. (eds) *Soil compaction and crop*  
814 *production*. Chapter 8, 167-190.

815 Sverdrup, H., Varfinge, P., Rosen, K.A.J., 1992. A model for the impact of soil solution  
816 Ca:Al ratio, soil moisture and temperature on tree base cation uptake. *Water air and Soil*  
817 *Pollution*. 61, 365-383.

818 Tan, X. Chang, S.X., Kabzems, R., 2008. Soil compaction and forest floor removal reduced  
819 microbial biomass and enzyme activities in a boreal aspen forest soil. *Biology and Fertility*  
820 *of Soils* . 44, 471-479.

821 Van der Linden, A.M.A., Jeurissen, L.J.J., van Veen, J.A., Schippers, B., 1989. Turnover of  
822 the soil microbial biomass as influenced by soil compaction. In J.A. Hanssen and K.  
823 Henriksen (Eds), *Nitrogen in organic wastes applied to soils*. Academic Press London, 25-  
824 36.

825 Vitousek, P.M., Melillo, J.M., 1979. Nitrate losses from disturbed forests: patterns and  
826 mechanisms. *Forest Sciences*. 25, 4, 605-619.

827 White, W.M., 1998. Reactions at the earth's surface: Weathering, soils and stream chemistry.  
828 Chapter 13. In *Geochemistry*. Wiley-Blackwell, 555-588.

829 von Wilpert, K., Schäffer, J., 2006. Ecological effects of soil compaction and initial recovery  
830 dynamics: a preliminary study. *European Journal of Forest Research*. 125, 129-138.

831 Wolt, J., 1994. *Soil solution chemistry: Application environmental science and agriculture*.  
832 Wiley, NY.

833 Zabowski, D., Ugolini, F.C., 1990. Lysimeter and Centrifuge Soil Solutions: Seasonal  
834 Differences between Methods. *Soil Science Society of America Journal*. 54, 1130-1135.

835 Zeller, B; Recous, S; Kunze, M; Moukoumi, J; Colin-Belgrand, M; Bienaime, S; Ranger, J;  
836 Dambrine, E. 2007. Influence of tree species on gross and net N transformations in forest  
837 soils. *Annals of Forest Science*. 64, 2, 151:158.

838 Zhao, W., Zhang, J.B., Müller, C., Cai, Z.C., 2017. Effects of pH and mineralisation on  
839 nitrification in a subtropical acid forest soil. *Soil Research*. 56, 3, 275-283.

840

841 **Figure list**

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

847 Figure 2. Nitrate (N-NO<sub>3</sub>) concentrations in the soil solutions of the control (C) and  
848 compacted (T) treatment at Azerailles. A, B and C indicate the initial, intermediate and final  
849 period, respectively.

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

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

856 Figure 5. Nitrate (N-NO<sub>3</sub>) concentrations in the soil solutions of the control (C), compacted  
857 (T), limed (A) and compacted and limed (TA) treatments at Clermont-en-Argonne. A, B and  
858 C indicate the initial, intermediate and final period, respectively.

859 Figure 6. Sulphate (SO<sub>4</sub>) concentrations in the soil solutions of the control (C), compacted  
860 (T), limed (A) and compacted and limed (TA) treatments at Clermont-en-Argonne. A, B and  
861 C indicate the initial, intermediate and final period, respectively.

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

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

867

868 **Table list**

869 Table 1. Initial mean soil characteristics at the two experimental sites in 2007. CEC: cationic  
870 exchange capacity; Fe<sub>DCB</sub> and Al<sub>DCB</sub>: Fe and Al oxides (Mehra and Jackson, 1960).

871 Table 2. Mean soil characteristics at the Clermont-en-Argonne site in 2014; statistics concern  
872 the post-hoc test (see Materials and Methods for definitions) of the treatment effect. \*\*  
873  $p > 0.01$ ; \*  $0.01 < p < 0.05$ ; ~  $0.05 < p < 0.10$ ; NS non significant. Exch: exchangeable (  
874 cobaltihexamine chloride extraction); T(CEC): effective cationic exchange capacity; S:T:  
875 base saturation; S-SO<sub>4</sub>: adsorbed sulphate (NaH<sub>2</sub>PO<sub>4</sub> extraction).

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

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

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

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

887 Table 7. Mean soil solution concentrations based on time and soil depth in the limed (A) and  
888 compacted and limed (TA) treatment at Clermont-en-Argonne. \*\*  $p > 0.01$ ; \*  $0.01 < p < 0.05$ ; ~  
889  $0.05 < p < 0.10$ .

890 Table 8. Mean soil solution concentrations based on time and soil depth in the compacted (T)  
891 and compacted and limed (TA) treatment at Clermont-en-Argonne. \*\*  $p > 0.01$ ; \*  
892  $0.01 < p < 0.05$ ; ~  $0.05 < p < 0.10$ .

