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1 **Impact of compaction on two sensitive forest soils in Lorraine (France) assessed by the**  
2 **changes occurring in the perched water table.**

3

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24

25 **Abstract**

26 The mechanisation of forestry operations is too recent in France to have enough perspective  
27 and scientific knowledge of the effects on extensively managed soils. Two experimental sites  
28 on soils sensitive to compaction (silty acidic soils laying on top of a clayey subsoil) were set  
29 in Lorraine (France). A gentle and controlled compaction of these physically very analogous  
30 soils was carried out during spring 2007 at the Azerailles site (AZ) and during spring 2008 at  
31 the Clermont-en-Argonne site (CA). Immediate changes were observed for all ecosystem  
32 physical, chemical and biological functioning indicators. Soil restoration dynamics were  
33 followed using continuous monitoring of numerous parameters, including soil moisture and  
34 occurrence of a perched water table (PWT) (monitored at a daily time step) and PWT  
35 chemistry (monthly time step). Mid-term monitoring (7 to 8 years) results showed that both  
36 soils shifted towards a hydromorphic soil type attested by the increase in PWT frequency and  
37 duration, which invaded the soil upper layers, leading to characteristic Fe, Mn and S mobility  
38 and a change in organic compounds stability. Though soil types were very similar, the PWT  
39 characteristics varied notably between both sites. The mean residence time of the PWT was  
40 shown to be a major driver of its geochemistry, but with strong interaction with soil  
41 characteristics. A previous study made on both sites suggested that soil clay content and clay  
42 mineralogy controls the PWT dynamics through effects on aggregation. From a PWT  
43 perspective, seven years of monitoring were insufficient to observe any soil compaction  
44 recovery in the richer soil of AZ but a partial recovery was observed for the chemically poorer  
45 soil (CA). Compaction durably impacted the two studied soils and the probability that a new  
46 compaction event may occur before the complete recovery from the first disturbance must be  
47 considered in forest management.

48

49 **Keywords**

50 Forest soils, compaction, restoration, perched-water-table

51

## 52 **1- Introduction**

53 Fine textured soils, more especially soils with a silty texture, are known to be very sensitive to  
54 physical degradation (MEDDE, 2015). This texture associates both the low reactivity of sands  
55 (small particles of quartz and feldspars with low specific area and no shrinking properties, and  
56 low cation exchange capacity) and the potential low permeability of de-structured clayey  
57 material. Sensitivity to degradation is increased with soil acidity because soil aggregation is  
58 low and unstable. Antagonistic characteristics occur in acid soils: low levels of flocculent  
59 alkaline earth cations (Ca and Mg) but high levels of flocculent Al (Haynes and Naidu, 1998),  
60 high levels of protonated organic matter and low biological activity. Aggregation regulates  
61 the organic matter turnover, the water and solute transfer, the gas exchange and consequently  
62 the microbial community structure and function (Six et al., 2004).

63 The mechanization of silviculture can lead to soil deformation when the applied pressure  
64 exceeds the soil bearing capacity; this phenomenon increases with soil moisture (Ampoorter  
65 et al., 2012). Compaction, which is the decrease in porosity without any change in soil mass  
66 (de Paul and Bailly, 2005), represents a major risk for soil sustainability. According to its  
67 intensity, to the soil characteristics and moisture, it can drastically change soil properties *e.g.*  
68 bulk density (Miller et al., 1996), porosity and mainly macro-porosity (Herbauts, 1996;  
69 Bruand et al., 1996), soil hydraulic properties (Horton et al., 1994), water and gas transfer  
70 (Stepniewski et al., 1994), and consequently soil biota (Doran and Power, 1983; Brussaard  
71 and Faassen, 1994). Compaction changes root configuration and growth (Sands and Bowen,  
72 1978; Wronski and Murphy, 1994), root penetration (Heilmann, 1981) and it alters water and  
73 nutrient uptake of trees (Goranson et al., 2008; Alavi, 2002). It also decreases the earthworm  
74 biomass and their burrowing activity (Jordan et al., 2003).

75 The mechanization of forest practices represents a major risk for forest soil sustainability for  
76 fine textured acidic soils with low coarse material content if traffic of machinery is not strictly  
77 regulated according to soil moisture. Inappropriate management practices could lead to more  
78 or less irreversible changes (Pischedda et al., 2009) because, on the one hand, remediation of  
79 physical degradation is costly and technically difficult, and on the other hand, natural  
80 restoration of porosity is slow, especially in acidic soils where earthworms are not efficient  
81 (Lee, 1985), dominated by epigeous worms whose habitat is limited to the soil surface layers  
82 (Lee and Foster, 1991). Observations made in various situations, very often uncontrolled in  
83 terms of soil moisture at the time of compaction, but also in terms of machinery (real  
84 constraint per soil unit area, number of passes...), led to the conclusion that restoration of soil  
85 porosity takes a long time. For example, observations made on skid trails showed that the soil  
86 remained compacted for 30-40 years (literature quoted by Wronski and Murphy, 1994);  
87 observations made on military fields still showed compaction traces after 50 to 100 years; in  
88 Germany, the decreased gas diffusion still persisted after 10 years (Schack-Kirchner, 1994);  
89 the restoration of porosity and soil organic matter turnover rate was not achieved 10 years  
90 after compaction (Rab, 2004). In some specific conditions, restoration was more rapid *e.g.*  
91 soil bulk density was restored 5 years after compaction in a sandy soil (Page-Dumroese et al.,  
92 2006).

93 In fine textured soils with low permeability in the deep soil layer due to an abrupt change in  
94 clay content, a perched water table (PWT) generally occurs after heavy rain events when soil  
95 is wet and evaporation rate low (Rockefeller et al., 2004) *i.e.* during the winter period in  
96 temperate countries. This is an aggravating factor for soil degradation.

97 It could then be hypothesized first, that mechanization of practices in forests developed on  
98 soils sensitive to physical degradation, would reduce the soil porosity and increase the  
99 occurrence frequency of a PWT leading to hypo or anoxia processes in the soil, decreasing its

100 ability to sustain its major functions, and second that the time lapse before complete recovery  
101 on this soil group would depend on soil mineral fertility *i.e.* quicker when higher because of  
102 its role on soil biological activity.

103 Forest soils on the Lorraine plateau fall in the category of non-hydromorphic but very  
104 sensitive soils to physical degradation (silt material laying on heavy clay, acid conditions)  
105 (Staub, 2009). Because there is little information regarding the impact of land use on epi-  
106 saturation and more or less no information on the duration of the phenomenon, we selected  
107 physical and chemical characteristics of the perched water table as an indicator of soil  
108 degradation and restoration in two experimental sites, where a controlled compaction was  
109 carried out.

110 The objectives of the present study were then:

- 111 i- To identify the impacts of a controlled and limited soil compaction of sensitive soils  
112 on the occurrence of a perched water table (frequency, level) and on geochemical  
113 indicators of redox phenomena (ferrous iron, sulphur, manganese, total geochemistry),
- 114 ii- To clarify the effect of the mineral fertility level on these processes, comparing two  
115 soil environments in the plateau lorrain, submitted to the same stress of compaction,
- 116 iii-To monitor the dynamics of the same parameters on a medium term, in order to  
117 identify the time necessary for recovery of soil porosity,

118

## 119 **2 Material and methods**

### 120 2.1 Study sites

121 *Location and climate:* two experimental sites were set up in the North-East part of France, at  
122 Azerailles (54) (AZ thereafter), in the ‘Hauts Bois’ estate forest (48° 29'19"N,6°41'43" E) and  
123 at Clermont-en-Argonne (55) (49° 06' 23" N, 5° 04' 18" E) in the ‘Grand Pays’ estate forest  
124 (CA thereafter). The elevation of the sites is respectively 270 and 300 m a.s.l. for AZ and CA

125 with a maximum of 8 m (AZ) and 3 m (CA) level variation within each site. The average  
126 annual precipitation and temperature over a 30-year period (Météo-France data), are 920 and  
127 1000 mm.year<sup>-1</sup> and 8.5°C and 9°C respectively for AZ and CA.

128 *Forest stand prior to harvesting:* the previous stands were a mature high forest dominated by  
129 *Fagus sylvatica* L. and secondarily by *Quercus petraea* L. at AZ, and high forest originating  
130 from the transformation of an old coppice with standards at CA, dominated by *Fagus*  
131 *sylvatica* L. and *Quercus petraea* L. with some *Betula verrucosa* Ehrh., *Acer platanoides* L.  
132 and *Populus tremula* L.

133 *Soil characteristics:* soil description and selected soil parameters were measured before  
134 setting up the experimental designs, on samples taken from pits distributed over the entire site  
135 area (5 ha): 17 pits were dug at AZ and 13 at CA. For fine earth characterization, soil samples  
136 were collected in each pit at systematic depths (0-10; 10-20; 20-30; 30-45; 45-60; 60-75, 75-  
137 90; 90-110 cm). Soil samples were air-dried at the laboratory and sieved to separate coarse  
138 material from fine earth (<2mm); soil moisture was measured after oven-drying at 105°C for  
139 all samples. To estimate the soil bulk density, 250 cm<sup>3</sup> steel cylinders were used to collect two  
140 replicated samples every 10 cm in all the pits. Bulk density was calculated as the ratio  
141 between the soil mass (oven dried at 105°C over 72h) and the cylinder volume (a correction  
142 was made according to the coarse fragment content). The density of the solid was measured  
143 on dried and finely ground (200 µm) soil samples (one per block × depth) using pycnometers  
144 (Micrometrics).

## 145 2.2 Methods used for soil analysis

146 Particle size distribution was measured after the digestion of organic matter by H<sub>2</sub>O<sub>2</sub>, by  
147 sedimentation in deionized water, adding when necessary some drops of NaOH 1N for a  
148 perfect suspension; sampling was carried out with a Robinson pipet at a fixed level in the  
149 column, at times corresponding to specific particle sizes according to the Stokes law at a

150 fixed temperature; particles bigger than 50 $\mu$ m were separated by sieving ; soil pH was  
151 measured in both 1M KCl and in deionized water, with a soil to solution weight ratio of 1:2.5  
152 (Mettler TSDL25 pH meter). Cation Exchange Capacity and exchangeable cations were  
153 measured by the cobaltihexamine method (Ciesielski et al., 1997). Total soil C<sub>org</sub> and N<sub>org</sub>  
154 were determined with a elemental analysis system (ThermoQuest CE Instrument NCS 2500);  
155 total content of Al, Fe, Mg, Ca, K, Na, Mn in soil fine earth (<2mm) were determined after a  
156 HF digestion and ICP-AES measurements at the Inra-Soil Analysis Laboratory – Arras). Total  
157 chemical clay analysis was performed by the CNRS-CRPG rock and mineral analysis  
158 Laboratory using LiBO<sub>2</sub> alkaline fusion and dissolution in 1N HNO<sub>3</sub>; concentrations were  
159 measured with a ICP-OES instrument for major element and by ICP-MS for trace elements  
160 (Carignan et al., 2001). Fe-oxides were quantified according to Mehra and Jackson (1960).  
161 Soil clay mineralogy was characterized for 8 soil layers sampled from one central pit at each  
162 site (8 horizons each). The clay fraction was separated from the fine earth fraction (<2mm)  
163 according to Robert and Tessier (1974). The soil organic matter cement was digested using  
164 daily additions of dilute hydrogen peroxide (20 volumes which corresponds to a 1:5.5 dilution  
165 of the 110v mother solution) and heating at about 40°C until total elimination of organic  
166 carbon. Samples were then transferred to glass columns filled with deionized water to  
167 separate particle classes according to Stockes law of sedimentation for dilute systems. The  
168 clay fraction (<2  $\mu$ m) and the fine silts were separated by siphoning until total disappearance  
169 (10 to 15 siphoning operations are usually necessary), then, the coarser fractions (coarse silts,  
170 fine and coarse sands) were quantified by sieving with deionized water. Clay minerals were  
171 then saturated by a cation absent of the clay structure (Ba) in order to directly obtain the  
172 Cation Exchange Capacity (CEC) from total chemical analysis.

173

174 2.3 Site setup and monitoring

175 Both sites were clear-cut over a 6 ha surface area, logs were removed using a cable-harvesting  
176 system, and in order to minimize the soil disturbance, all the slash was removed manually or  
177 with an iron horse.

178 *Experimental design:* each site was divided into three blocks positioned after a low scale soil  
179 mapping, each treatment was randomly distributed in each block. Each individual plot is 30 ×  
180 50 m. In AZ, four treatments were applied: control (C), trafficked (T), trafficked and de-  
181 compacted by disking (D), and trafficked and local de-compaction at the plantation points (P).  
182 At CA, because the soil was more acidic, a liming treatment was added, control limed (L) and  
183 trafficked limed (TL). In the present study only C and T treatments will be considered.

184 *Experimental compaction:* In each trafficked plot, the same full-loaded forwarder drove for an  
185 equivalent of two passes. The forwarder (VALMET 840) traffic, took place in May 2007 and  
186 March 2008 respectively in the AZ and CA sites. The tyres (60 cm large) were inflated to the  
187 same pressure (360 kPa) and the total weight of the machine was of 23 and 17 t in the AZ and  
188 CA sites respectively, because the CA site was wetter at the time of traffic than the AZ site.  
189 At AZ, the mean soil surface volumetric water content of the 0-10 cm layer, was  $0.41 \text{ m}^3 \text{ m}^{-3}$   
190 and ranged from  $0.28 \text{ m}^3 \text{ m}^{-3}$  to  $0.53 \text{ m}^3 \text{ m}^{-3}$  at the time the forwarder drove on the soil, while  
191 at CA it was  $0.47 \text{ m}^3 \text{ m}^{-3}$  and varied from 0.25 to 0.59. Heavy traffic resulted in ‘ruts’  
192 averaging 5 cm in depth at both sites (Goutal et al., 2013).

193 *Compaction effects on bulk density and soil porosity:* changes in bulk density were measured  
194 by comparing values in non compacted (2 replicates x 6 horizons [each 10 cm from 0 to 60  
195 cm] x 3 blocks) and in compacted areas (4 replicates x 9 horizons [each 5 cm from 0 to 30 cm  
196 and then each 10 cm from 30 to 60 cm depth] x 3 blocks) one month after compaction; very  
197 deep ruts and creeping zones were avoided during sampling.

198 Soil porosity was calculated from bulk ( $d_a$ ) and real ( $d_r$ ) soil densities using the formula total  
199 porosity =  $1-(d_a/d_r)$ . Soil macroporosity was measured by the Wind methodology in one

200 profile of each block at depths [0-10, 15-25, and 30-40 cm], as described by Hopmans et al.  
 201 (2002). Briefly, soil micro-porosity was derived from the parameters obtained by the Wind  
 202 method, using the relation between the matric potential and the pore diameter given by the  
 203 Jurin/Young-Laplace laws ( $pF = \log(h)$ );  $pF$  is the matric potential and  $h$  is the height in cm of  
 204 the water column in the capillary; then  $\Delta h$  is inversely proportional to the pore diameter.

