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**Soil conditioners effects on hydraulic properties, leaching processes
and denitrification on a silty-clay soil**

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Abstract

Agricultural landscapes are often affected by groundwater quality issues due to fertilizers leaching. To address this worldwide problem several agricultural best practices have been proposed, like limiting the amount of fertilizers and increasing soil organic matter content. To evaluate if these practices may promote groundwater quality enhancement, vadose zone retention time and complex biogeochemical processes must be known in detail. In this study, sequential undisturbed column experiments were performed to determine the amount of nutrients and heavy metals leached after simulated stormwater events. The column was amended with urea then flushed for two pore volumes, then straw residuals were incorporated and flushed for two pore volumes and finally compost was incorporated and flushed for six pore volumes. Dissolved ions, major gasses and heavy metals were

26 determined in leachate samples. Nitrate and nitrite were leached in the urea treatment producing the
27 highest concentrations, followed by compost and straw residuals. The redox conditions were aerobic
28 in all treatments and pH was circumneutral or slightly basic. Denitrification was low but increased
29 with the addition of straw residuals and compost. Heavy metals were all at very low concentrations
30 except for lead and cadmium, which slightly exceeded threshold limits (10 and 1 $\mu\text{g/L}$, respectively)
31 in all the treatments. The compost treatment, after three pore volumes, was affected by clay swelling
32 due to sodium dispersion, which in turn provoked a reduction of porosity and hydraulic conductivity.

33

34 **Keywords**

35 Aquifer recharge, fertilizers leaching, denitrification, heavy metals, compost, clay swelling.

36

37 **1. Introduction**

38 Agricultural activities have affected and keep affecting the environmental quality, since they consist
39 of intensive soil use, which is generally accompanied by the addition of organic and/or inorganic
40 conditioners (Antonopoulos & Wyseure, 1998; Shah et al., 2019). To ensure that environmental
41 quality is not worsen by agricultural activities, it is important to tune the use of amendments on the
42 basis of soils' and plants' requirements and to consider advantages and disadvantages of their use,
43 such as: alteration of the pristine water quality, impoverishment of soil's fertility, nutrients leaching
44 towards groundwater, and variation of soil's physical-chemical properties (Kay et al., 2012; Shah et
45 al., 2019; Zhang & Wang, 2019). The most striking environmental problem of agricultural activities
46 is the groundwater contamination by nitrate (NO_3^-) due to fertilizers leaching (Tilman et al., 2001).
47 NO_3^- is the main groundwater contaminant worldwide (Schlesinger, 2009), since being the most
48 stable nitrogen (N) species it can migrate to great distances from the input zone (Puckett et al., 2011).
49 To solve this problem, recent studies have tried to fully understand the denitrification process in soils
50 (Castaldelli et al., 2019; Putz et al., 2018) and shallow aquifers (Colombani et al., 2019; Hinshaw et
51 al., 2020; Utom et al., 2020). A clear correlation between denitrification and dissolved organic carbon

52 (DOC) in soils have been found at the global scale (Taylor & Townsend, 2010), since DOC is the
53 principal electron donor for heterotrophic denitrification (Kim et al., 2019). More specifically, it has
54 been found that the labile fraction of DOC drives the in-situ denitrification (Xu et al., 2018) and its
55 reactivity, combined with temperature, determines the denitrification rate (Mastrocicco et al., 2019a;
56 Zarnetske et al., 2011). Nevertheless, to fully determine the redox conditions and the main
57 biogeochemical reactions not only the reactants but also the products must be monitored. These are
58 usually dissolved gasses like O₂, CO₂, CH₄ and N₂ (Mastrocicco et al., 2019b; Rivett et al., 2008).
59 Beside nutrients, also heavy metals may become important groundwater pollutants in agricultural
60 settings (Busico et al. 2018; Wongsasuluk et al., 2014), since they can influence both the human
61 health and the ecological status of the affected environments (Ke et al., 2017; Kumar et al., 2019; Li
62 et al., 2014). In general, heavy metals are introduced in agricultural landscapes via manure, pesticides
63 and fertilizers' impurities (Belon et al., 2012; Kirschke et al., 2019). Furthermore, heavy metals'
64 solubility and mobility in soils and in groundwater depend also on pH and Eh conditions. In fact,
65 heavy metals' mobility in soils is reduced by increasing pH, soil organic matter (SOM) content and
66 Eh (Sauvé et al., 2000), and is also largely affected by surface complexation reactions on amorphous
67 Fe-hydroxides (Bonten et al., 2008). The latter usually are unstable (dissolve) at low pH and low Eh
68 values, so such conditions may trigger heavy metals release in groundwater (Apul et al., 2005;
69 Colombani et al., 2015). Thus, to fully understand the heavy metals' fate and transport processes it is
70 imperative to assess the Eh and pH conditions and the main redox sensitive species.