893

894 **Supplementary material**

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

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

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

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

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

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

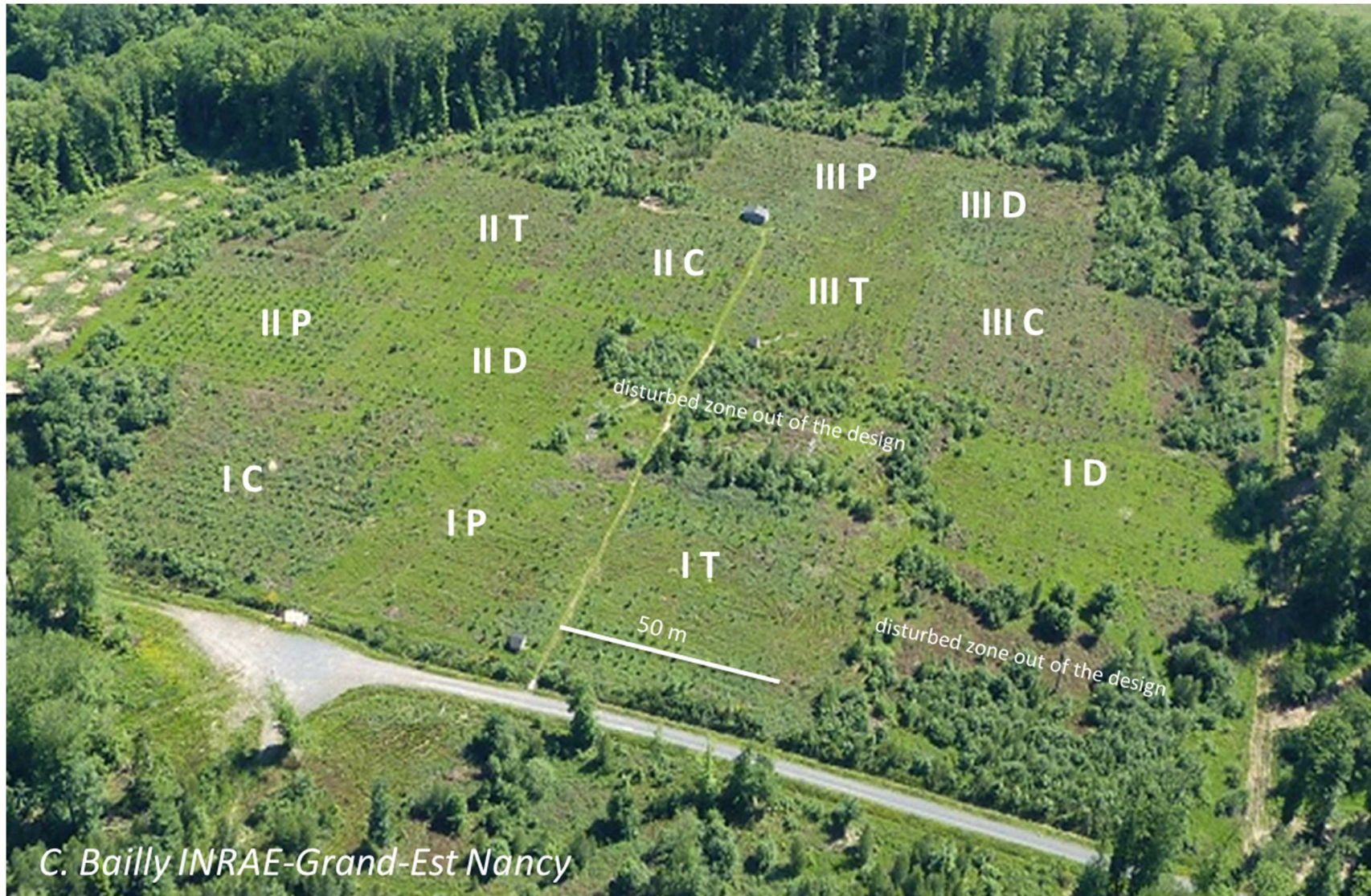
913 Supplementary material 7 (B. Zeller, unpublished data). Mineralisation and nitrification rates  
914 at Azerailles and Clermont-en-Argonne in 2011-2012. Measurements performed using the  
915 Raison et al. (1987) in situ incubation method (five replicates of the 0-15 cm layer in mature  
916 forest,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