205 *Monitoring of the meso- and pedo-climates* in each site, rainfall, atmospheric vapour  
 206 saturation, soil temperature, and soil moisture were recorded continuously (every four hours)  
 207 on specific data loggers (DL2e Data Logger, Delta-T devices Ltd, England for rainfall and  
 208 soil temperature, and Trase “B.E.” by Soil Moisture, Sols Mesures - France, for soil water  
 209 content) located approximately in the centre of the experimental design. Time domain  
 210 reflectometry (TDR) probes and temperature sensors (five replicates per depth  $\times$  treatment)  
 211 were inserted into the soil at three depths (15, 30 and 50 cm in the undisturbed soil; 10, 25  
 212 and 45 cm in the compacted soil) (only one block equipped in each site). The captor depths in  
 213 the trafficked plots were selected to account for the volume change after compaction. The  
 214 TDR measurements (soil dielectric constant) were converted to volumetric water content  
 215 using calibration curves according to Heathman *et al.*, (2003) and derived from laboratory  
 216 calibration of TDR data, using undisturbed soil cores of each site.

217 The mean volumetric water content per day and the mean bulk density values were used to  
 218 calculate the daily air-filled porosity, defined as the volume occupied by air to the volume of  
 219 soil.

$$220 \quad \varepsilon_A = 1 - \frac{\rho_B}{\rho_S} - \theta_V \quad [1]$$

221 where  $\varepsilon_A$  is the soil air-filled porosity in  $\text{m}^3 \text{m}^{-3}$ ,  $\rho_B$  is the soil bulk density in  $\text{g cm}^{-3}$ ,  $\rho_S$  is the  
 222 density of the solid in  $\text{g cm}^{-3}$ , and  $\theta_V$  is the soil volumetric water content in  $\text{m}^3 \text{m}^{-3}$ .

223 The soil perched water table level was measured using Diver pressure probes (Diver, by Van  
 224 Essen Instruments, SDEC France), collecting data every four hours from June 2009 (figure

225 1B). These captors were installed in piezometers, distributed over the entire area of the plots,  
226 in the two C and T treatments (2 per treatment/plot and per block). The piezometers were  
227 built with a porous 3 cm diameter pipe inserted in a vertical drilled hole at a maximum depth  
228 less than 60 cm in order to avoid perforating the clayey floor, except one piezometer  
229 specifically installed in the clay layer at about 90 cm depth. Quartz sand was used to ensure  
230 the contact with soil, and bentonite was introduced around the top ten cm of the pipe in order  
231 to avoid direct water transfer from the soil surface.

232 The chemistry of the water table was collected each month since 2008 at both sites with a  
233 specific device designed to collect water without any contact with the atmosphere, especially  
234 for analysing the  $\text{Fe}^{2+}$  and sulphur concentrations; samples were also used for total chemistry  
235 (figure 1A). This device consists of a solid compartmentalized casing, perforated at specific  
236 depths in order to collect specific levels of the PWT in contact with the main differentiated  
237 soil layers *e.g.* from 0 to 10, between 15 to 25, and between 45 to 55 cm (one was installed in  
238 the clay layer at 90 cm in the C treatment of each block).

239 Total chemistry of the PWT: after collection, samples were filtered next day at the laboratory  
240 with 0.45  $\mu\text{m}$  Metriciel® acetate membrane filters and stored in the dark at 4°C. Samples  
241 were analyzed for pH (Mettler DL 70 ES Titrator ); anions ( $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{H}_2\text{PO}_4^-$ ,  $\text{NO}_2^-$ ,  $\text{SO}_4^{2-}$ ,  
242 F) were measured by ion chromatography (Dionex ICS2100); N- $\text{NH}_4^+$  was determined by  
243 molecular absorption spectrometry (Skalar San++ System) ; total Si, Al, Fe, Mg, Ca, K, Na, P  
244 and S were determined by ICP-AES (Agilent Technologies 700 series) ; total dissolved  
245 organic carbon (TOC) was measured with a Shimadzu TOC-L instrument.

246 *Ferrous iron and sulphur in the PWT*: dissolved reduced elements were used as indicators of  
247 the redox status of the PWT. Measurements were organized to allow the most accurate  
248 quantification: tests showed that measurement performed the next day in the laboratory were  
249 the most appropriate. Samples were first filtered through 0.45 $\mu\text{m}$  cellulose acetate membrane

250 with filters fixed on syringes in order to avoid all contact with atmosphere. Quantification was  
251 performed by spectrophoto-colorimetry (Shimadzu UV-1800). All measurements were  
252 duplicated. Ferrous iron was quantified using the phenantroline method (Fortune and Melon,  
253 1938): two mL of a buffer solution made of an admixture of potassium hydrogen phthalate  
254 and hydrochloric acid and 2 mL of a phenantroline solution were added to 5 mL of filtered  
255 samples. Measurements were made at 510 nm; calibration standards ranged from 0 to 2.00  
256 mg.L<sup>-1</sup>. Detection limit was 0.03 mg.L<sup>-1</sup>.

257 Sulphur was measured using the methylene blue method (the reaction of sulphur with FeCl<sub>3</sub>  
258 and N,N-dimethyl-p-phenylenediamine form methylene blue) (Centre D'expertise En Analyse  
259 Environnementale Du Québec, 2010): 1mL of the reagent was added to 5 mL of the filtered  
260 sample. Detection of the complex was made at 664 nm; calibration standards ranged from 0 to  
261 1.0 mg.L<sup>-1</sup>. Detection limit was 0.1 mg.L<sup>-1</sup>.

262

#### 263 2.4 Calculations and statistics

264 All calculations and statistics were carried out with R software (Core Team R, 2013) on two  
265 datasets per site corresponding to the PWT main physical characteristics *i.e.* depth level,  
266 thickness (from 2009 to 2015) and chemical properties (from 2008 to 2016).

267 A new variable, the annual average duration of PWT, was calculated from the PWT level  
268 dataset; it represents the number of days per year during which the PWT was at a level lower  
269 than about 44 cm depth, *i.e.* the clayey floor. For this, we calculated the average annual  
270 duration of corresponding captors for each plot, and weighted the average of each captor by  
271 considering the real number of days per year during which the captor was functional.

272 An analysis of variance (anova) was applied on each site from a linear model to test the  
273 significance of the fixed effect of one or more factors, related to the soil treatment, the period  
274 of time (year and seasons) and the spatialization (depth), on different quantitative variables:

275 PWT (1) daily level, (2) annual average duration and (3) chemistry properties (i.e. 21  
276 chemical compounds). For the two first quantitative variables, an analysis was carried out  
277 either considering all blocks or per block. The general form of the model is the following:

$$Y = \mu + \sum_{(i,j)} Fef_i^{(j)} + Ref + \varepsilon \quad (I)$$

278 With  $Y$  the quantitative variable,  $\mu$  the grand mean of the model,  $Fef_i^{(j)}$  the  $i$ -th fixed effect  
279 of an individual factor ( $j = 1$ ) or combining a number of  $j$  factors,  $Ref$  the random effect  
280 normally distributed with mean 0 and variance  $\sigma_R^2.Id$  and  $\varepsilon$  the random error term normally  
281 distributed with mean 0 and variance  $\sigma^2.Id$ .

282 For the PWT daily level, a total of three factors (soil treatment, year and season) and all  
283 possible double and triple interactions were tested as fixed effects. The factor representing the  
284 number of the captor was added in the model as a random effect, and the variance of the error  
285 term was weighted by the number of measures collected for each day. Otherwise, groups for  
286 the season factor were defined from the astronomical dates and nested within groups of the  
287 year factor, to test interactions combining the two periods of time. Thus, each year started on  
288 March 21<sup>th</sup> and finished on March 20<sup>th</sup> of the following year. For the analysis per block, the  
289 data of block 2 at CA collected from 2009 to 2012 were excluded because of a large amount  
290 of missing data. For the PWT annual average duration, only the soil treatment factor was  
291 tested as a fixed effect and a non-random effect was added in the model. For the PWT  
292 chemistry, three factors corresponding to the soil treatment (C and T), the annual time period  
293 and the sampling depth with all possible double interactions were tested as fixed effects at  
294 CA, and only the two first factors with their interaction at AZ. The interaction between the  
295 three factors was not considered in the model because the sample size was too small. The  
296 factor related to the number of the block was added in the model as a random effect. The

297 sampling depths retained in the analysis are 25 and 45 cm for CA and 45 cm for AZ. For the  
298 other depths, sample sizes were too unbalanced between the two soil treatments.

299 In order to obtain a general overview of the compaction effect on PWT solutions, we used a  
300 standardized principal component analysis (PCA), first for individual sites, and second for  
301 comparing both sites. The PCA highlighted the impact of several relevant factors (site, block,  
302 soil treatment, and annual and seasonal time period). The PCA led to reducing the initial data  
303 represented in a  $P$ -dimensional space to a  $A$ -dimensional subspace, such as  $A < P$ . The new  
304  $A$ -dimensions generated represent the principal components (PCs), a linear combination of  $P$   
305 initial quantitative variables. We only considered a limited number of PCs  $a \in \{1, \dots, A\}$  from  
306 the PCA model, representing about 50 % of the total cumulative explained variance  
307 (maximum 4).

308 Otherwise, we calculated the  $T^2$ -Hotelling's and  $Q$ -residual distances to detect and identify  
309 outliers in the dataset (Jackson & Mudholkar, 1979). The indices provided complementary  
310 information by describing the variation of each observation within and outside the new  $a$ -  
311 dimensional subspace respectively. Consequently, deleting observations with a high value of  
312 the  $T^2$ -Hotelling's distance would have a large impact on the PCA model, but deleting those  
313 with a high value of the  $Q$ -residual distance would have a limited impact on results. Finally,  
314 factors were represented as the centroid of observations projected in the  $a$ -dimensional  
315 subspace, which belong to it. The dispersion of observations around the centroids, was  
316 represented by a 95 % confidence ellipse (Worley et al. 2013).

### 317 **3- Results**

#### 318 **3.1 The soils**

##### 319 3.1.1 General characteristics

320 At both sites soils are classified as Luvisol (ruptic) according to IUSS (2014), they are  
321 polycyclic *i.e.* developed from two geologic materials, a continental quaternary silt loam layer

322 approximately 50 cm thick, laying on a more ancient clayey material. At AZ the fluvial loamy  
323 quaternary layer lies on weathered marls of the Keuper; in CA the loamy quaternary material  
324 lies on weathered gault of the Cenomanian. This strong textural discontinuity causes a limited  
325 temporary water logging, but did not lead to hydromorphic soils; hydromorphic features were  
326 limited in both cases to the very lower part of the silty layer, at the contact with the clay rich  
327 layer. Consequently, these soils are considered as highly sensitive to compaction.

328 Nevertheless, this feature masked significant differences between the soils of the two sites  
329 (Goutal et al. 2011, Bedel et al., 2016) *e.g.* the clay content in both the upper and lower layers  
330 are lower at CA than at AZ respectively (13 to 15 at CA vs 22 to 24 at AZ) and (33 to 34 at  
331 CA vs 45 to 60 at AZ) (table 1); the clay mineralogy at AZ is an almost pure Illite in the deep  
332 soil layer and an complex admixture of Illite, kaolinite, chlorite and vermiculite, associated  
333 with interstratified and intergrade minerals in the upper soil layers. At CA, the clays in the  
334 deep clayey layer consist in an admixture of kaolinite, illite and a swelling clay of the Fe-  
335 beidellite group. In the soil upper layers, the same spectrum was identified, but the swelling  
336 Fe-Bedellitic material strongly decreased although still present in both pure and interstratified  
337 phases (Bedel et al., 2018).

338 Soil geochemical context: both soils are acidic, at CA the  $\text{pH}_{\text{water}}$  was about 4.5 in the upper  
339 soil layers (0-45cm) and around 5.0 in the deep clayey horizons (below 60 cm), while at AZ  
340 the upper organic horizon has a significantly higher pH of about 4.8 that decreases to 4.6 in  
341 the loamy horizons poor in organic matter (10-45cm), then increases to 5.0 in the deeper  
342 clayey horizons. Organic C content was the same in the [0-10 cm] layer of the two sites (2.6  
343  $\text{g } 100\text{g}^{-1}$ ), but about two fold lower in the next horizons at CA compared with AZ.  $\text{N}_{\text{org}}$  is  
344 lower at CA (1.4 vs 1.8  $\text{g kg}^{-1}$  in the [0-10 cm] horizon), and then about two fold lower in CA  
345 compared to AZ. The C:N ratio was higher in CA than in AZ soils (18 vs 15 on the [0-20 cm]  
346 layer). Cation exchange capacity at CA, varied from 3.5 to 4.0 in surface and from 16 to 18

347 cmol+ kg<sup>-1</sup> in depth and at AZ it varied from 4.0 to 4.5 in surface and from 12 to 15  
348 cmol+ kg<sup>-1</sup> in depth. The “base” cation saturation rate was about two fold higher for  
349 comparable depths in the upper layers at AZ than at CA (63 vs 29% respectively for [0-10  
350 cm] ; 24-30 vs 12-15% respectively for [10-45 cm]), but similar in the deep layers (50-70% at  
351 AZ vs 45-60 % at CA).

### 352 **3.1.2 Changes in soil bulk density and porosity due to compaction**

353 The initial dry bulk density was systematically about 10% higher at CA than AZ for both C  
354 and T treatments (Table 2). Because very limited recovery of bulk density was observed  
355 during site monitoring, this data set was used for the soil porosity and soil water reservoir  
356 content calculations. Total porosity was functionally linked to dry bulk density, with a  
357 common statistical linear relation, for both sites and treatments. On average, macro porosity  
358 represented 40 % of the total porosity at AZ and 48 % at CA. After compaction macro  
359 porosity was reduced by 70 % at AZ but only 56 % at CA.

360

## 361 **3.2 Physical parameters of the perched water table (PWT)**

### 362 **3.2.1 level and duration of the PWT**

363 The reference level expressed relative to the soil surface (level 0) is about the same at  
364 Azerailles (AZ) and at Clermont en Argonne (CA) ca. about 44-45 cm (table 3). It  
365 corresponds to the minimum level of measurement of the “Divers”.

366 At both sites, and for both the C and the T treatments, the highest mean and maximal levels  
367 occurred during the winter period. In both cases the highest levels were for the compacted  
368 treatment, but the difference with the control was larger at AZ than at CA, and it was more  
369 pronounced for the mean (60%) than for the maximum (18%) levels.

370 The thickness of the PWT is another way to present the data (table 3):

371 - In winter, in C the mean thickness was 2.2 cm in AZ while it was 5 cm in CA; the  
372 maximum thickness was 18.8 cm in AZ while it was 25.6 cm in CA,

373 - In winter, in T the mean thickness was 12.6 cm in AZ while it was 9.5 cm in CA; the  
374 maximum thickness was 33.1 cm in AZ while it was 38.2 cm in CA.

375 In the control C, considering all the seasons, the mean values for the thickness of the PWT  
376 during 7 years tended to be larger in CA than AZ, for both mean and maximum values, while  
377 in the compacted T treatment, they tended to be the largest in AZ except for the maximum  
378 levels in autumn and in winter.

379 Over the 7 years of monitoring, during the winter period when the PWT occurred the most  
380 frequently, the maximum levels in both C and T treatments did not change significantly at  
381 AZ. These maximum levels varied more widely in the C (extreme values of -16.5 cm in 2010  
382 and -35 cm in 2013), than in the T (extreme values of -8.3 cm in 2015 and -11.9 cm in 2012)  
383 (data not shown). The mean PWT levels during the same winter period showed a significant  
384 decrease for C ( $r = 0.71$  significant for a probability of 5%) and a quasi statistically significant  
385 increase in T ( $r = 0.68$  significant for a probability between 5 and 10 %). The fluctuation was  
386 larger in the T (range between -36.8 cm in 2010 and -27.8 cm in 2014 and 2015) than in the C  
387 treatment (range between -40.9 cm in 2013 and -40.8 cm in 2010). Over the 7 years, the  
388 winter rainfall did not change significantly (range between 140 and 260 mm per year) (figure  
389 2A).