71 In this study two different soil conditioners, straw residuals (SR) and compost (Comp), have been
72 compared versus standard synthetic urea fertilizer (U) to assess nutrients and heavy metals leaching
73 from an undisturbed silty-clay soil column subject to extreme rainfall events. SR are usually
74 incorporated in topsoils to improve soil fertility and to increase crop yields (Liu et al., 2014). Recent
75 studies showed that SR have different beneficial effects on soil properties, like increasing soil water
76 content, while decreasing dry bulk density (ρ_b ; Zhao et al., 2019). Comp is a product of biodegradation
77 of organic substrates and it represents a way to recycle organic solids and agri-food wastes, reducing

78 social costs and promoting the circular and green economy (Hargreaves et al., 2008). Recent studies
79 proved that Comp application increases the availability of labile SOM (Liu et al., 2018), while
80 reducing NO₃⁻ leaching (Basso & Ritchie, 2005) especially in sandy soils (Shrestha et al., 2010).
81 Furthermore, it was argued that Comp incorporation in topsoils is beneficial to some physical soils'
82 proprieties as porosity (Giusquiani et al., 1995) and soil water retention capacity (Ramos, 2017;
83 Sorrenti & Toselli, 2016). Nevertheless, Comp could increase the mobilisation of harmful elements,
84 so caution is required in utilising Comp on soils with elevated concentrations of heavy metals
85 (Beesley & Dickinson, 2010), even though Farrell et al. (2010) demonstrated that Comp application
86 may reduce metals' availability.

87 In addition to leaching of solute species, also physical changes can be induced by SR or Comp
88 incorporation. Buchmann & Schaumann (2018) stated that the application of Comp reduces clay
89 swelling, improves soil porosity and increases soil structural stability. On the other hand, Hanson et
90 al. (1999) found that fine grained soils may be affected by reduced permeability by sodium (Na⁺)
91 induced clay swelling with consequent disruption of soil's aggregates, so attention must be paid to
92 the Comp salinity and Na⁺ content. In fact, clay swelling may cause a reduction of soil permeability,
93 because clay minerals once dispersed from soil's aggregates may fill soil pores and reduce water flow
94 (Tao et al., 2019).

95 From this brief review, it is clear that studies that tackle altogether the complex interactions of nutrient
96 and heavy metals leaching coupled with the soil physical changes induced by soil conditioners are
97 still lacking. The present study aimed to fill this gap monitoring both physical changes and leaching
98 behaviour in well controlled laboratory conditions using SR and Comp as conditioners and U fertilizer
99 as standard practice.