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

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

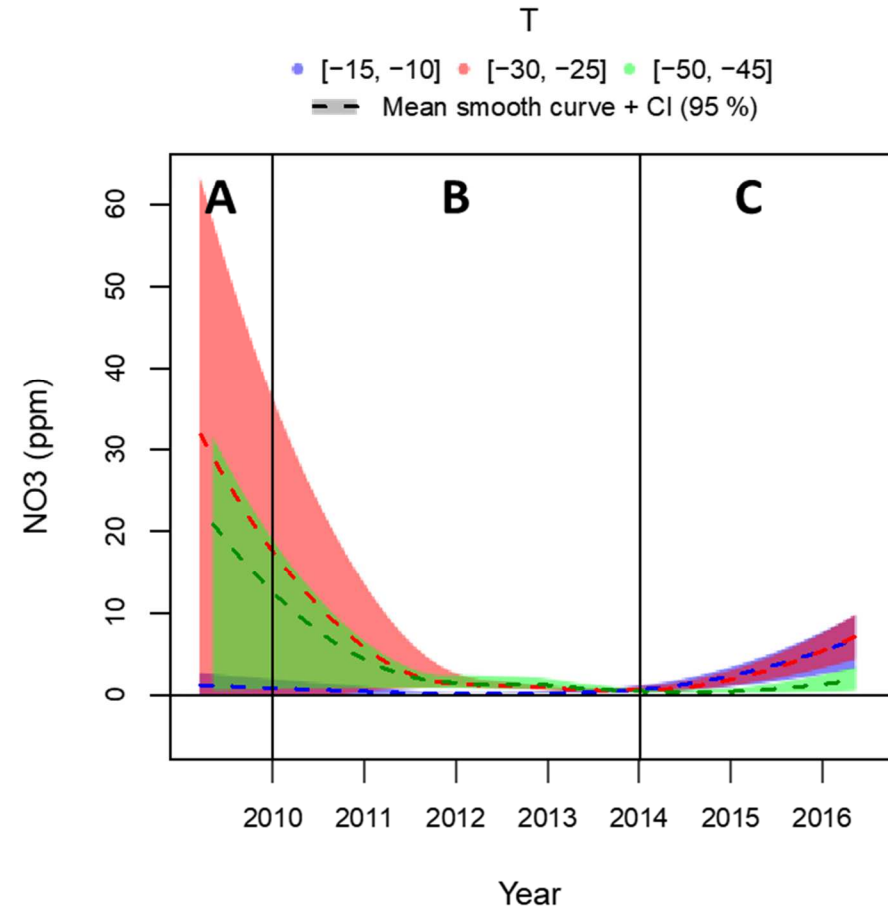
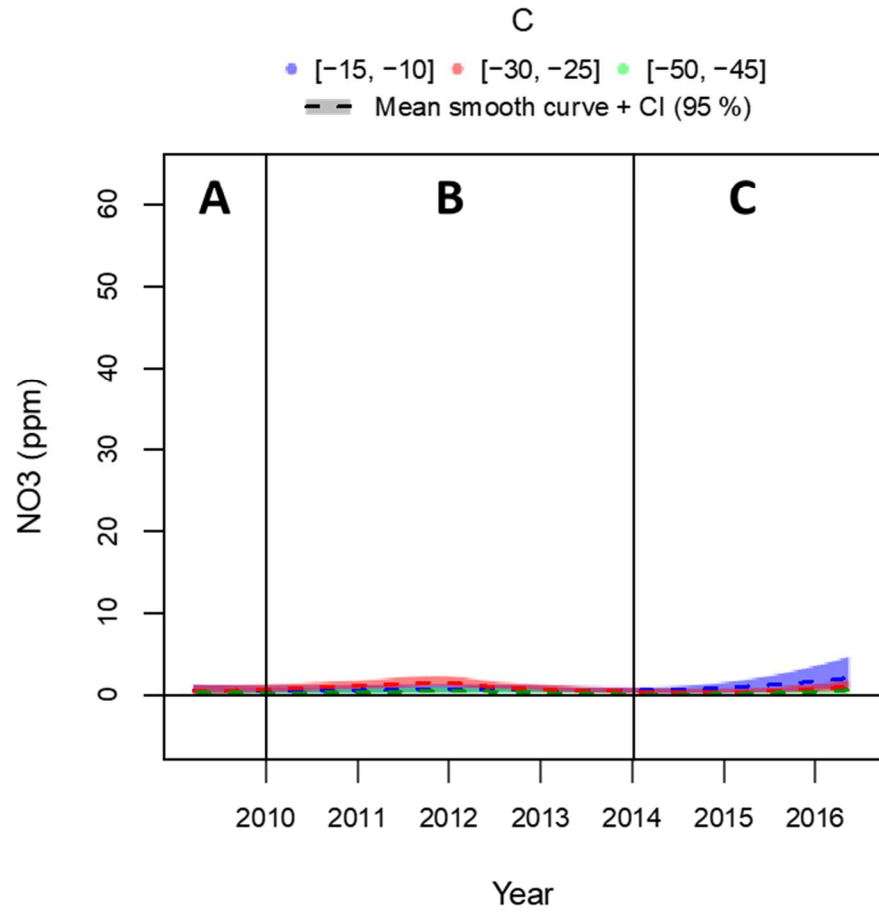
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925 **Figure 1**