390 At CA the maximum level of the PWT in winter did not change significantly between 2009  
391 and 2015 in the C treatment, while it decreased significantly in the T treatment ( $r=0.76$   
392 significant for a probability of 5%). The range of variation was from -15.1 cm in 2010 and -  
393 23.8 cm in 2013 in the C, and, between -2.3 cm in 2010 and -10.5 cm in 2015 in the T  
394 treatment (data not shown). During the same period, the mean level significantly increased in  
395 the control C ( $r = 0,92$  significant for a probability of 5%), while it did not change

396 significantly in the compacted T plots (figure 2B). During the winter period, the rainfall  
397 increased significantly between 2009 and 2015 ( $r = 0.81$ ); this was also the case when  
398 cumulating autumn and winter rainfalls.

399

### 400 3.2.2 Duration of the PWT: time changes during the 7 years of observation

401 In the control C treatment, a PWT occurred during some events at both sites (table 4): on  
402 average over the 7 years of monitoring, the PWT lasted 26 days per year in AZ and 41 days in  
403 CA. The PWT occurred mainly during the winter period, *e.g.* 13 days in AZ and 23 days in  
404 CA. The compaction strongly increased the frequency of occurrence of the PWT at both sites,  
405 at AZ in particular with 136 days per year (comparatively at CA, 78 days per year). The  
406 increase in frequency mainly occurred during the winter period *e.g.* + 45 days in AZ and + 12  
407 days in CA, site where nevertheless the increase in frequency was evenly spread out during  
408 the whole wet period.

409 Additional relevant information came from the mean duration of a PWT event, comparing the  
410 C and T treatments, for different fixed levels, at the two experimental sites (table 5). A first  
411 divergence between the C and T treatments was observed for the number of events; this  
412 difference increased with the thickness of the PWT, *e.g.* the T: C ratio varied from 1.8 for the  
413 5 cm thickness to 6.7 for the 20 cm thickness at AZ, while it varied from 1.9 to 2.6 at CA for  
414 respectively the same levels. A larger difference appeared when considering the duration of  
415 events *e.g.* in C the mean duration was 4 to 5 times higher at AZ than at CA, and in the T it  
416 was 12 to 17 times higher at AZ, according to the thickness selected (5 to 20 cm). The ratios  
417 T: C were of 3.4 to 3.9 at AZ while they only varied from 1 to 1.2 according to the thickness  
418 considered at CA.

419 The changes in terms of duration for the occurrence of PWT during the 7 years of  
420 observation, showed no significant trend for the whole year, in both C and T treatments at CA

421 and AZ. During the winter wet period no significant trend was noticed at CA but a significant  
422 increase in the number of days with PWT appeared in the T treatment of AZ (from 50 to 70  
423 days), and a concomitant trend (only significant at 10%) to a decrease in the duration of PWT  
424 in the control C (from 20 to 10 days) (figure 3).

425 In terms of mean residence time of the PWT (figure 4), at AZ, no significant trend was  
426 noticed for the T (mean value =93 hours), but a constant decrease (only significant at 10%)  
427 from 40 to 20 hours in the C plots (mean value =30 hours) was found during the winter  
428 period (scenario 15 cm). Fluctuations were far more limited in the C than in the T. At CA,  
429 the pattern was rather different with very similar significant decreasing trends (significant at  
430 5%) in winter for T (mean value =12 hours) and C (significant at 10%) (mean value =  
431 9hours). Differences between the C and T treatments at CA decreased from 2008 and 2011  
432 and the MRT of the PWT was very similar between treatments thereafter.

433

### 434 **3.3 Chemistry of the PWT**

#### 435 3.3.1 Compaction effect on element concentration in the PWT

436 At Azerailles in the C, no sample was collected for water chemistry at 15 cm depth and only  
437 one sample was collected at 30 cm. Statistics were only possible for the deeper soil layer to  
438 directly compare C and T plots, which of course represents only a part of the compaction  
439 effects. Mean results for the observation period presented in the table 6 show that the effect of  
440 compaction was strongly significant for most elements, directly (treatment effect 15 over 22  
441 measured elements) or indirectly (interaction treatment x year, 6 over 22 cases). At 45 cm  
442 depth, compaction increased the Fe, F,  $\text{SO}_4^{2-}$ , S, P,  $\text{Mn}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$  and DOC concentrations,  
443 but decreased  $\text{Cl}^-$ , Si,  $\text{Ca}^{2+}$ ,  $\text{NH}_4^+$ , TN and  $\text{N}_{\text{org}}$  concentrations. Year effect was significant (18  
444 over 22 cases) for all elements but  $\text{Fe}^{2+}$ , Si,  $\text{K}^+$  and  $\text{H}^+$ . The interaction between treatment and  
445 year was significant for  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2+}$ ,  $\text{Na}^+$ , TN,  $\text{N}_{\text{org}}$  concentrations. In general, in the T

446 treatment, concentrations decreased with depth for all elements except for F,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , Si,  
447  $\text{Na}^+$ ,  $\text{NH}_4^+$ .

448 At CA where the frequency and duration of PWT were higher than at AZ in the soil surface  
449 layers, the PWT chemistry dataset was sufficient to carry out statistical analysis for the  
450 medium and deep PWT levels (the number of samples was 5 vs 55, 37 vs 96 and 203 vs 225  
451 respectively for C and T and for the 10, 25 and 45 cm). The compaction effect (table 7) was  
452 significant for both levels for most elements (14 and 17 vs 22 and 17 and 19 vs 22,  
453 respectively for the 25 cm and 45 cm depths). For the 25 cm depth PWT level, compaction  
454 increased  $\text{Fe}^{2+}$ ,  $\text{NO}_3^-$ ,  $\text{Cl}^-$ , P, Fe, Al,  $\text{NH}_4^+$  and DOC concentrations, but decreased F,  $\text{SO}_4^{2+}$ ,  
455 Si, and  $\text{Mg}^{2+}$  concentrations. For the 45 cm depth PWT level, no significant differences were  
456 observed between C and T treatments.

457 Correlations between anions (DOC,  $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ) and cations were used to identify the  
458 general impact of compaction on the geochemical control of elemental chemistry in the PWT  
459 at both sites.

460 At AZ, in the upper level (10 cm) of the T plot, the DOC controlled Fe and Al concentrations,  
461 but also secondarily Mg, Ca and K. Nitrate had little influence, and  $\text{SO}_4^-$  and  $\text{Cl}^-$  ensure the  
462 control of alkaline and alkaline-earths cations. At 25 cm depth in the T, the same geochemical  
463 control was observed, but nitrate influence increased. The impact of compaction was only  
464 statistically analysed at 45 cm depth, where C and T showed no great differences in terms of  
465 relative geochemical control: the DOC effect became negligible, nitrate, sulphate and chloride  
466 controlled the cation mobility. The compaction effect led on concentration changes of the  
467 anion drivers (see table 6), especially for  $\text{SO}_4^{2-}$ , which could be an expression of S-  
468 compounds reduction, sulphate still being in equilibrium in a moderately reductive  
469 environment (White, 1998).

470 At CA, the compaction resulted in an increase in DOC control on Fe and Al for all levels of  
471 the PWT, a decrease in  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$  controls on cations at the upper levels, but in the  
472 reinforcement of the role of these anions for the deepest level.

### 473 3.3.2 PCA for identifying the main effects of compaction

474 PCA was carried out only for PWT levels where treatments can be compared e.g. 45 cm depth  
475 level at AZ, and 25 and 45 cm depth at CA.

476 At each site, the three first axis explained more than 40 % of the total variance. The  
477 compaction effect was strong on PWT geochemistry, with explanatory variables mostly  
478 significantly different between the C and T treatments (in perfect agreement with the Anova  
479 results in tables 6 and 7). The spreading out of individual observations did not alter the  
480 significant difference in the position of the centroids of C and T populations in the plane of  
481 the axis 1&2 (figure 1A and 1B; supplementary material section).

482 PCA was also very helpful for highlighting the site effect: 49.2% of explanation of the  
483 variance was obtained with only 3 axis. Most variables were involved in the site  
484 discrimination. The different types of soil bedrocks easily explained both anion and cation  
485 differences. The similar constraint from compaction led to site dependant responses. The site  
486 effect is very well discriminated on all the combinations of the 3 first axis (see figure 2 of the  
487 supplementary material section, presenting data on the combination of axis 1 and 2). Its  
488 indicated that the single soil type in the two sites, encompassed rather different behaviours,  
489 illustrated by not a unidirectional but a centrifugal translation of C and T centroids along the  
490 axis 1.

### 491 3.3.3 Time changes on element concentration in the PWT

492 Before presenting the results, it is necessary to underline the difficulties occurring, first  
493 because of the sampling frequency for geochemistry, which was done once a month in the  
494 present study. Second, the changes in PWT geochemistry integrate several effects already

495 presented, namely: i- the clear-cutting effect which was considered as real if present in both C  
496 and T treatments, but considering a possible delayed effect at 45 cm depth, ii- the compaction  
497 effect that gave significant differences between C and T treatments, iii- the year-to-year  
498 changes in rainfall that increased the variability with a possible confounding effect in case of  
499 gradient, and iv- the soil porosity restoration effect which tended to reverse or at least  
500 decrease the initial differences between treatments.

501 At AZ, where sampling concerned more or less exclusively the deeper soil layer in the  
502 control, the clear-cutting effect appeared for some elements DOC, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup> and NH<sub>4</sub><sup>+</sup>, but  
503 was delayed for the three last ones. The compaction effect was significant for numerous  
504 elements like Cl<sup>-</sup>, Si, Ca<sup>2+</sup> (<0 impact) and for SO<sub>4</sub><sup>2-</sup>, DOC, Mg<sup>2+</sup>, Na<sup>+</sup>, NH<sub>4</sub><sup>+</sup>, Fe<sup>2+</sup>, Mn<sup>2+</sup> (>0  
505 impact) (table 7). The year-to-year variability was high for almost all elements. The most  
506 general trend was a decrease in the initial effect of both clear-cutting and compaction, and  
507 then a stabilisation of the compaction effect (~~figure 7~~ figure 5; case of Fe<sub>2</sub><sup>+</sup>). Only in two  
508 situations, the dampening of the compaction effect was observed: the effect tended to  
509 disappear during the very last years of monitoring, when the concentrations became the same  
510 in C and T (case of mineral-N; see ~~figure 8~~ figure 6 for NH<sub>4</sub><sup>+</sup>) or when they converged  
511 towards non-significant differences (SO<sub>4</sub><sup>2-</sup>). The compaction impact and its duration can be  
512 estimated on the upper soil layers for some elements, but the risk of a confounding effect  
513 between compaction and clear-cutting is real, as no sample was collected in the control. It was  
514 possible to rule in the situation of convergence of concentrations towards a single value: this  
515 was the case for DOC and mineral-N at 10 and 25 cm, and for Al and Fe<sup>2+</sup> at 10 cm depth.

516 At CA, the clear-cutting effect appeared for Si, SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, DOC, Mg<sup>2+</sup> and Ca<sup>2+</sup>. The  
517 compaction effect was significant for all elements except for Na<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup> for all levels  
518 (table 7). The year-to-year variability was high for Fe<sup>2+</sup>, NH<sub>4</sub><sup>+</sup>, DOC and Mn<sup>2+</sup>. Significant  
519 decreasing trends were observed for numerous elements like Si, Al<sup>3+</sup>, Fe<sup>2+</sup>, Mg<sup>2+</sup>, Ca<sup>2+</sup>, Mn<sup>2+</sup>,

520  $\text{Na}^+$ ,  $\text{NH}_4^+$ ,  $\text{Cl}^-$ , and DOC. Finally, a dampening of the initial effect of compaction appeared  
521 for  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Al}^{3+}$ , DOC,  $\text{NH}_4^+$ ,  $\text{Cl}^-$  and  $\text{NO}_3^-$  (upper level) but not for  $\text{SO}_4^{2-}$ , Si  
522 and  $\text{NO}_3^-$  (lower level) (Figure 9 figure 7 presents the case of  $\text{SO}_4^{2-}$  where no dampening  
523 effect was observed).

#### 524 3.3.4 Effect of residence time on PWT geochemistry

525 Chemistry of the PWT was related to its residence time using the mean concentrations  
526 and mean-residence times for the specific levels (10, 20 or 45 cm) and for the period  
527 considered (wet season or whole year). Three types of situations were observed at AZ for the  
528 relations calculated for the 45 cm level *i.e.* nil ( $\text{NO}_3^-$ , DOC,  $\text{NH}_4^+$ ,  $\text{Cl}^-$ ), positive ( $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$ ,  
529  $\text{Mg}^{2+}$ ,  $\text{Al}^{3+}$ ,  $\text{Na}^+$ ,  $\text{SO}_4^{2-}$ ) (the example of  $\text{Fe}^{2+}$  is presented in figure 10 figure 8), or negative  
530 ( $\text{Ca}^{2+}$ , Si) relations. At CA, these relations calculated for the 25 and 45 cm levels showed that  
531 the concentrations of only three elements were related to MRT (DOC,  $\text{NH}_4^+$  and  $\text{Fe}_2^+$ ). More  
532 significant relations were observed for the upper (significant at 5%) than in the deeper  
533 (significant at 10%) PWT level. ~~For all other elements no relation appeared between MRT~~  
534 ~~and PWT chemical composition.~~

535

## 536 4 Discussion

### 537 4.1 Soil compaction drastically changed the PWT behaviour

538 At both sites, compaction led to a decrease in soil porosity. Macro-porosity was the most  
539 affected as it has been commonly observed (de Paul and Bailly, 2005). Consequently, for the  
540 same rainfall input, the soil moisture tended to increase more in the T than in the C treatment,  
541 because the size of the reservoir is smaller, and because during the wetter period of the year  
542 the soil bottom is sealed. Vertical transfer of rainfall input was more limited in the T  
543 treatment than in the control C thus increasing the number of occurrences (x 4 at AZ and by 2  
544 at CA), the height and mean residence time (x by 5 at AZ and by 2 at CA) of a perched water

545 table in the T treatment. Though the soil physical characteristics (a silty soil laying on a  
546 clayey subsoil) at the two experimental sites are similar, PWT dynamics, although showing  
547 the same relative trends, were notably different in terms of absolute values.

548 What environmental characteristics are able to explain the specific behaviour of PWT in each  
549 site? Mean total annual rainfall was exactly the same during the study period, so was the  
550 decrease in total porosity due to compaction in both sites (from 45 to 50 dm<sup>3</sup> per m<sup>3</sup>). Soil  
551 characteristics like clay content (25 at AZ vs 15 % at CA) and total porosity (530 at AZ vs  
552 500 dm<sup>3</sup> per m<sup>3</sup> at CA), and climatic parameters like rainfall in autumn (+6,5 mm) and in  
553 winter (+65 mm) in the CA site, may explain the higher PWT occurrence in the control (C) at  
554 CA than in AZ (41 days vs 26). But all these parameters failed to explain why the mean  
555 number of days with PWT in the T treatment was lower at CA when compared to AZ (78 vs  
556 136). The soil texture and mineralogy, and more particularly its clay fraction, on the one  
557 hand, and the soil Ca-Mg saturation on the other hand, were found to play a major role in the  
558 stability of the soil structure in the two sites (Bedel et al., 2018).