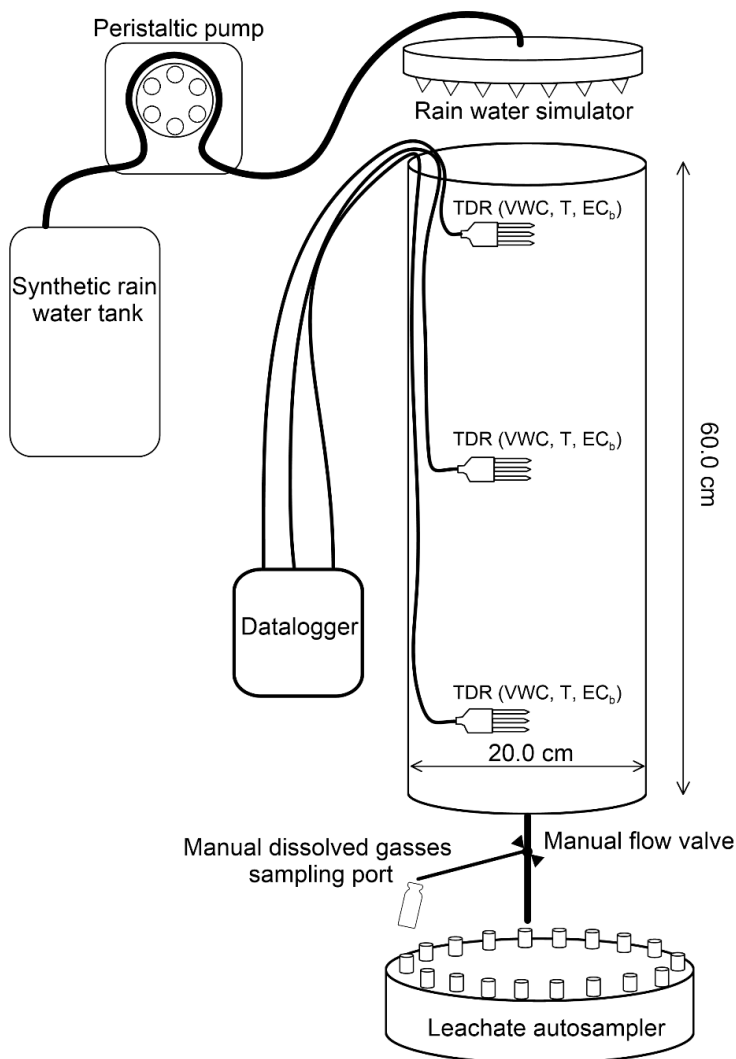
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101 **2. Material and Methods**

102 **2.1. Soil column experimental set up**

103 The soil used in the experiment was collected from an agricultural field in the Po River Plain, within
104 the central-eastern part of the province of Ferrara, Italy (GPS coordinates 44° 47' 41" N and 11° 42'
105 20" E). The soil has a clayey silty texture, and the depositional environment is typical of delta plain
106 distal parts. The physical-chemical characteristics of the soil have been described previously in detail
107 in Mastrocicco et al. (2019a) and the undisturbed soil column is the same employed in the previously
108 published experiment.

109



110

111 Figure 1: Schematic representation of the laboratory apparatus used in the intact soil column leaching
112 experiment.

113

114 Briefly, the leaching experiments were conducted at laboratory conditions at 25 °C to be
115 representative of field conditions during summer time when the majority of storm water events take
116 place in the Po river plain area (Isotta et al., 2014). A large plexiglass column was employed with an
117 internal diameter of 19.6 cm and length of 60.0 cm, provided with polyethylene post-chamber with
118 2.5 mm porous disc and 2 cm layer of quartz sand, to avoid material loss (Fig.1). The undisturbed
119 soil profile consisted of 55 cm of Hypocalcic Haplic Calcisols that was collected in a lowland
120 agricultural field in the province of Ferrara (Mastrocicco et al., 2019a). An 8 channels peristaltic
121 pump (Minipuls-3 Gilson, UK) was placed on the top of the column as rainfall simulator, at different
122 flow rates (1.46, 2.85 and 4.98 rpm) to reproduce a storm event of 227 mm in 47 hours with synthetic
123 rainwater (mono-distilled water). The choice of selecting the timing and intensity was to be consistent
124 with the previous study (Mastrocicco et al., 2019a) that mimicked a field observed stormwater event.
125 To avoid possible preferential flow due the 8 dripping points, the rainfall simulator was manually
126 rotated approximately every 10 minutes during the simulated rainfall events. Prior to start the
127 experiments, the column was flushed with 2 pore volumes of synthetic rainwater and left drain until
128 stable Volumetric Water Content (VWC) was attained. In the first experiment, 100 kg-N/ha of urea
129 in crushed granules (Table 1) was applied on the top of the soil column and left for 15 days before to
130 start the stormwater event. After all the leachate was collected, the column was flushed with 2 pore
131 volumes of synthetic rainwater and finally was drained with a vacuum pump until the initial VWC
132 was attained. The second experiment was performed on the same undisturbed column by placing 5
133 cm of undisturbed topsoil collected in the field from a plot where SR of maize were left on ground
134 from the previous year. The topsoil was collected approximately 10 days before the experiment from
135 the field site after a rainy period with a plexiglass column of the same diameter but with sharpened
136 edges and 20 cm long. The plexiglass was gently pushed down to 5 cm from the ground surface; then
137 the nearby soil was removed with a shovel and the topsoil was removed with the aim of a large flat
138 blade brought to the laboratory and gently pushed with a piston on the top of the undisturbed soil
139 column used in the U experiment. The measured amount of N in the topsoil with SR was