926

927 **Figure 2**

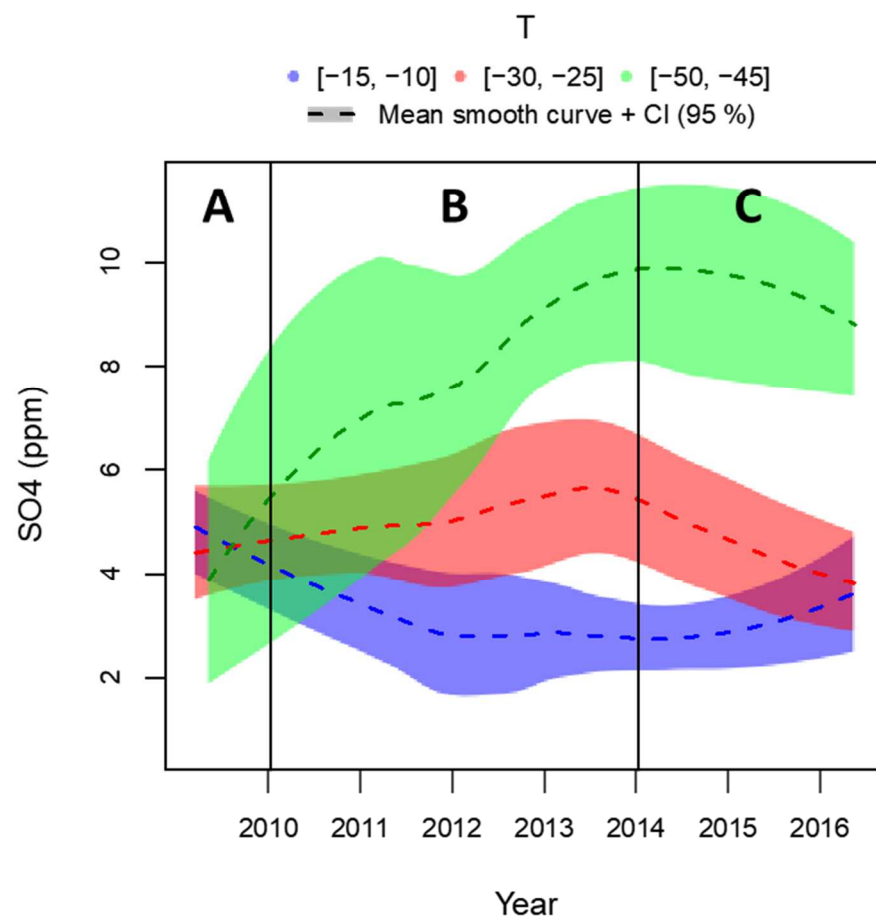
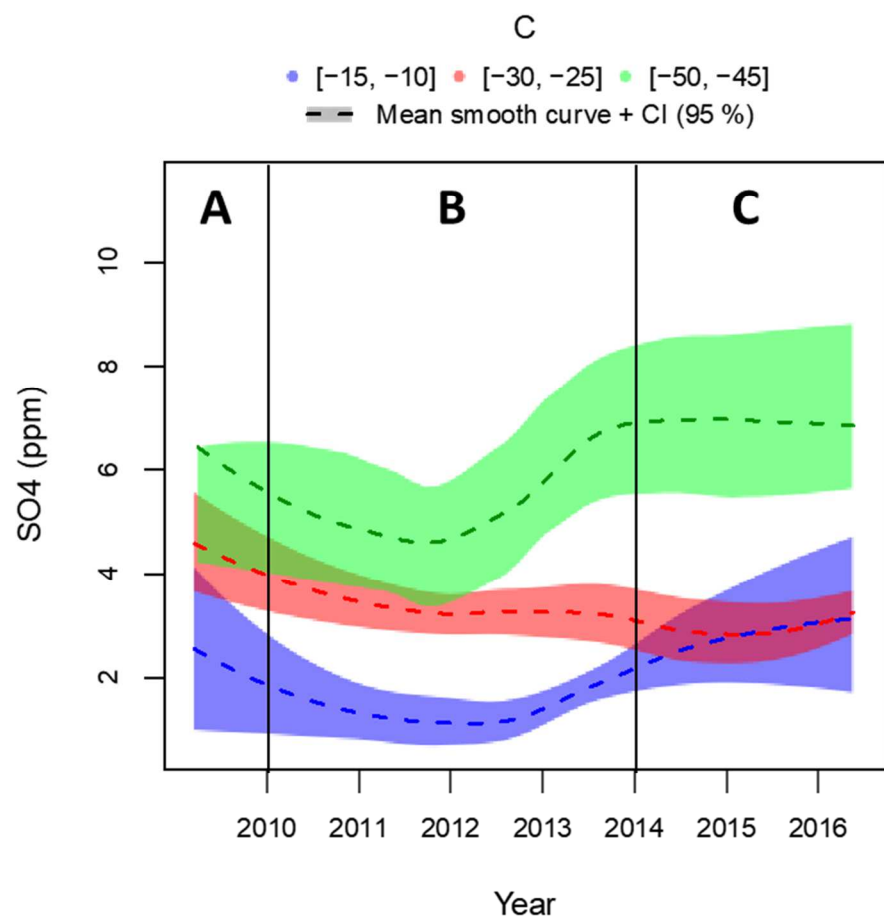


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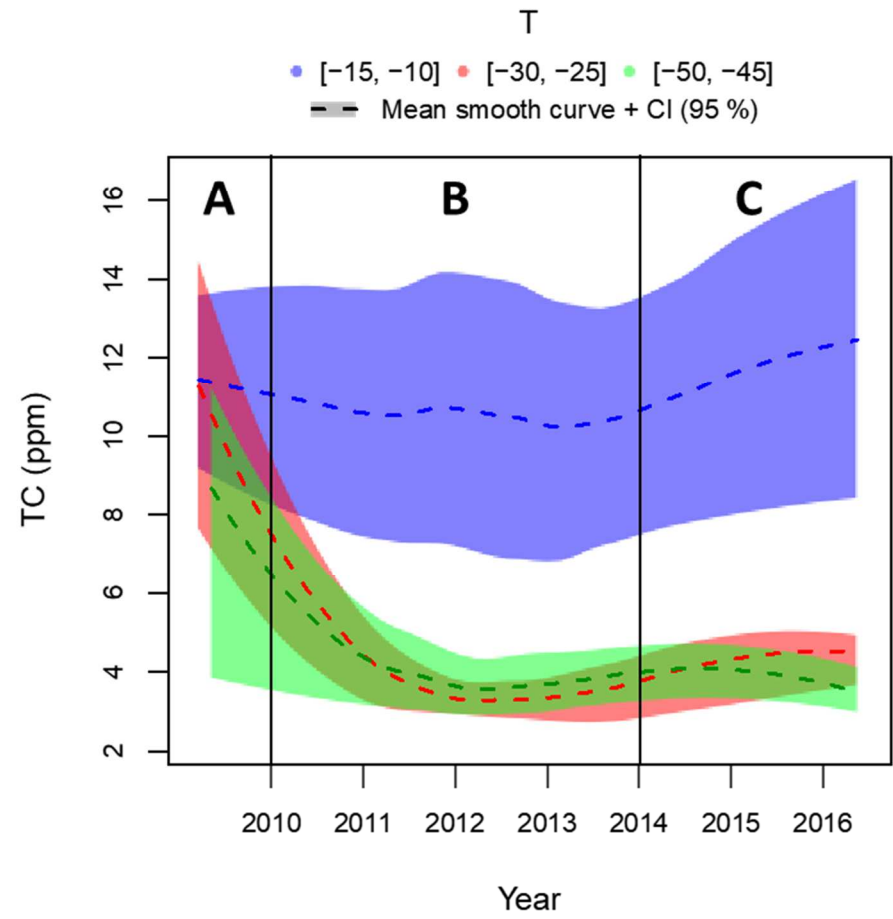
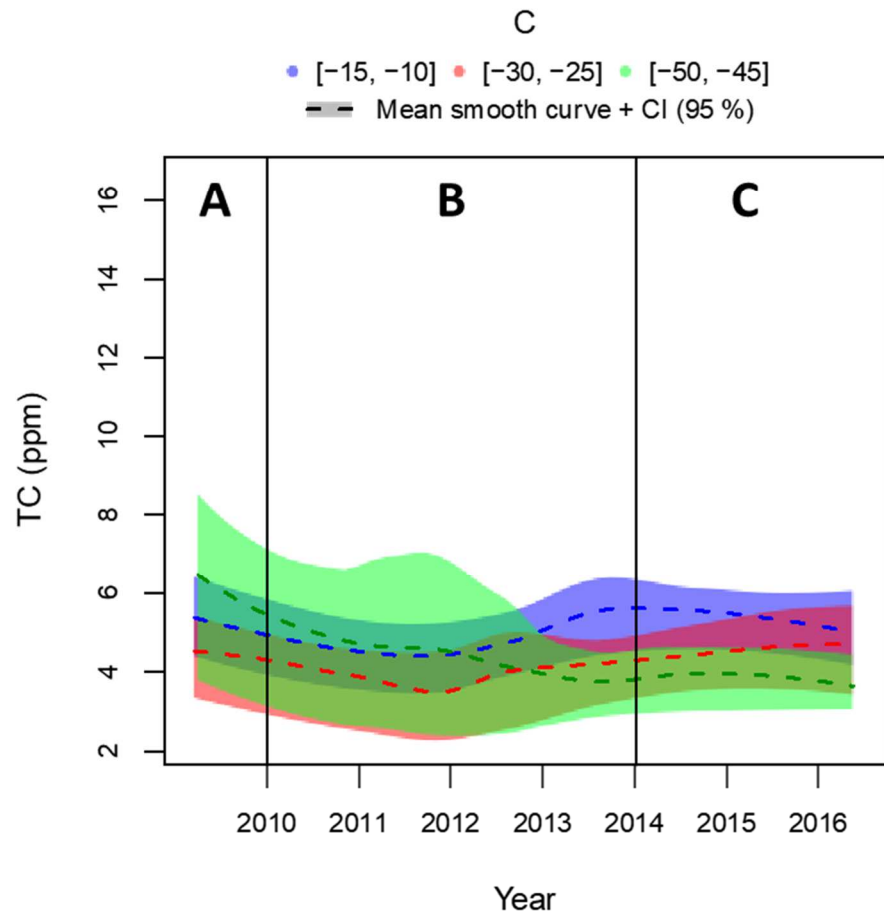