559 We hypothesised a complex and somewhat antagonistic role of the clay fraction, which would  
560 interact with the soil richness, higher at AZ (mean soil “base” cation saturation value of 37)  
561 than at CA (mean value of 19):

562 i- The higher clay content at AZ favoured a relatively more stable structure than at CA.  
563 After compaction, which destroyed the structure and increased the soil physical resistance  
564 (Goutal et al, 2013), this higher clay content would play a major role in the loss of soil  
565 permeability; the “base cation” rate being not enough high to compensate for the loss of  
566 structure,

567 ii- The occurrence of a swelling beidellite-Fe clay type at CA (dominant in the subsoil,  
568 and significant in the soil) (Bedel et al., 2018) was shown to be negative for the soil structural

569 stability at CA, but would be efficient for a rapid cracking of the compacted soil when soil  
570 moisture decreased.

571 Compaction therefore drastically changed the geochemical functioning of the soils, and two  
572 parameters had strong consequences on it: i- the level reached by the PWT in the soil, which  
573 mean value was multiplied by 5 in winter at AZ and by 2 at CA, because of the soil  
574 horization, and, ii- its duration, as the mean annual number of days of occurrence was  
575 multiplied by 4 at AZ and by 2 at CA, and as its mean residence time (MRT) was multiplied  
576 by 4 at AZ and only by 1.1 at CA.

577 One major effect of compaction was the fact that PWT invaded upper soil layers, which  
578 were never or very rarely affected by waterlogging processes. It is very well known that upper  
579 soil layers contain most of the organic C, the organic forms of many other elements, and the  
580 biological populations and activity. Compaction led to new soil forming-processes, which  
581 strongly impacted both mineral (ion exchange, dissolution/precipitation, weathering rate) and  
582 biological (organic C, N, P, S mineralization) processes. These two soils, classified as  
583 sensitive to physical degradation, shifted towards typical hydromorphic soils, only a few  
584 months after the compaction stress. The question of the reversibility of the processes is  
585 strongly relevant, but difficult to investigate, just because no control situation is available for  
586 the dynamics of changes in the upper soil layers of the compacted treatment. However,  
587 whether restoration occurred or not, element redistribution clearly marked soil morphology  
588 (unpublished information of the site database) with hydromorphic traits *e.g.* thin iron pans,  
589 Fe/Mn stains or concretions, or drainage losses (Fe, Mn, C and nutrients), bleached areas, and  
590 decreased the soil quality for all its functions.

591 Changing the MRT strongly impacted the processes leading to the geochemistry of the PWT.  
592 When looking at common specific soil layers temporally waterlogged in both the C and T  
593 treatments we found three cases:

594 1- Though trends were observed between C and T, these differences were not statistically  
595 significant suggesting that MRT was not long enough to mobilize more than the immediately  
596 available reserve of compounds, by ion exchange, by dissolution reactions, or by mixing with  
597 tightly bound water,

598 2- Significant negative relation between MRT and the concentration of a limited amount  
599 of very soluble compounds suggesting a simple dilution effect, and,

600 3- Significant positive relation between elemental concentrations (*e.g.* Fe, Mn and S) and  
601 MRT indicating that the duration of waterlogging changed a physical parameter which led to  
602 the development of specific processes affecting these sensitive elements to redox. This PWT  
603 duration effect promoted the development of slower processes like dissolution of meta-stable  
604 compounds, exchange with more tightly bound water, or even with the subsoil compartment.  
605 Indirect effects of changes in the environment led for example to the mobilization of elements  
606 that are not directly sensitive to redox processes like Al of mix-hydroxides. The mobilization  
607 of Al and sulphur in turn may mobilize compounds such as available cations or anions after  
608 ion-exchange or dissolution, and/or, change biological processes affecting directly C and N  
609 compound stability.

610 At AZ, the rather long MRT (1 day in the C but 4 days in the T) led to the three situations  
611 aforementioned while at CA, the shorter MRT (less than half a day in both C and T) led to  
612 only types 1 and 3. Paradoxically, it was at CA that the highest Fe<sup>2+</sup> concentrations were  
613 observed, suggesting that the redox conditions in solution for iron reduction were reached the  
614 most rapidly after waterlogging (~~figure 11~~ figure 9). This was not explained by more labile  
615 Fe-bearing compounds at CA compared to AZ: the Fe<sub>DCB</sub>: Fe<sub>Tot</sub> ratios suggested a higher  
616 lability at AZ. From a previous study, we hypothesized that the massive structure of the acidic  
617 CA soil when wet (Bedel et al., 2018), would rapidly lead to anoxic conditions.

618

619 **4.2 PWT time changes used as an indicator of the dynamics of soil restoration after**  
620 **compaction**

621 In the present experimental designs, changes occurring after compaction integrated several  
622 effects which had consequences on both physical and chemical characteristics of PWT *e.g.* i-  
623 the clear-cutting effect, ii- the changes in vegetation including both understory and oak  
624 developing plantation, iii- the year-to-year variability of the climate, and finally iii- the  
625 hypothetical restoration of soil porosity.

626 The change in soil porosity and its consequences on PWT were easy to characterize. The  
627 deconvolution on a relatively short time series of the global signals to identify the effects of  
628 individual parameters on porosity dynamics, was far more complex. It is known that clear-  
629 cutting and vegetation development have opposing effects on the soil water regime and soil  
630 water chemistry: the former usually increases soil moisture and elemental concentrations in  
631 soil solutions, while the latter does the reverse (Dyck et al., 1994). Year-to-year changes in  
632 the rainfall amount were able to disturb these general effects, especially when a systematic  
633 gradient occurred.

634 At AZ no changes were recorded in the rain amount along the study period. The mid-term  
635 trend was a reduction of the PWT in the control (attested by a significant decrease in mean  
636 level, duration in days, duration of individual events) but to an increase of the PWT in the  
637 compacted treatment (significant at 10% for the mean level and 5% for the duration in days).

638 At CA, where the winter-autumn rainfall significantly increased during the period of  
639 monitoring, the trend was close to a decrease of the difference of PWT physical  
640 characteristics between C (significant mean level increase in winter, and a individual event  
641 duration decrease) and T (significant decrease of the maximum level and of the duration of  
642 individual events).

643 Physical traits of the PWT led to the conclusion that no restoration of the soil porosity  
644 occurred 7 years after compaction at AZ, but that some restoration occurred at CA.  
645 We hypothesize that the mean level of PWT, which integrates all the PWT episodes, is a more  
646 robust indicator of soil restoration than the maximum level, which could be the result of few  
647 events.

648 The aforementioned confusing effects and the fact that at AZ no significant sampling was  
649 possible in the upper soil layers, made it more difficult to use the PWT geochemistry traits as  
650 indicators for soil restoration after compaction. Similarly to clear-cutting effects for example,  
651 some compaction effects could be mitigated and/or delayed in the deep soil layers. The  
652 vertical distribution in the soil profile of numerous elements in the T treatment, positively  
653 (DOC,  $\text{NH}_4^+$ ,  $\text{NO}_3^-$ ,  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{K}^+$ ,  $\text{Al}^{3+}$ ) or negatively ( $\text{Mg}^{2+}$ , Si,  $\text{SO}_4^{2-}$ ) correlated with soil  
654 depth, consolidated this point.

655 Taking all these parameters into account led to the conclusion that indexes of soil restoration  
656 using PWT geochemistry showed very limited changes in AZ where only mineral-N indicated  
657 some restoration. At 45 cm depth, sensitive element like  $\text{Fe}^{2+}$  or  $\text{Mn}^{2+}$  did not show any  
658 changes with time, excepted the decrease in the strong initial effect of compaction. The  
659 behaviour  $\text{Na}^+$  was peculiar and seemed to indicate a degradation of the situation! There was  
660 probably a more pronounced restoration rate in the upper soil layers, but we already presented  
661 the difficulty to estimate it.

662 On the contrary, at CA, all elements but Si and  $\text{SO}_4^{2-}$ , for both 20 and 45 cm levels and  $\text{NO}_3^-$   
663 at 45 cm, showed a significant dampening of the initial effect of compaction. As previously  
664 explained, we hypothesized that clay content and nature, through the soil structure stability  
665 was a major parameter controlling the physical characteristics of the PWT, and indirectly its  
666 geochemistry.

667 The PWT physical and geochemical indicators were in rather good agreement, and both  
668 suggest the restoration of soil porosity in the specific situation of each experimental site. This  
669 was clearer at CA in a situation where the PWT flooded the medium and lower soil layers of  
670 both the C and T treatments, than at AZ, where only the lower layer could be investigated  
671 with both physical and chemical indicators, limiting the relevance of the information collected  
672 from the geochemical investigation.

673 Our experience leads to the conclusion that physical traits of the PWT, far easier to monitor  
674 than chemical ones, could be investigated alone for a satisfactory diagnosis of the restoration  
675 of soil porosity. Nevertheless, to characterize the short and long terms effects on all the  
676 components of soil fertility, the geochemical traits add strongly relevant information.

677

#### 678 **4.3 Consequences for forest management?**

679 Using the PWT as an indicator of forest soil recovery after application of a limited  
680 compaction stress showed its relevance and its ability to sort between two relatively similar  
681 situations inside an identical soil type.

682 We hypothesized that the richer soil would recover more rapidly than the poorer one, because  
683 recovery should be related to soil quality, including physical (better structure stability),  
684 chemical (richness in 'base cations') and biological (flora indication, earthworms activity).

685 This hypothesis was not verified.

686 At AZ, because limited or no soil recovery occurred during the 7 years after compaction, and  
687 because the complete recovery would not happen suddenly, the probability that an additional  
688 mechanized silviculture operation would take place before the complete restoration of the first  
689 disturbance is very high (in France rotation lengths are about 8 to 10 years for coniferous and  
690 12 to 15 years for broadleaved species). The effects of a second compaction event would be  
691 more dramatic and virtually impossible to predict. In such conditions, mechanized forest

692 operations must be strictly regulated to ensure the sustainable management of the forest:  
693 extraction tracks are recommended. This practice is already applied by forest managers in  
694 State-owned forests in France (Pischedda et al., 2009) but its evaluation is still on-going  
695 because the trafficability of the tracks must be maintained. Concerning the consequences of  
696 the disturbance, an unknown parameter is the mechanical behaviour of forest soils that have  
697 never been impacted by strong and repeated mechanical constraints: their pre-consolidation  
698 point (threshold pressure separating an elastic and recoverable soil deformation from a plastic  
699 and non recoverable soil deformation) should change, modifying the reversibility of the  
700 compaction (Dias Junior and Pierce, 1995).

701 The consequences on vegetation appeared to be site-dependent. On the short-term time scale,  
702 tree mortality increased (strongly at AZ and less at CA) and tree growth was reduced in T  
703 treatments compared to C (at both sites) (Ranger et al., 2015). In both cases, cleaning  
704 operations for eliminating the strong competition of understory vegetation in the compacted  
705 plots increased the costs for ensuring the development of young oak stands. Compaction  
706 directly affects the tree root system by increasing the soil bulk density and the soil physical  
707 resistance (Goutal et al., 2017). The resulting hydromorphy, drastically changing the  
708 functioning of the soil, represented a strong constraint for vegetation in terms of root  
709 respiration, water and nutrient uptake. The limited but real soil restoration at the low fertility  
710 site of CA was fortunate: Bedel et al. (2016) demonstrated that trees mobilised the sub-soil  
711 water and nutrient reserves during the dry periods. Nevertheless, it is necessary to  
712 demonstrate that the restoration of the deepest layers of the soil is real by investigating the  
713 soil solid phase (volume mass, physical resistance, morphology...). Any degradation of soil  
714 quality represents a real constraint for the durability of such ecosystems in the long term.

715

716

717 **5 Conclusions**

718 1- The results demonstrated that the limited controlled compaction of two sensitive silty  
719 soils belonging to the same ruptic neo-luvisols type, immediately and drastically changed the  
720 soil water regime, as shown by the physical and geochemical characteristics of the perched  
721 water table. Both soils shifted towards a hydromorphic type attested by an increase in the  
722 number of occurrences of a PWT and its duration, which flooded the soil upper layers and  
723 lead to characteristic mobility of Fe, Mn and S. Stability of organic C and N compounds was  
724 also changed: our first hypothesis is validated.

725 2- Even within the same soil type, a polycyclic soil composed of a 50 cm silty stratum  
726 laying on a clayey subsoil, the PWT characteristics notably varied. The mean residence time  
727 of the PWT was shown to be a major driver of its geochemistry, but with strong interaction  
728 with soil characteristics. A previous study made on both sites (Bedel et al.,2018) suggested  
729 that soil clay content and clay mineralogy controlled the PWT behaviour through aggregation.

730 3- Seven years after the application of the constraint were not enough to observed  
731 significant recovery, judged from the PWT, in the richer soil of AZ, but led to partial recovery  
732 of the poorer one at CA: our second hypothesis is not validated.

733 4- Short-term negative consequences on soil and vegetation were easily observable.  
734 Long-term consequences were more complex to simulate, most especially in the richer soil of  
735 AZ where little recovery occurred after seven years. This means that compaction durably  
736 impacted the soils and that the probability of a new compaction before the complete recovery  
737 of the first disturbance, has to be considered. Contrarily to agriculture soils that have been  
738 subject to compaction for years, forest soils have not, and their reaction to successive  
739 disturbances needs to be reliably investigated, particularly for changes in their intrinsic  
740 mechanical characteristics.

741

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751

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873

874 **Caption for tables and figures**

875

876 Table 1: Main soil characteristics for both sites

877 Table 2: Changes in soil bulk density and porosity due to compaction at both sites

878 Table 3: Mean seasonal level (A) and thickness (B) of the Perched Water Table at the two  
879 sites

880 Table 4: Mean duration of periods with or without perched water table according to seasons at  
881 both sites

882 Table 5: Impact of treatments (control C vs compacted T) on the mean annual number and  
883 duration of the perched water table events, for fixed levels, at the two sites

884 Table 6: Mean chemical characteristics of the perched water table at Azerailles during the  
885 observation period (mean values for concentration, results of the Anova test when possible).

886 Table 7: Mean chemical characteristics of the perched water table at Clermont-en-Argonne  
887 during the observation period (mean values for concentration, results of the Anova test when  
888 possible).

889

890 Figure 1: Design for PWT monitoring, physical characteristics (A), and chemistry (B)

891 Figure 2: Dynamics of the mean annual level of the PWT for the 2009-2015 period in the C  
892 and T treatments respectively at Azerailles (A) and at Clermont en Argonne (B).

893 Figure 3: Dynamics of the duration of occurrence of the perched water table in winter at both  
894 sites (Azerailles - green; Clermont en Argonne - red) (C control; T compacted)

895 Figure 4: Dynamics of the duration of individual winter events at both sites (Azerailles -  
896 green; Clermont en Argonne - red) in the control (C) and in the compacted (T) plots

897 Figure 5: The dynamics of  $\text{Fe}^{2+}$  according to the level of the PWT at the experimental site of  
898 Azerailles (54) in the C (control) and T (compacted) treatments.

899 Figure 6: Recovery after compacting; example given by the dynamics of  $\text{N-NH}_4^+$   
900 concentration in the PWT at the experimental site of Azerailles (54) in the C (control) and T  
901 (compacted) treatments.