140 approximately 30 kg-N/ha. The same stormwater event was repeated and the leachate collected; then
141 the column was flushed using 2 pore volumes of synthetic rainwater and again drained with a vacuum
142 pump until the initial VWC was attained. In the last experiment the topsoil with SR was removed and
143 substituted with 5 cm of topsoil mixed with 0.09 kg of mature Comp from urban organic waste,
144 corresponding approximately to 30 ton/ha of Comp. The measured amount of N in the topsoil
145 amended with Comp was approximately 92 kg-N/ha. Given that Comp effects should last for more
146 cropping seasons, in this last experiment the stormwater event was repeated 6 times to evaluate the
147 Comp long-term effects. Three Decagon probes (5TE) were installed inside the column at 5, 30 and
148 45 cm to monitor VWC, Temperature (T) and Soil Bulk Electrical Conductivity (EC_b). All probes
149 were connected to a Decagon data logger (ECH2O) recording every 10 minutes. The 5TE probes
150 instead of microsensors were chosen since they have a small diameter (0.7 cm) and the probe were
151 inserted horizontally, so the disturbance was relatively low. Besides, the 5TE has a volume of
152 influence of 0.3 L, which can provide a comprehensive averaged information on VWC and EC_b
153 around the probe, capturing the variations through the monitored column plane. The leachate samples
154 were collected through an effluent tube fixed at the bottom of the column and discharging into a
155 Redifrac Pharmacia Biotech collector equipped with 15 mL vials. A manual switch was used to
156 sample 6 mL exetainer glass vials for dissolved gasses. pH, Electrical Conductivity (EC) and
157 Temperature (T) were monitored using a portable Hanna instruments meter. Soil's EC_b was
158 converted in EC according to the model of Mortl et al. (2011) and subsequently all EC data were
159 converted into salinity with standard conversion factors (APHA, 1999). It was chosen to not install
160 suction cups within the column to avoid interferences with the unsaturated flow, since negative
161 pressure during sampling could induce changes in the leaching rate.

162

163 Table 1: Composition of selected water-soluble fraction of Urea (U), Straw residuals (SR), Compost
164 (Comp) and synthetic rainwater (SR) applied onto the soil column.

i.d.	pH	N_{TOT} (ppm)	NO₃⁻ (ppm)	NH₄⁺ (ppm)	Na⁺ (ppm)	Cl⁻ (ppm)	SO₄²⁻ (ppm)	Cd (ppb)	Pb (ppb)
U	6.8	220	4.4	0.1	55.6	40.5	136	0.6	2.5
SR	7.5	10.3	0	0.1	8.1	5.7	32.3	<0.1	<0.1
Comp	7.6	134	4.1	32.6	450	72.6	7.8	1.6	1.1
SR	6.5	<0.1	0.12	<0.1	0.15	0.26	0.51	<0.1	<0.1

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2.2. Sampling and analytical methods

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Sediment parameters, especially Total Organic Carbon (TOC) and soil texture, are often utilised to evaluate soil water retention, in fact Rawls et al. (2003) introduced a method based on two different pedotransfer equations to quantify VWC at the field capacity (θ_{33}) and at the wilting point (θ_{1500}). ρ_b and soil moisture were determined using gravimetric methods.