930 **Figure 3**



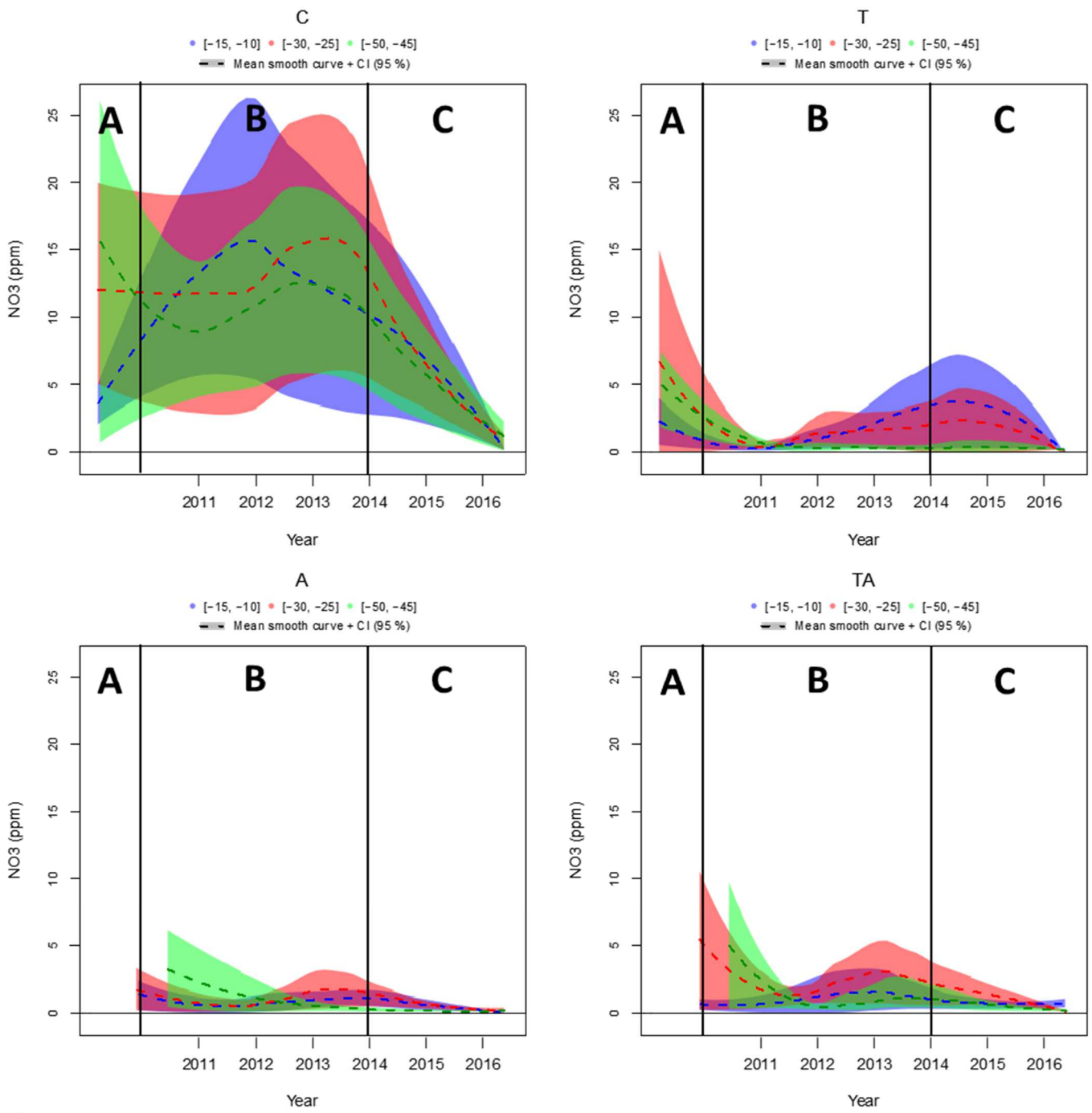
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933 **Figure 4**