902 Figure 7: Non recovery after compaction; example given by the dynamics of  $\text{SO}_4^{2+}$   
903 concentration in PWT for the C and T treatments of both 30 and 50 cm levels at the  
904 experimental site of Clermont-en-Argonne (55)

905 Figure 8: Relation between mean residence time of PWT and its  $\text{Fe}_2^+$  concentration at the  
906 experimental site of Azerailles (54)

907 Figure 9: Comparison of the relation between the mean residence time (MRT) of the perched  
908 water table (PWT) and its  $\text{Fe}_2^+$  concentration in the two experimental sites (Azerailles –  
909 green; Clermont en Argonne – red) (C control; T compacted).

910

911 Supplementary material

912 Figure I: PCA showing the main effects of compaction at the experimental sites of Azerailles  
913 (A) and Clermont-en-Argonne (B) (C control; T compacted – level considered 45/50 cm)

914 Figure II: Site effect on PWT chemistry shown by PCA (Azerailles AZ; Clermont en Argonne  
915 CA) (C control; T compacted – levels considered 25/30 cm and 45/50 cm)

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

*all data referred to soil fine earth dried at 105°C except CECclays referring to the clay fraction itself*

Table 1

site	treatment	soil depth (cm)	mean bulk density	density of solid	total porosity	macroporosity
Azerailles	C	0-10	0.97	2.62	62.8	19.7
	C	10-20	1.23	2.62	53.2	25.4
	C	20-30	1.29	2.64	51.0	24.0
	C	33-43	1.34	2.66	49.5	16.3
	C	50-60	1.34	2.69	50.2	
	T	0-5	1.17	2.62	55.4	6,3
	T	06-11	1.31	2.62	50.1	
	T	12-17	1.36	2.62	48.2	6,3
	T	18-23	1.44	2.62	45.1	
	T	25-33	1.41	2.64	46.7	
	T	35-45	1.43	2.66	46.4	6,3
T	50-60	1.38	2.69	48.6		
Clermont-en-Argonne	C	0-10	1.12	2.62	57.4	16.0
	C	10-20	1.29	2.62	50.8	30.3
	C	20- 30	1.36	2.64	48.3	
	C	30-40	1.42	2.62	46.6	26.7
	C	40-50	1.44	2.62	45.7	
	C	50-60	1.46	2.66	45.0	
	T	0-5	1.23	2.62	53.1	11.2
	T	5-10	1.38	2.62	47.3	
	T	10-15	1.44	2.62	44.9	

	T	15-20	1.50	2.62	42.8	7.5
	T	20-25	1.51	2.64	42.8	11.0
	T	25-30	1.50	2.64	45.1	
	T	30-40	1.51	2.65	42.9	
	T	40-50	1.50	2.66	43.7	
	T	50-60	1.51	2.66	43.3	

C control; T compacted

Table 2

AZERAILLES	control C			compacted T			control C		compacted T		Δ (T-C)	
	PWT level			PWT level			PWT thickness		PWT thickness		PWT thickness	
	cm											
	base	maxi	mean	base	maxi	mean	mean	maxi	mean	maxi	mean	maxi
	Spring	-44.0	-34.0	-42.5	-43.6	-15.2	-36.2	1.5	9.9	7.4	28.4	5.9
Summer	-44.0	-39.2	-43.3	-43.9	-21.8	-40.2	0.7	4.7	3.7	22.1	3.0	17.4
Autumn	-44.0	-33.4	-42.8	-43.9	-12.4	-36.0	1.2	10.6	7.9	31.6	6.7	21.0
Winter	-44.0	-25.2	-41.8	-43.0	-10.0	-30.4	2.2	18.8	12.6	33.1	10.5	14.2

CLERMONT en ARGONNE	control C			compacted T			control C		compacted T		Δ (T-C)	
	PWT level			PWT level			PWT thickness		PWT thickness		PWT thickness	
	cm											
	base	maxi	mean	base	maxi	mean	mean	maxi	mean	maxi	mean	maxi
	Spring	-44.5	-27.8	-41.8	-44.6	-15.4	-39.2	1.3	12.4	2.8	23.9	1.5
Summer	-44.5	-37.2	-43.8	-44.6	-27.2	-43.3	0.7	7.3	1.4	17.4	0.6	10.1
Autumn	-44.5	-27.4	-42.1	-44.6	-12.6	-39.1	2.4	17.1	5.6	32.0	3.2	15.0
Winter	-44.5	-18.9	-39.6	-44.6	-6.4	-35.1	5.0	25.6	9.5	38.2	4.5	12.7

*base, maximum and mean level of the PWT represents the level integrated for the whole season relatively to the soil surface (level 0)*

Table 3

period	Perched Water Table	AZERAILLES				CLERMONT en ARGONNE			
		C	T	$\Delta$ (T-C)	statistics	C	T	$\Delta$ (T-C)	statistics
Spring	with	5	28	23		5	16	11	
Summer	with	1	13	12		2	6	4	
Autumn	with	7	37	30		11	21	10	
Winter	with	13	58	45		23	35	12	
year (mean value)	with	26	136	110	S	41	78	37	S
year (mean value)	without	339	229	-110	S	324	287	-37	S

S = significant, here for the whole experiment and for individual blocks (except for the block II at CA)

Unit = number of days

Table 4

level from the PWT floor	control C				compacted T				T:C ratio		T:C ratio	
	mean number of events		mean duration of events (hours)		mean number of events		mean duration of events (hours)		number of events		duration of events	
	AZ	CA	AZ	CA	AZ	CA	AZ	CA	AZ	CA	AZ	CA
+ 5 cm	12	12	38	7	21	23	135	8	1.8	1.9	3.6	1.1
+ 10 cm	8	9	31	7	19	23	118	7	2.4	2.6	3.8	1.0
+ 15 cm	5	8	25	6	20	20	98	6	4.0	2.5	3.9	1.0
+ 20 cm	3	7	21	5	20	18	71	6	6.7	2.6	3.4	1.2

AZ: Azerailles

CA: Clermont-en-Argonne

Table 5

traitement		depth	sampling points	sample size		Fe <sup>2+</sup>	F <sup>-</sup>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	S	P	Fe	Si	Mn	Mg	Al	Ca	Na	K	N-NH <sub>4</sub> <sup>+</sup>	TC	TN	Norg	H <sup>+</sup>	
						mg L <sup>-1</sup>																					
Control		15 cm	6	0																							
compacted		10 cm	6	82	mean	0.17	0.02	2.09	0.32	6.40	0.07	2.27	0.08	1.10	4.37	0.87	0.66	1.13	2.79	1.21	2.36	0.12	20.97	1.35	1.16	0.004	
					SD	0.16	0.01	0.49	0.29	1.49	0.08	0.7	0.07	0.62	0.56	0.86	0.16	0.71	0.68	0.25	1.04	0.14	10.88	0.76	0.76	0.001	
treatment effect t	(1)																										
year effect y	(1)																										
interaction txy	(1)																										

Control		30 cm	6	1	mean	0.04	0.00	1.09	2.66	4.58	0.00	1.64	0.04	0.86	5.79	0.14	0.29	1.07	1.47	0.88	1.12	0.29	10.45	0.96	0.07	0.01
compacted		25 cm	6	175	mean	0.11	0.03	1.74	0.43	8.05	0.02	2.82	0.04	0.76	4.46	1.69	0.54	0.74	2.24	1.30	1.07	0.15	13.17	0.77	0.51	0.009
					SD	0.05	0.01	0.69	0.40	2.55	0.02	0.85	0.02	0.36	0.46	1.20	0.09	0.36	0.48	0.35	0.26	0.10	3.52	0.29	0.27	0.003
treatment effect t	(1)																									
year effect y	(1)																									
interaction txy	(1)																									

Control		50 cm	6	181	mean	0.02	0.06	2.23	2.26	9.84	0.01	3.24	0.01	0.29	5.72	0.12	0.86	0.32	2.83	1.47	0.48	0.24	8.45	1.13	0.35	0.009
					SD	0.01	0.01	0.88	1.95	0.96	0.01	0.43	0.01	0.05	0.48	0.08	0.16	0.08	0.35	0.14	0.06	0.18	3.35	0.63	0.39	0.002
compacted		45 cm	6	295	mean	0.07	0.09	2.06	2.56	12.98	0.01	4.15	0.02	0.48	5.10	1.44	1.11	0.44	2.50	2.17	0.57	0.23	11.07	0.99	0.34	0.055
					SD	0.08	0.03	1.01	3.93	1.93	0.01	0.60	0.01	0.18	0.34	1.05	0.25	0.16	0.59	0.18	0.08	0.19	2.72	0.93	0.27	0.129
treatment effect t						***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	*	***	***	***
year effect y							***	***	***	***	***	***	***	***	*	***	*	***	***	***	***	***	***	***	***	*
interaction txy								***	***	**										***			***	***	***	

Control	(2)	70 cm	3	158	mean	0.01	0.04	7.49	0.66	10.63	0.02	3.58	0.01	0.16	7.33	0.04	1.35	0.16	3.95	3.15	0.38	0.33	7.06	0.76	0.30	0.008
---------	-----	-------	---	-----	------	------	------	------	------	-------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	-------

					SD	0.01	0.01	0.90	0.35	0.82	0.03	0.15	0.01	0.08	0.38	0.03	0.13	0.07	0.39	0.29	0.04	0.27	2.71	0.43	0.34	0.001
--	--	--	--	--	----	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	-------

(1) insufficient data for statistics

(2) no sampling device in the compacted treatment (T)

statistics

\*\*\* p>0.001

\*\*

0.01<p<0.001

\*

0.05<p<0.01

Table 6

		depth	sampling points	Sample size		Fe <sup>2+</sup>	F <sup>-</sup>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	S	P	Fe	Si	Mn	Mg	Al	Ca	Na	K	N-NH <sub>4</sub> <sup>+</sup>	TC	TN	Norg	H <sup>+</sup>	
						mg.L <sup>-1</sup>																					
Control		15 cm	6	5	mean	0.13	0.01	1.04	2.43	2.00	0.00	0.73	0.03	0.40	2.50	0.10	0.19	0.73	1.42	0.62	1.16	0.13	20.56	1.51	0.79	0.01	
					SD	0.05	0.01	0.34	0.29	1.00	0.00	0.07	0.01	0.07	0.50	0.05	0.03	0.24	0.32	0.05	0.53	0.16	7.51	0.44	0.52	0.00	
Compacted		10 cm	6	55	mean	0.28	0.01	1.64	1.31	2.01	0.04	0.89	0.04	0.51	2.22	0.20	0.30	0.69	1.89	0.71	2.08	0.70	29.70	2.64	1.44	0.01	
					SD	0.39	0.01	0.49	0.91	0.97	0.07	0.36	0.02	0.25	0.96	0.18	0.11	0.32	0.56	0.19	1.28	0.81	15.88	2.13	1.32	0.00	
treatment effect t	(1)																										
year effect y	(1)																										
interaction txy	(1)																										
Control		30 cm	6	37	mean	0.04	0.04	1.63	7.20	4.44	0.01	1.56	0.01	0.20	3.91	0.20	0.50	0.54	2.20	0.95	1.13	0.06	12.75	1.42	0.16	0.01	
					SD	0.02	0.04	0.89	9.93	1.86	0.02	0.65	0.01	0.17	1.01	0.22	0.28	0.23	1.11	0.26	0.39	0.04	7.02	0.82	0.97	0.00	
Compacted		25 cm	6	96	mean	0.15	0.02	1.73	2.32	2.48	0.02	0.98	0.03	0.44	2.93	0.23	0.32	0.69	1.86	0.82	1.39	0.39	22.41	1.95	0.97	0.01	
					SD	0.15	0.01	0.54	1.38	1.21	0.04	0.35	0.02	0.34	0.94	0.25	0.14	0.44	0.44	0.20	0.55	0.37	12.05	1.11	1.10	0.00	
treatment effect t						***	***		***	***		***	***	***	***		***	**				***	***				
year effect y						***	***	***		***	**	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	*
interaction txy	(1)																										

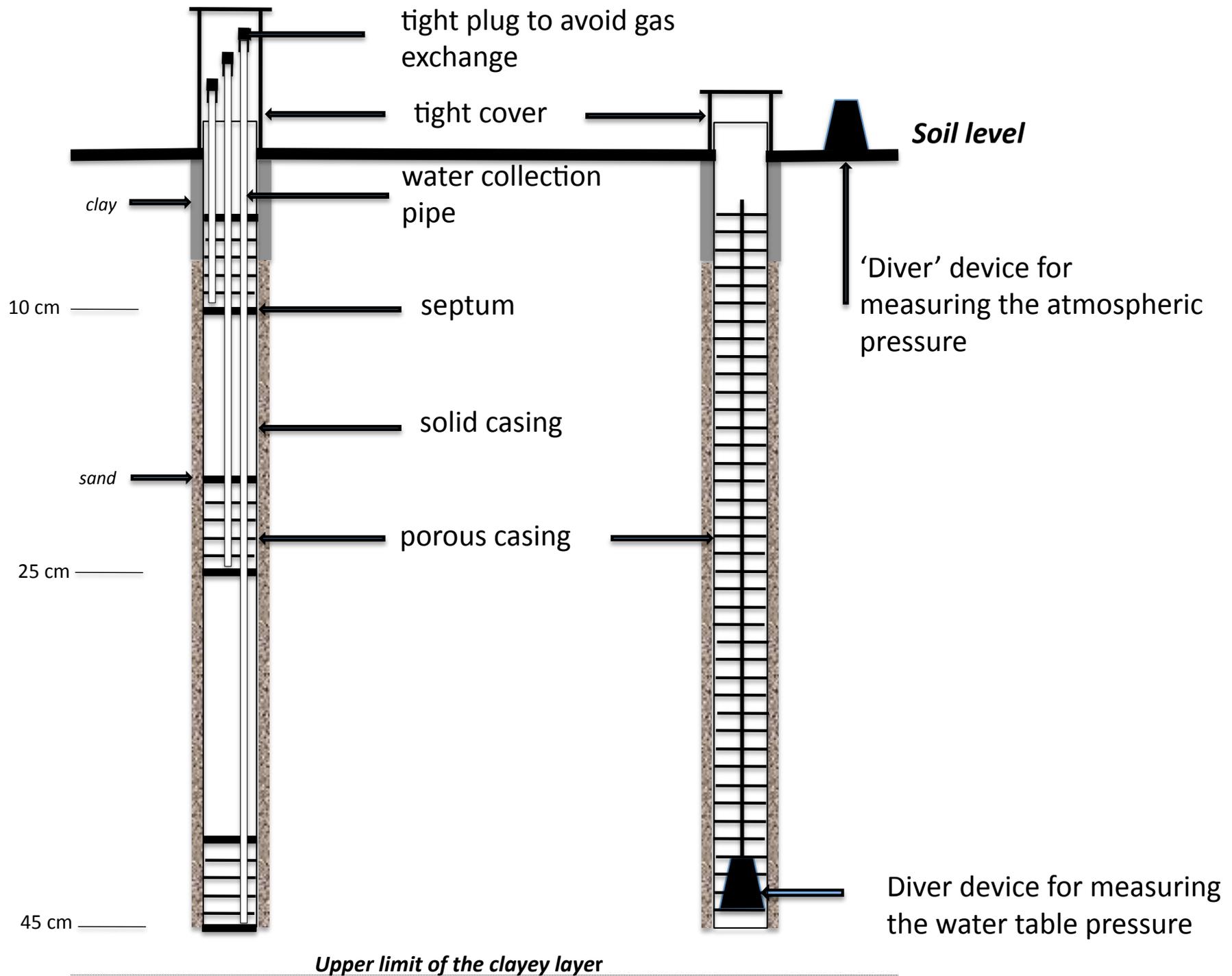
Control	50 cm	6	203	mean	0.0 3	0.0 4	1.7 8	3.22	7.67	0.01	2.4 8	0.0 1	0.1 8	5.6 5	0.1 1	0.8 8	0.2 5	2.4 2	1.4 0	0.4 8	0.31	12.0 9	1.5 3	0.71	0.0 1	
				SD	0.0 3	0.0 2	0.6 9	4.2	2.12	0.02	0.6 7	0.0 1	0.0 7	0.8 8	0.0 6	0.3 4	0.0 7	0.8 9	0.2 2	0.2 2	0.1 2	0.25	3.31	1.1 8	0.26	0.0 0
Compacted	45 cm	6	225	mean	0.1 3	0.0 4	2.0 5	3.50	5.25	0.01	1.7 9	0.0 2	0.3 9	4.6 8	0.3 5	0.9 6	0.5 4	2.5 3	1.3 9	0.9 1	1.99	34.0 5	4.1 6	0.84	0.0 1	
				SD	0.1 3	0.0 2	0.4 4	2.1	4.00	0.08	1.5 1	0.0 1	0.1 8	1.3 4	0.3 6	0.6 1	0.1 8	1.5 1	0.4 3	0.9 5	4.82	47.9 4	6.3 9	1.21	0.0 0	
treatment effect t					***	***	***	***	***		***	***	***	***	***		***		***		***	***	*	***		
year effect y					***	***	***	***	***	***	***	*	***	*	***	***	***	***	***	***	***	***	***	***		
interaction txy								*			*	*				***	**	***	**			**				
depth effect 30-50 vs25-45 cm																										
						***	*		***		***			***		***	***	***	***	***		**				
Control	(2) 70 cm	3	93,00	mean	0.0 2	0.0 2	1.9 4	2.65	8.84	0.04	2.7 8	0.0 1	0.1 2	7.0 6	0.0 5	1.1 1	0.1 5	2.6 7	1.5 7	0.3 2	0.31	11.3 5	1.2 0	0.59	0.0 1	
				SD	0.0 2	0.0 1	0.6 6	2.49	3.17	0.07	0.9 2	0.0 0	0.0 3	1.7 0	0.0 3	0.2 8	0.0 4	0.7 4	0.2 4	0.0 8	0.25	7.38	0.8 3	0.15	0.0 0	

(1) insufficient data for statistics

(2) no sampling device in the compacted treatment (T)

statistics                      \*\*                      \*                      p>0.001                      \*\*                      0.01<p<0.001                      \*                      0.05<p<0.01

Table 7



**B- Piezometer for water sampling**

**A- Piezometer for measuring water level**

**Figure 1**

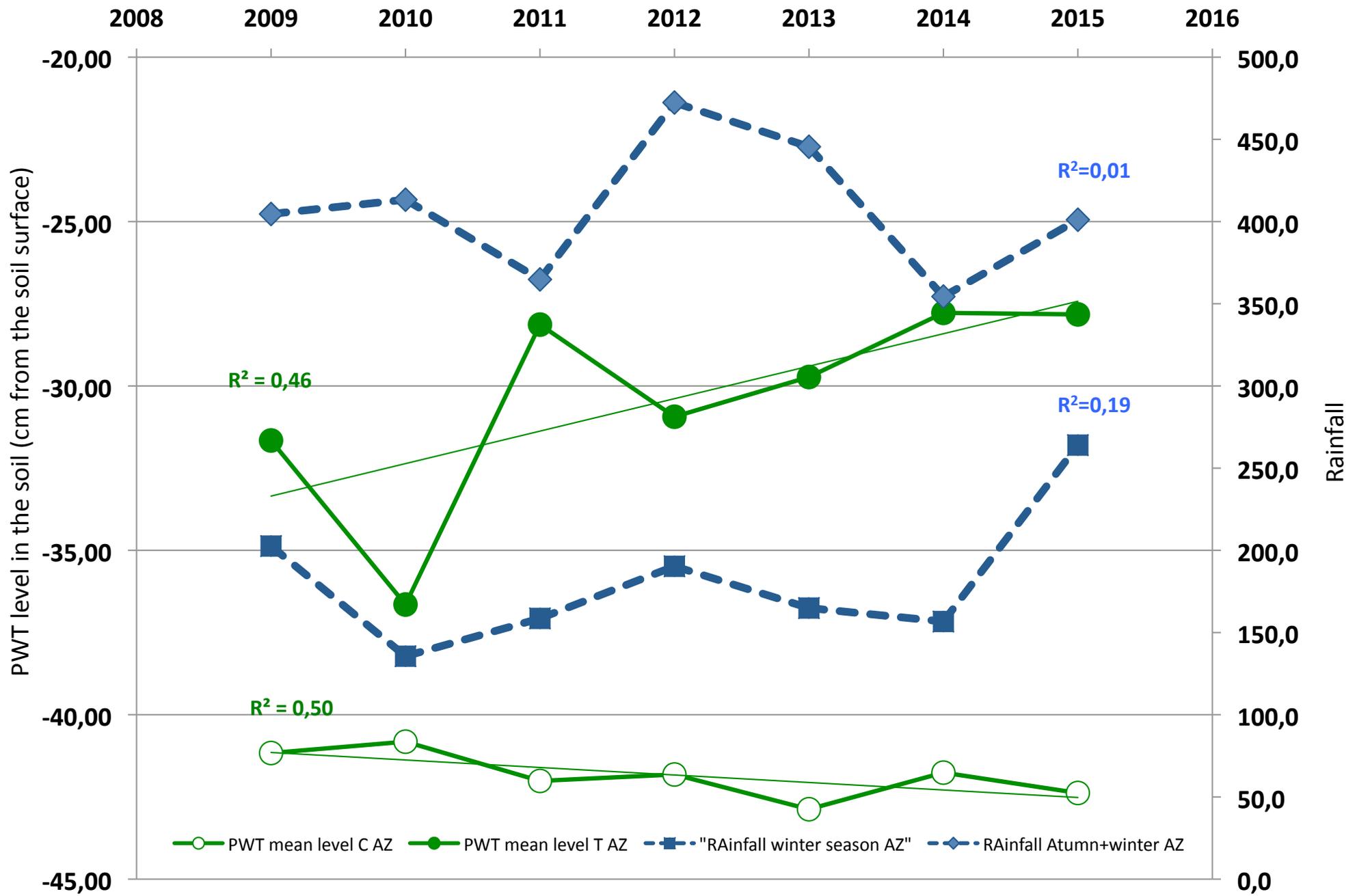


Figure 2A

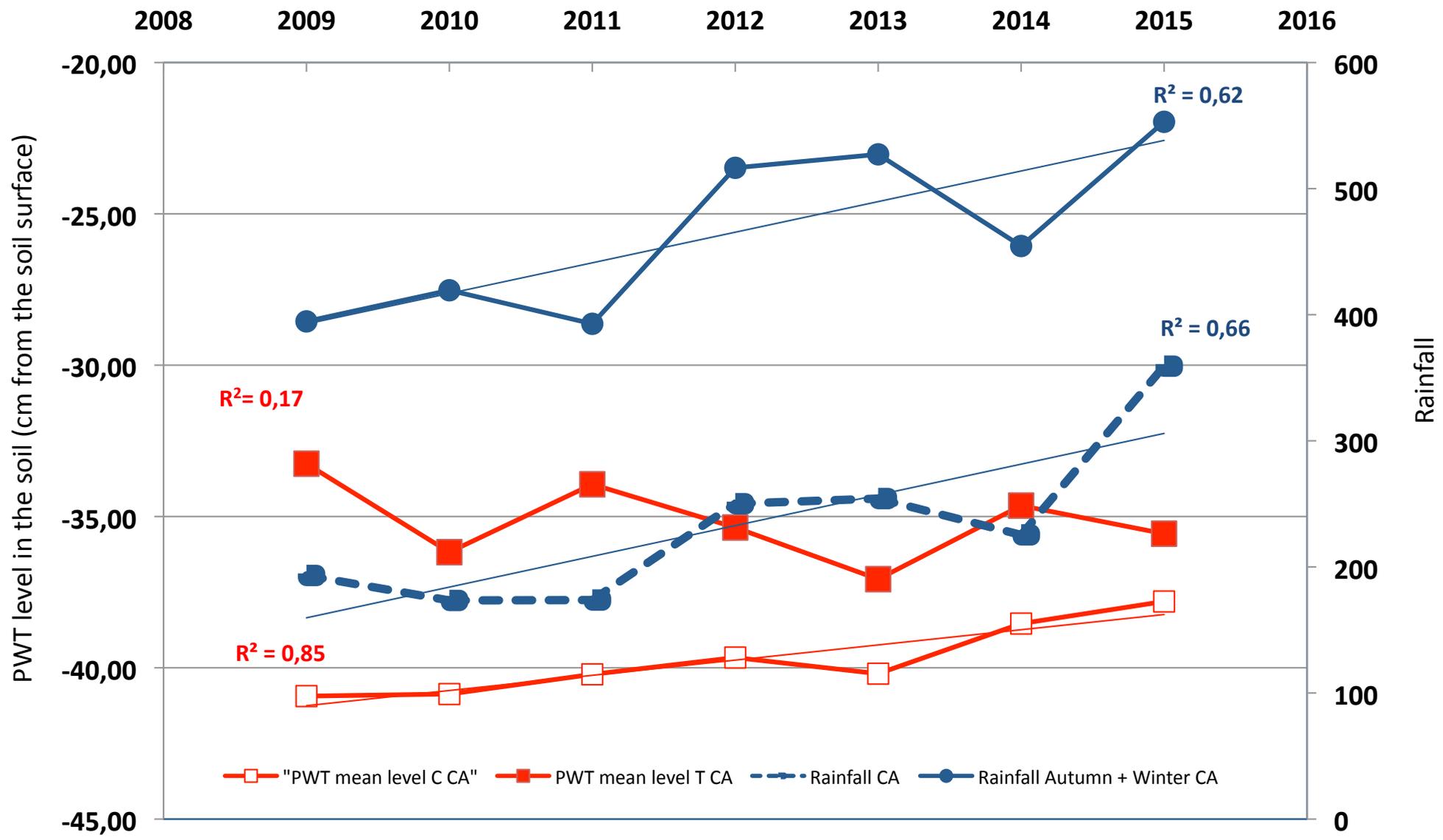


Figure 2B

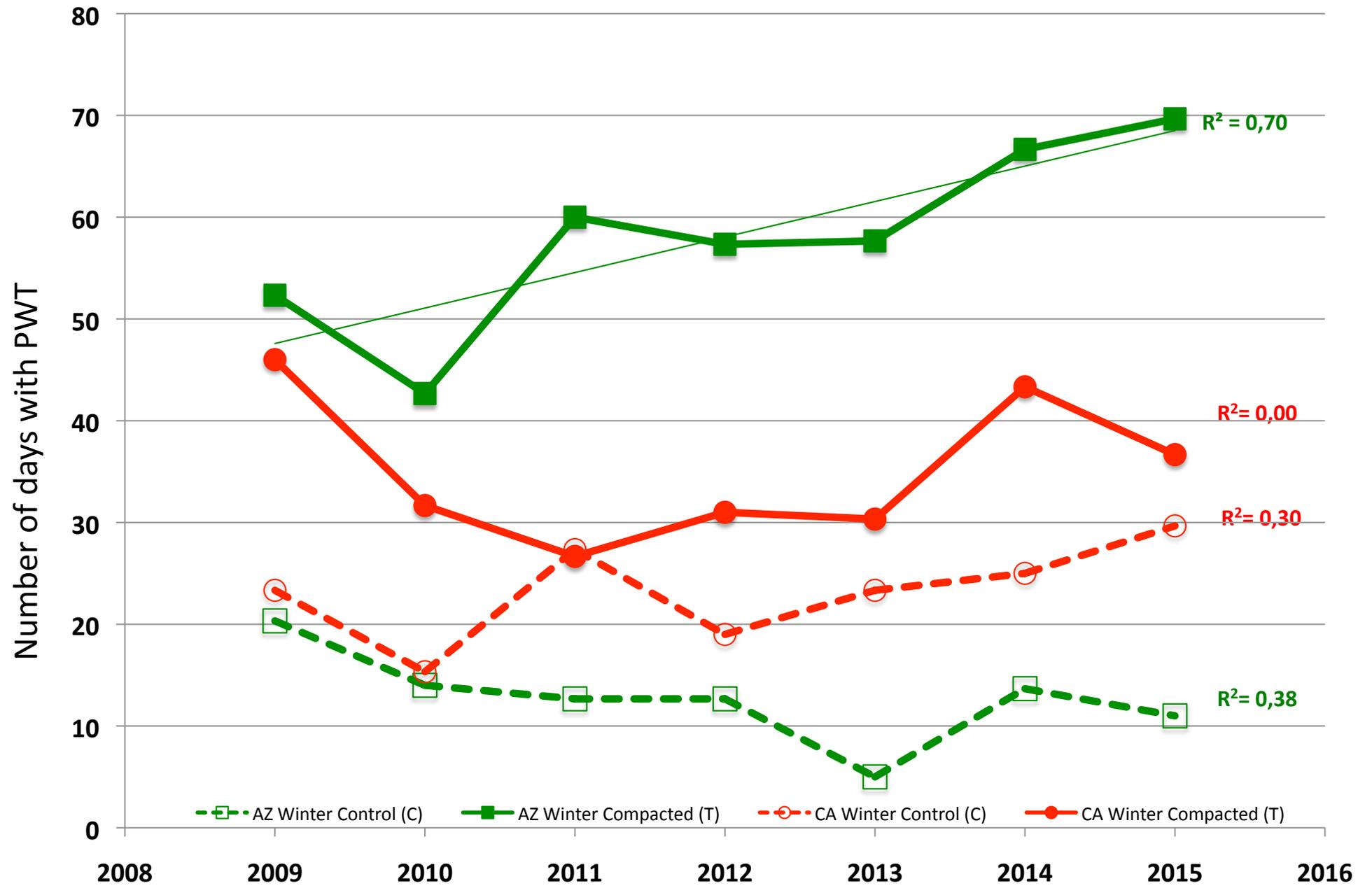


Figure 3

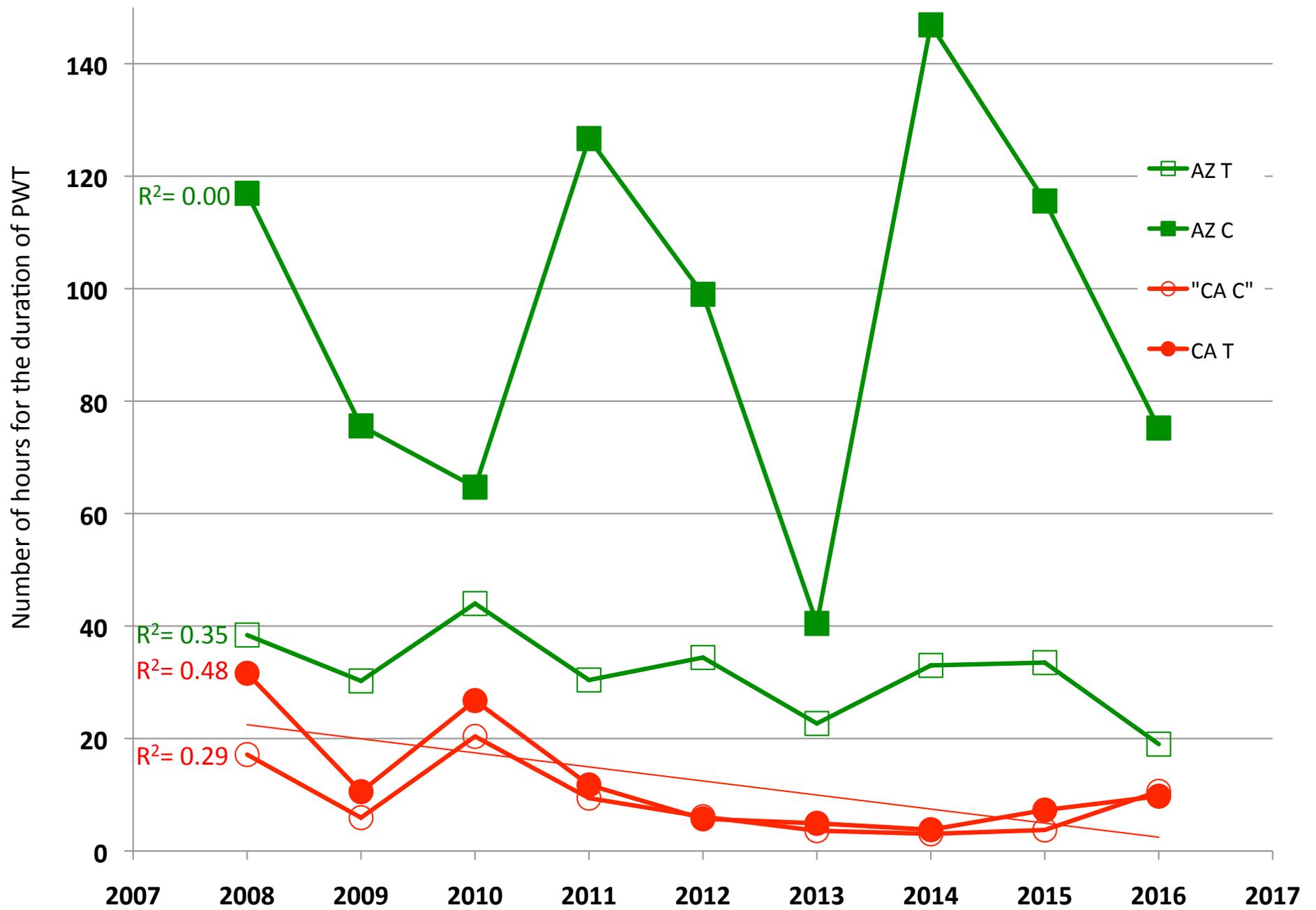


Figure 4

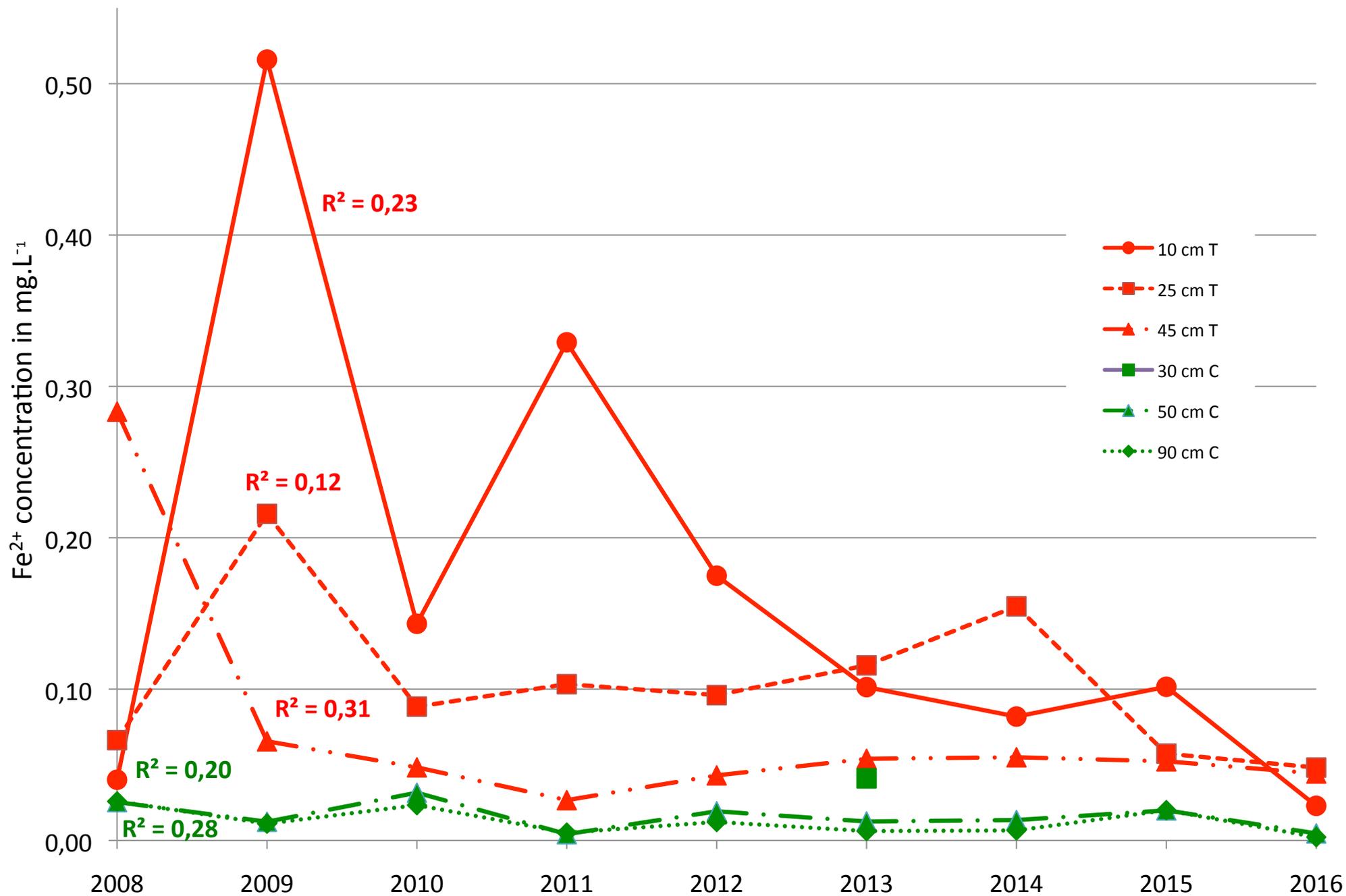


Figure 5

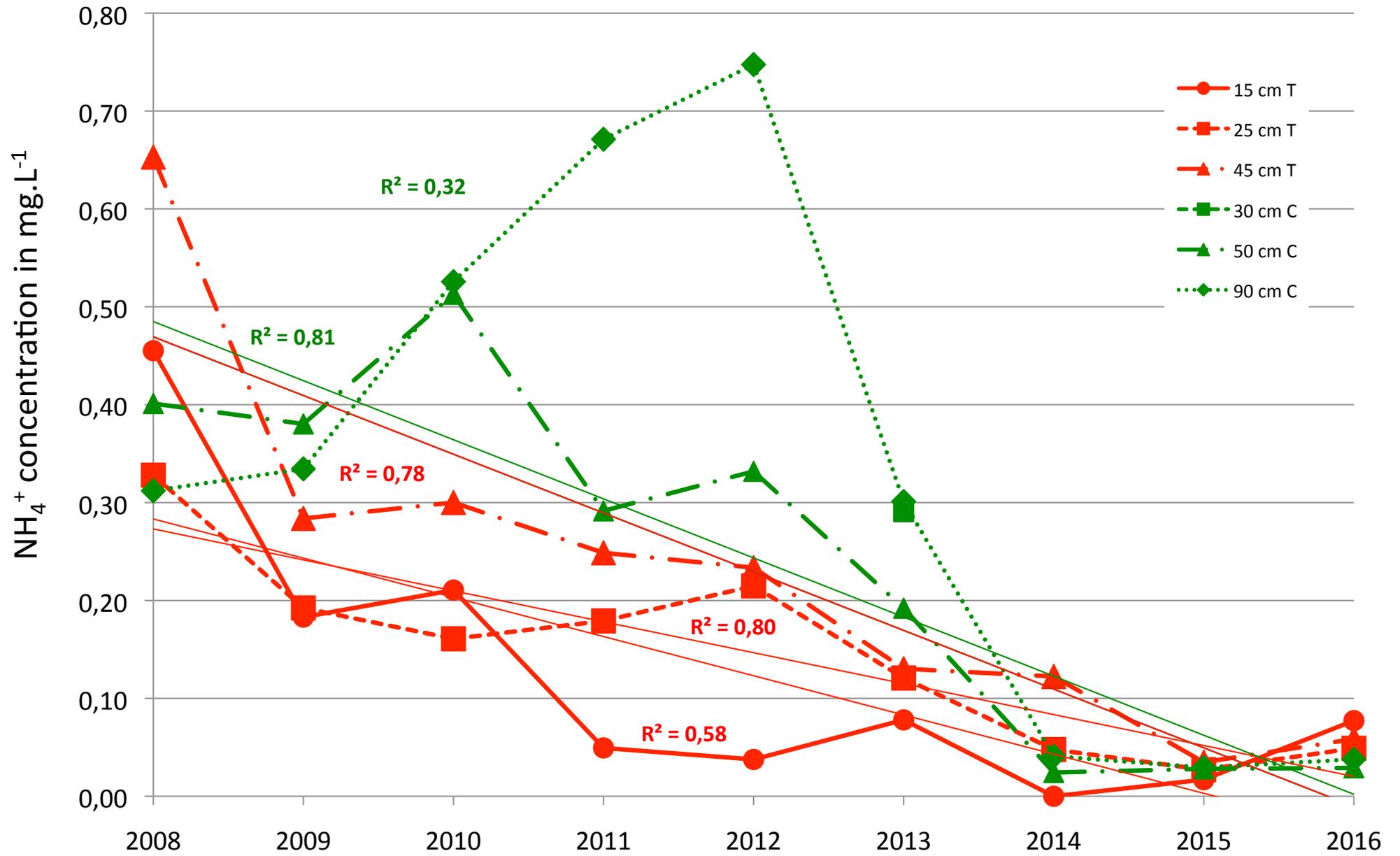