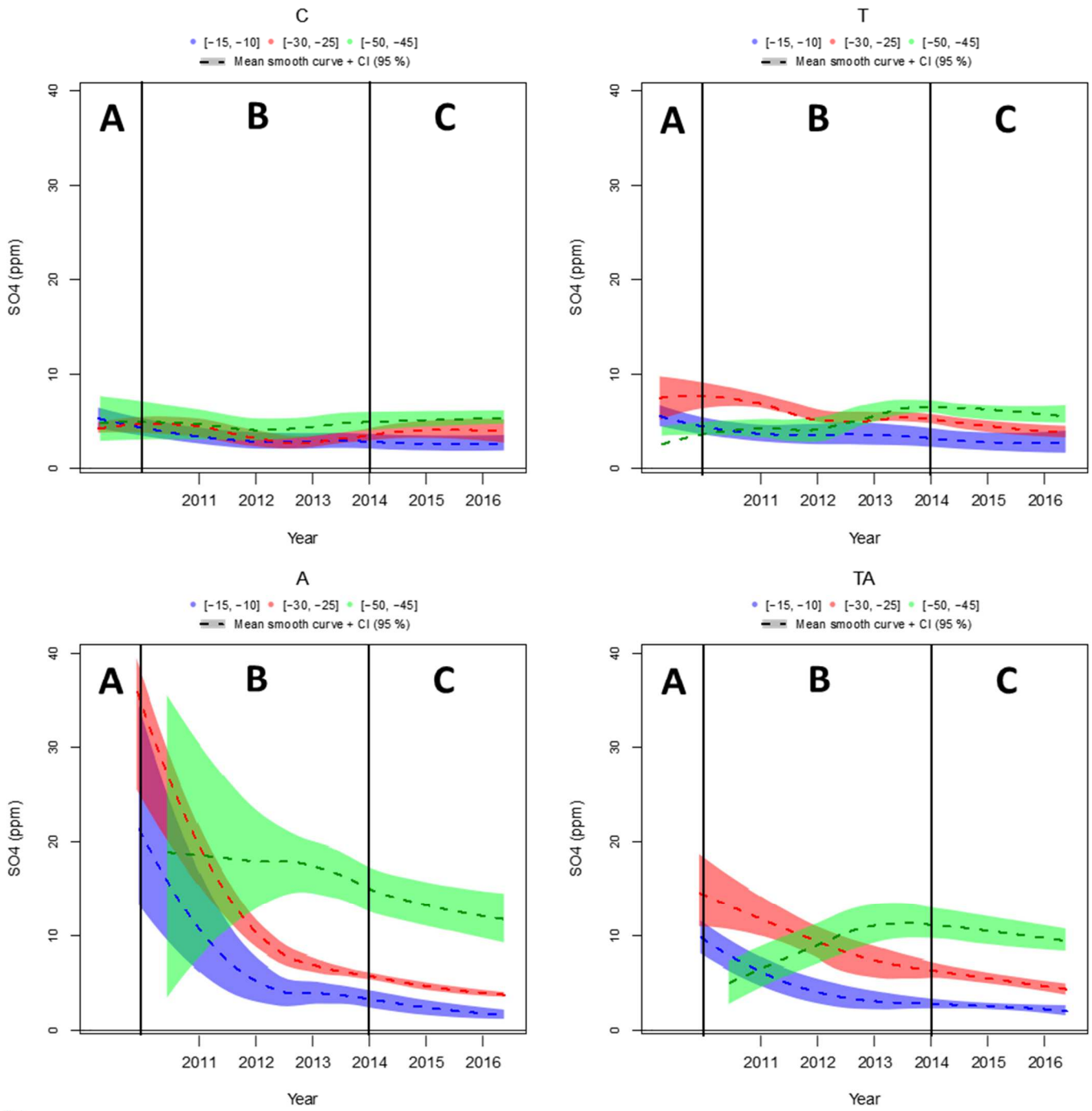


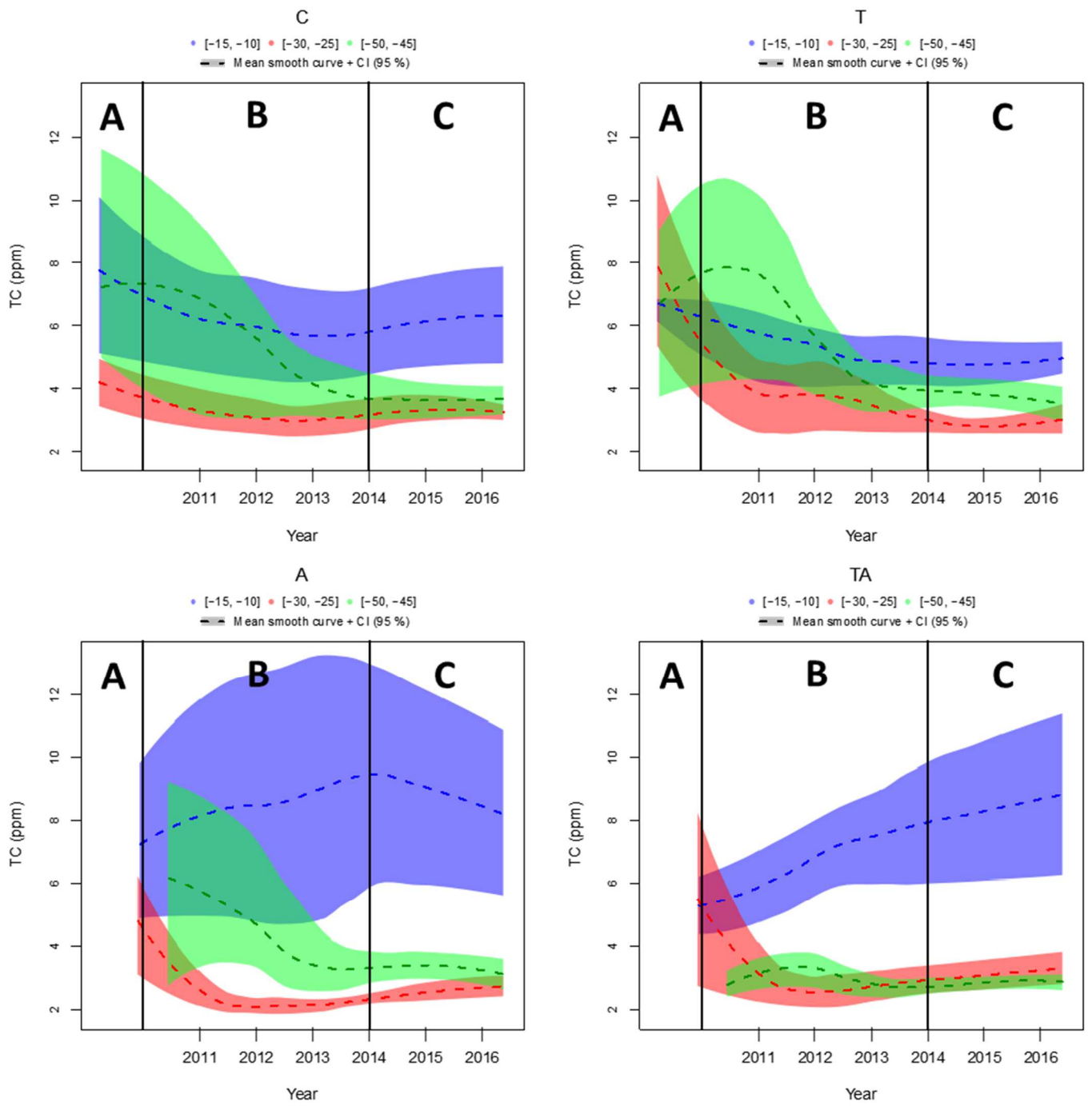
934

935 **Figure 5**

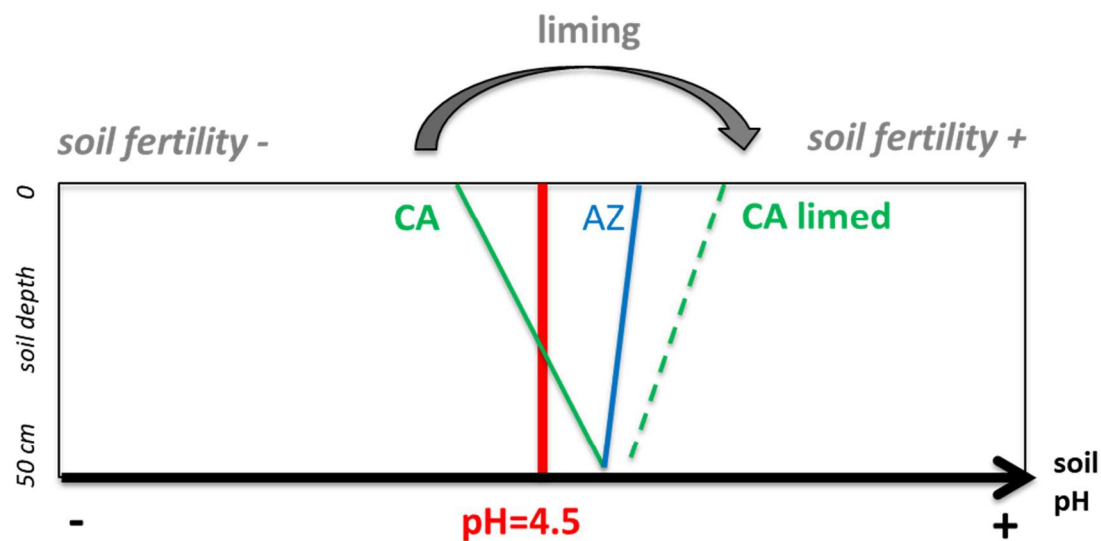


936  
937





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

	Depth cm	pH <sub>H2O</sub>	pH <sub>KCl</sub>	C org g.kg <sup>-1</sup>	N org g.kg <sup>-1</sup>	Particle size distribution					CEC <sup>(1)</sup> cmol+. kg <sup>-1</sup>	Ca <sub>exch</sub> cmol+. kg <sup>-1</sup>	[Ca+Mg+K +Na] saturation %	Fe <sub>DCB</sub> %	Al <sub>DCB</sub> %	CEC clays <sup>(2)</sup> cmol+. kg <sup>-1</sup>	Total elements			
						Clay g.kg <sup>-1</sup>	Fine Silt g.kg <sup>-1</sup>	Coarse Silt g.kg <sup>-1</sup>	Fine Sands g.kg <sup>-1</sup>	Coarse Sands g.kg <sup>-1</sup>							Ca	Mg	Fe	Al
Azeraillles (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 referred to soil fine earth dried at 105°C except CECclays referring to the clay fraction itself