Figure 6

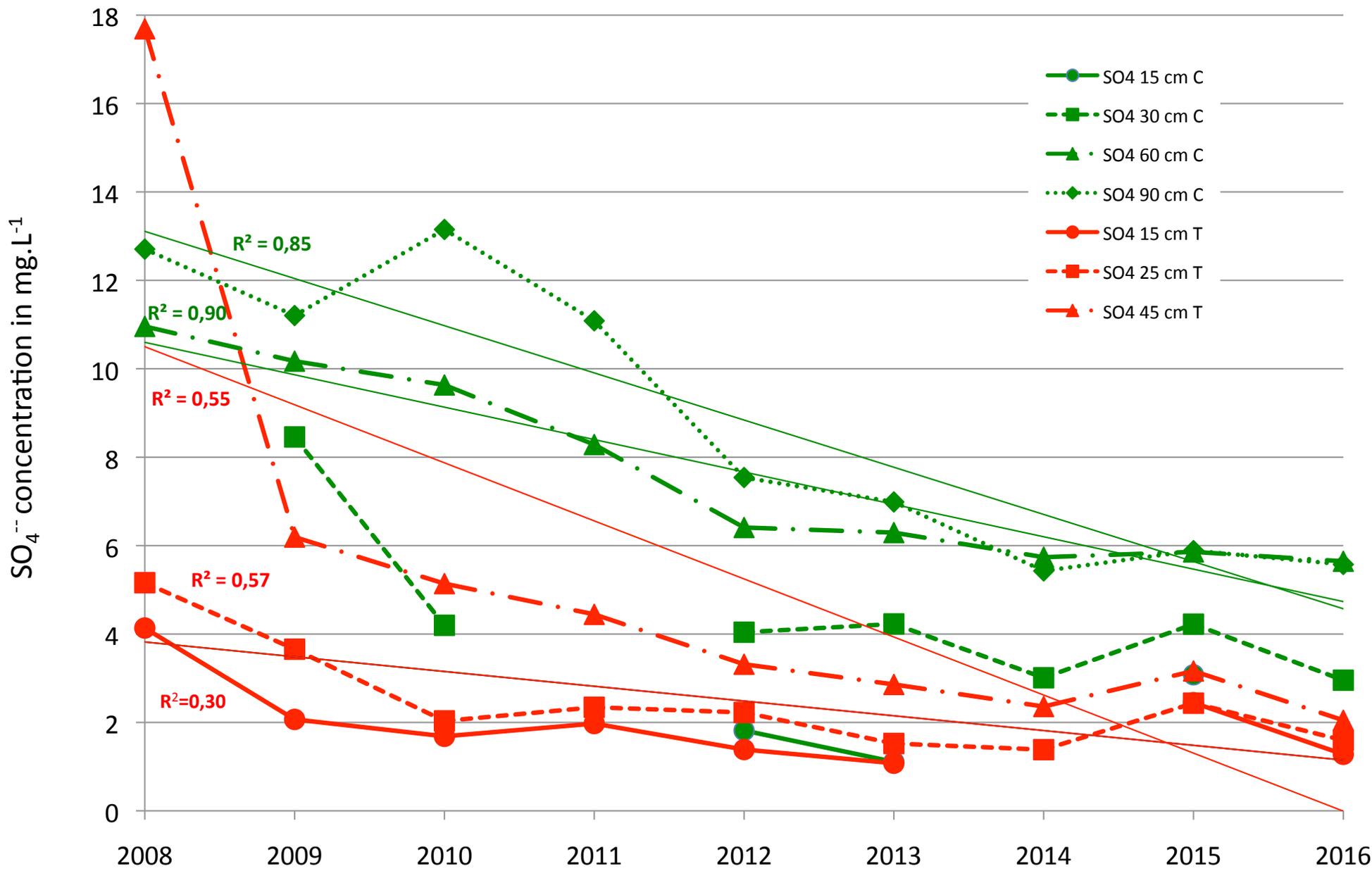


Figure 7

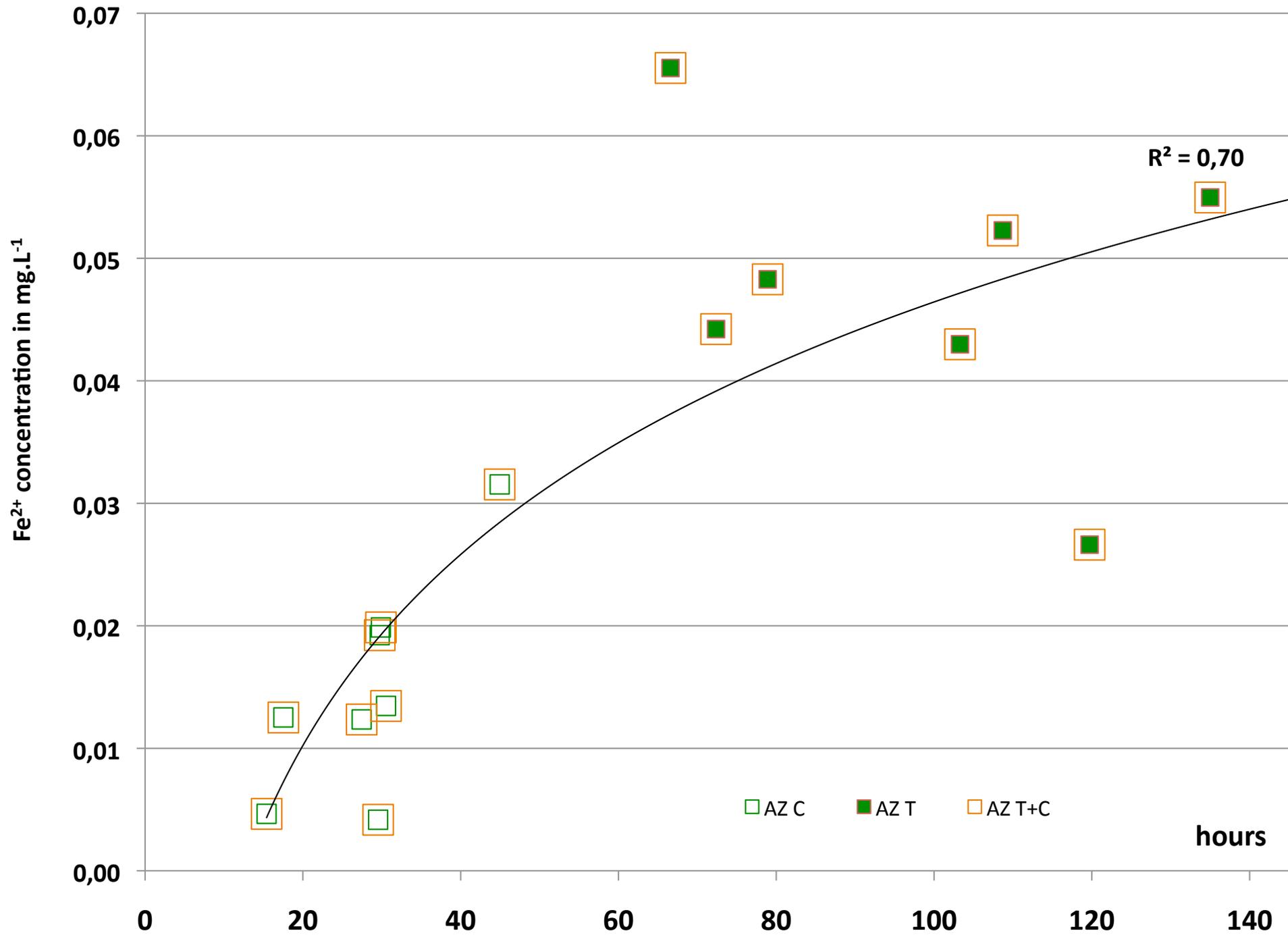


Figure 8

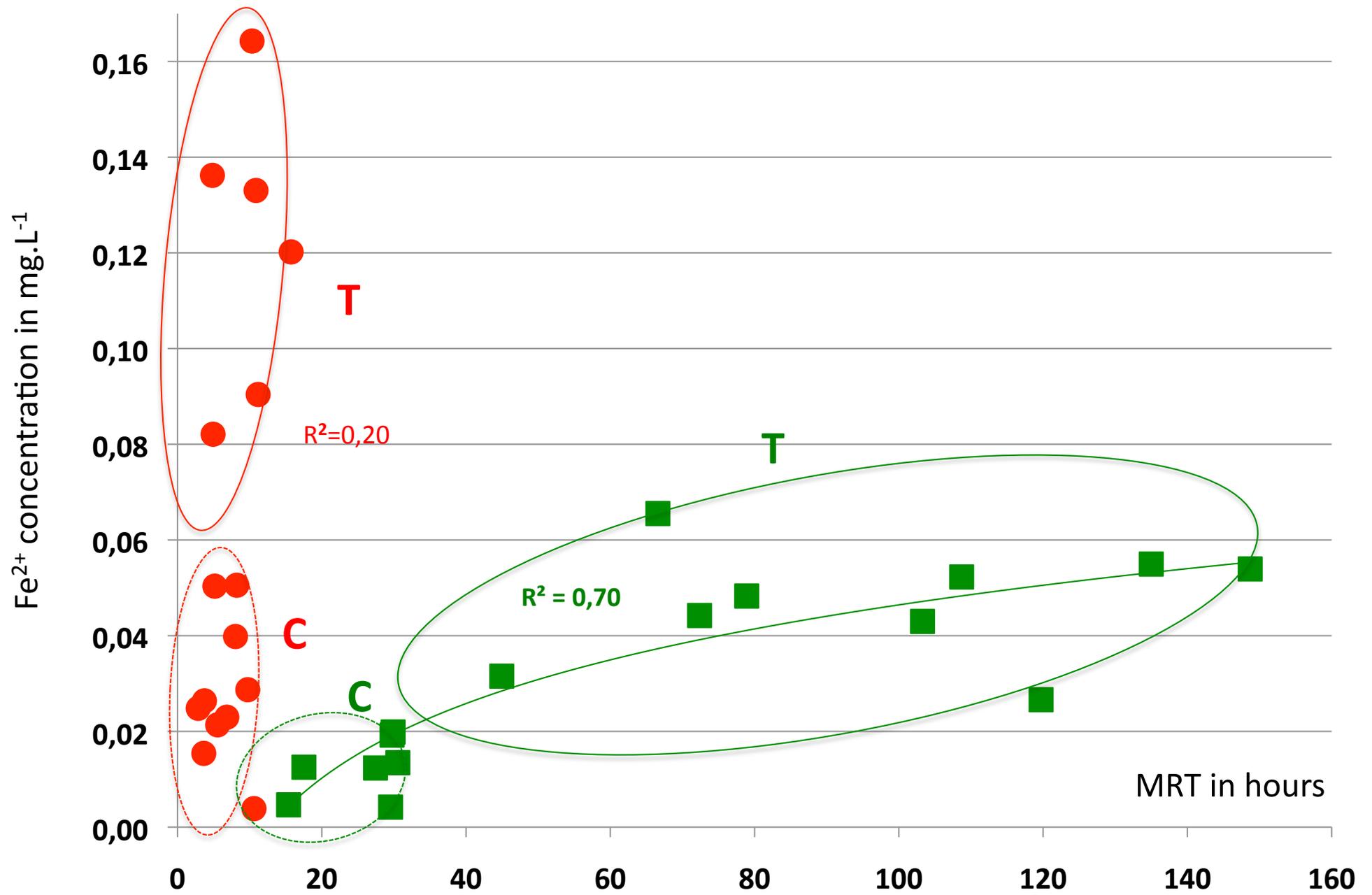
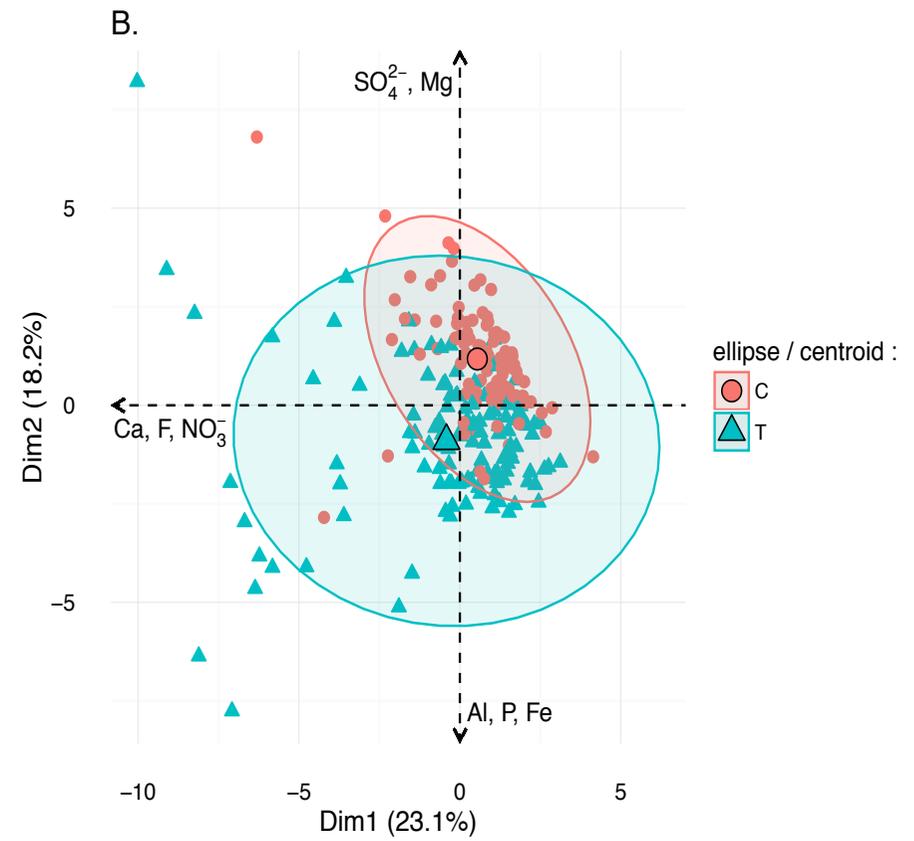
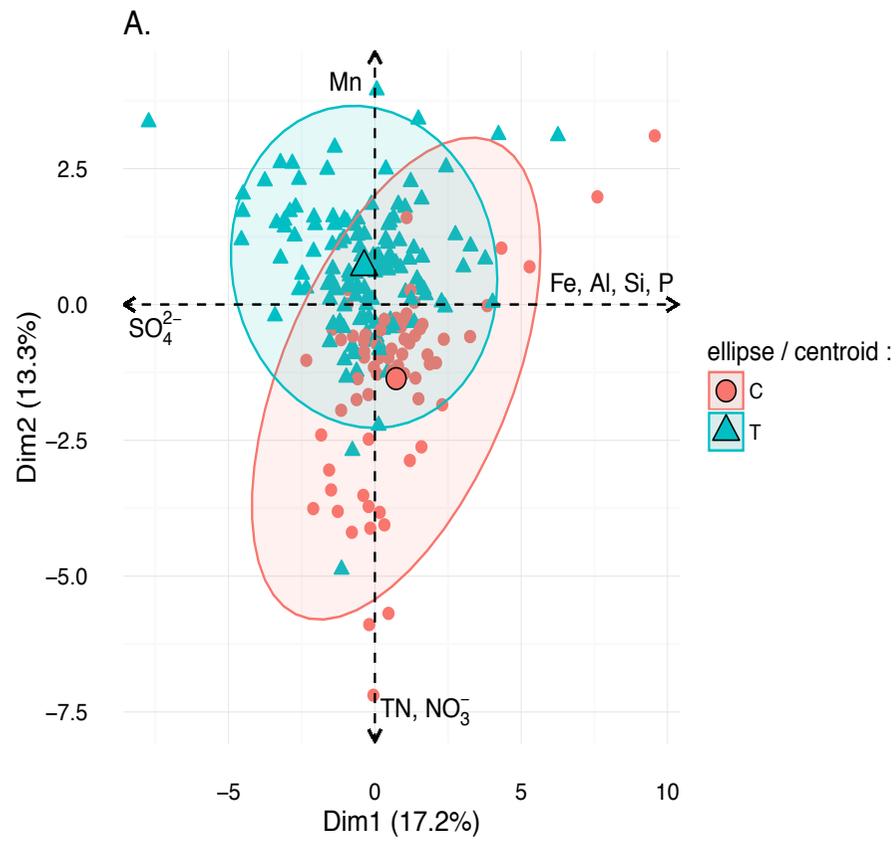
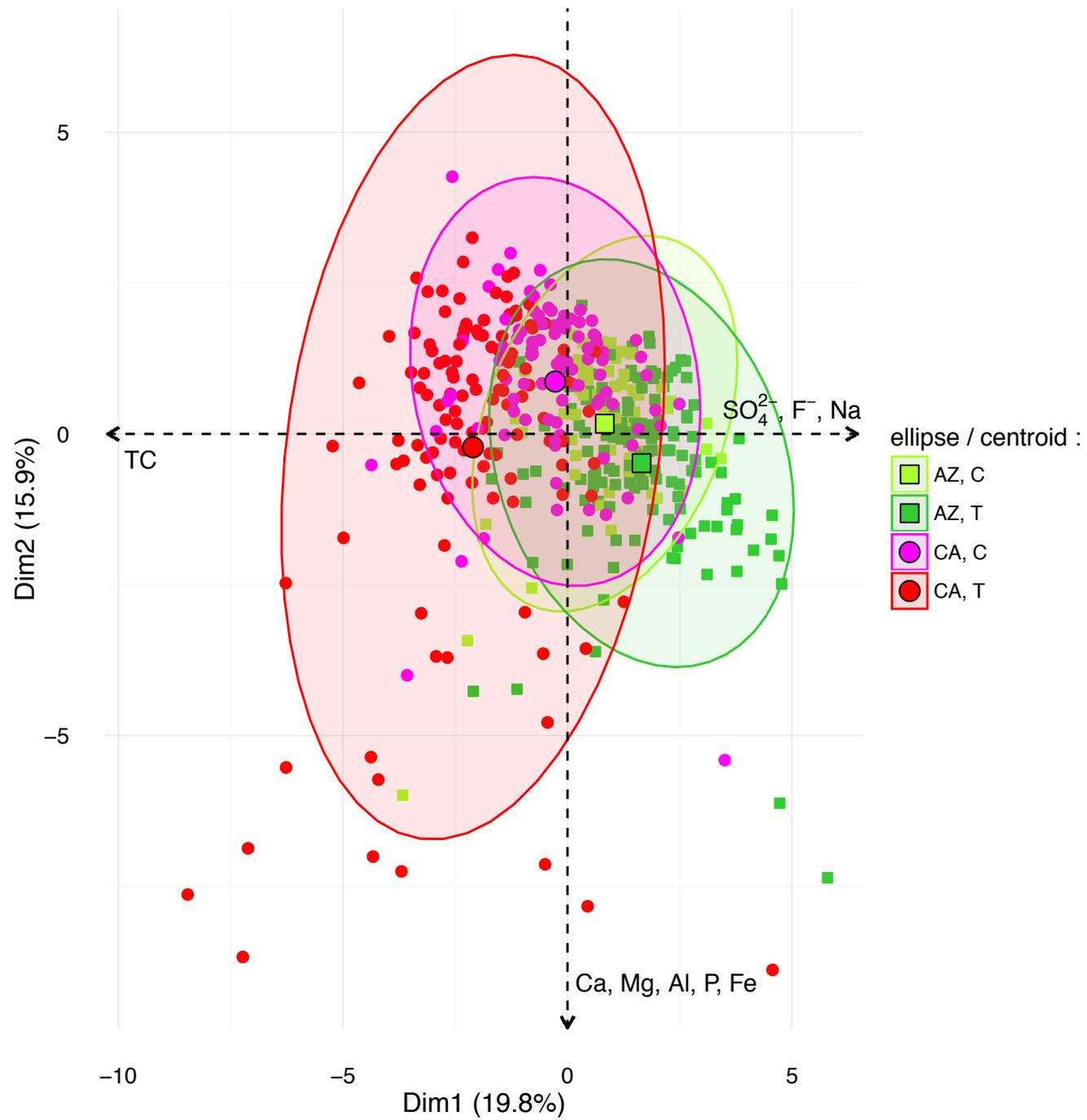


Figure 9



Supplementary material – Figure I



Supplementary material – Figure II