<sup>(1)</sup> CEC of the fine earth

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

Treatment	Horizon cm	pH <sub>water</sub>	pH <sub>KCl</sub>	Ca <sub>exch</sub>	Mg <sub>exch</sub>	Mn <sub>exch</sub>	K <sub>exch</sub>	H <sup>+</sup>	Al <sup>3+</sup> titrated	acidity	T (CEC)	S:T	S-(SO <sub>4</sub> ) mg.kg <sup>-1</sup>
		UpH						cmolc.kg <sup>-1</sup>					
<b>Control C</b>	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
<b>mean</b>		<b>4.61</b>	<b>3.74</b>	<b>0.36</b>	<b>0.14</b>	<b>0.25</b>	<b>0.16</b>	<b>0.23</b>	<b>4.75</b>	<b>4.99</b>	<b>5.92</b>	<b>0.17</b>	<b>1.23</b>
<b>Compacted T</b>	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
<b>mean</b>		<b>4.67</b>	<b>3.73</b>	<b>0.68</b>	<b>0.25</b>	<b>0.27</b>	<b>0.21</b>	<b>0.20</b>	<b>5.47</b>	<b>5.67</b>	<b>7.11</b>	<b>0.22</b>	<b>1.55</b>
<b>Limed A</b>	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
<b>mean</b>		<b>4.83</b>	<b>3.86</b>	<b>1.32</b>	<b>0.72</b>	<b>0.33</b>	<b>0.35</b>	<b>0.17</b>	<b>5.02</b>	<b>5.19</b>	<b>7.92</b>	<b>0.36</b>	<b>1.64</b>
<b>Compacted and limed TA</b>	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
<b>mean</b>		<b>4.78</b>	<b>3.83</b>	<b>1.03</b>	<b>0.59</b>	<b>0.29</b>	<b>0.31</b>	<b>0.17</b>	<b>4.48</b>	<b>4.65</b>	<b>6.88</b>	<b>0.33</b>	<b>1.86</b>
<i>post-hoc test C vs T</i>	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
<i>post-hoc test A vs TA</i>	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
<i>post-hoc test C vs A</i>	0 - 10 cm	**	**	**	**	NS	NS	**	**	**	**	**	NS
	10 - 20 cm	**	NS	NS	**	NS	**	NS	NS	NS	NS	NS	NS
<i>post-hoc test T vs TA</i>	0 - 10 cm	*	*	*	**	NS	NS	~	**	**	~	**	NS
	10 - 20 cm	~	NS	NS	**	NS	*	NS	NS	NS	NS	NS	NS



952 a)

AZERAILLES	depth (cm)	C				T				C					T				
		Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	IS <sub>C</sub>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	IS <sub>T</sub>	Mg <sup>2+</sup>	Al <sup>3+</sup>	Ca <sup>2+</sup>	K <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>	Mg <sup>2+</sup>	Al <sup>3+</sup>	Ca <sup>2+</sup>	K <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>
		μeq.L <sup>-1</sup>				μeq.L <sup>-1</sup>				μeq.L <sup>-1</sup>					μeq.L <sup>-1</sup>				
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

CLERMONT en ARGONNE	depth (cm)	C				T				C					T				
		Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	IS <sub>C</sub>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	IS <sub>T</sub>	Mg <sup>2+</sup>	Al <sup>3+</sup>	Ca <sup>2+</sup>	K <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>	Mg <sup>2+</sup>	Al <sup>3+</sup>	Ca <sup>2+</sup>	K <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>
		μeq.L <sup>-1</sup>				μeq.L <sup>-1</sup>				μeq.L <sup>-1</sup>					μeq.L <sup>-1</sup>				
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

CLERMONT en ARGONNE	depth (cm)	A				TA				A					TA				
		Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	IS <sub>A</sub>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	IS <sub>TA</sub>	Mg <sup>2+</sup>	Al <sup>3+</sup>	Ca <sup>2+</sup>	K <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>	Mg <sup>2+</sup>	Al <sup>3+</sup>	Ca <sup>2+</sup>	K <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>
		μeq.L <sup>-1</sup>				μeq.L <sup>-1</sup>				μeq.L <sup>-1</sup>					μeq.L <sup>-1</sup>				
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

953

954 b)

depth (cm)	AZERAILLES	CLERMONT en ARGONNE				
	(IS <sub>T</sub> -IS <sub>C</sub> ) / IS <sub>C</sub>	(IS <sub>T</sub> -IS <sub>C</sub> ) / IS <sub>C</sub>	(IS <sub>A</sub> -IS <sub>C</sub> ) / IS <sub>C</sub>	(IS <sub>TA</sub> -IS <sub>A</sub> ) / IS <sub>A</sub>	(IS <sub>TA</sub> -IS <sub>T</sub> ) / IS <sub>T</sub>	
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

955

956





963 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																	
<b>Initial period [2009-2010]</b>																			
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																			
<b>Intermediate period [2011-2013]</b>																			
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			**	~	**	**	**	**	*	**	**	**	**	**	**	**	**	**	**
<b>Final period [2014-2016]</b>																			
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			**	*	**	**	**	**	**	**	**	**	**	*	**	**	**	**	**

		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																	
<b>Initial period [2009-2010]</b>																			
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											*								
<b>Intermediate period [2011-2013]</b>																			
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				~	**	**	**	**	**	**	**	**	*	**	**	**	**	**	**
<b>Final period [2014-2016]</b>																			
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			**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**

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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																			
<b>Initial period [2009-2010]</b>																			
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																			
<b>Intermediate period [2011-2013]</b>																			
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			*	**	**	**	**	**	**	**	**	**	**	**	**	~	**	**	**
<b>Final period [2014-2016]</b>																			
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			**	**	**	*	**	**	**	**	~	**	~	**	**	**	**	*	**