Major anions (F^- , Cl^- , NO_2^- , Br^- , NO_3^- , SO_4^{2-}) were determined on 0.22 μm filtered leachate samples by ion chromatography with an isocratic dual pump (ICS-1000 Dionex) equipped with an AS9-HC high-capacity column and an ASRS-Ultra 4-mm self-suppressor. An AS-40 Dionex auto-sampler was employed to run the analysis, while quality control (QC) samples were run every 30 samples. The detection limit was 0.1 mg/L.

An ICP-OES (PerkinElmer, USA) was used to quantify major cations and trace metals (Ca, Cu, Cd, Fe, Mg, Mn, Ni, Pb, Zn) in leachate water samples after acidification with ultrapure 1 M nitric acid and filtering on 0.22 μm ; and for the soil analyses using the aqua regia extraction method (ISO 11466, 1995). The detection limit for leachate samples was 0.1 $\mu g/L$ and for soil samples was 1.0 mg/kg. A Pharmacia 300 UV/VIS spectrophotometer with appropriate reagent tests (Hach-Lange, UK) was employed to quantify Na^+ , K^+ , DOC, NH_4^+ , NO_3^- and PO_4^{3-} . The detection limit was 0.1 mg/L. Alkalinity was determined using an Alkalinity test (Merk, Germany). Total N (N_{tot}) was measured in the water soluble fraction was extracted from the solid matrices samples by using Milly-Q (Millipore, USA) water and a sediment to water weight ratio of 1:10; leachates were analysed with LCK 238 LatoN cuvette tests and a CADAS 100 UV/Vis spectrophotometer (Hach-Lange, UK). The

186 detection limit was 0.1 mg/L. Soil exchangeable sodium percentage (ESP) was calculated using the
187 sodium absorption ratio (SAR) of the saturation extract of the soil and Comp following the procedure
188 in Choudhary & Kharche (2018).

189 Samples for Ar, N₂ and CH₄ determination were collected by overflowing at least 2 times 6-mL gas-
190 tight glass vials (Exetainer®, Labco, High Wycombe, UK) and preserved by adding 100 µL of 7 M
191 ZnCl₂ solution to inhibit microbial activity (Babich and Stotzky, 1978). Water samples were analysed
192 by MIMS-Membrane Inlet Mass Spectrometry (Bay Instruments, USA), a PrismaPlus quadrupole
193 mass spectrometer with an inline furnace operating at 600 °C to allow for O₂ removal. The Ar, N₂
194 and CH₄ concentrations were quantified by the ion current detected at m/z ratios of 40, 28, and 15,
195 respectively. The detection limit was 1.0 µmol/L. CO₂ was calculated using the PHREEQC-3
196 geochemical code (Parkhurst & Appelo, 2013), knowing major ions, pH and alkalinity.

197 A modified method from Blicher-Mathiesen et al. (1998) to estimate the N₂ excess (N_{2Exc}) was
198 applied, since it was recently demonstrated to provide reliable N_{2Exc} estimates in field conditions at
199 the same experimental site (Mastrocicco et al., 2019b). Briefly, the method allows to calculate the
200 amount of N₂ degassed (N_{2Deg}) and the N_{2Exc} via the following equations:

$$201 \quad N_{2Deg} = N_{2Tot} \left(\frac{N_{2Atm}/N_{2EQ}}{Ar_{Atm}/Ar_{EQ}} \right) \ln \left(\frac{Ar_{EQ}}{Ar_{Tot}} \right) \quad (1)$$

$$202 \quad N_{2Exc} = (N_{2Tot} + N_{2Deg}) - N_{2EQ} \quad (2)$$

203 where Ar_{Atm} is the volumetric fraction of Ar in the atmosphere with saturated air and N_{2Atm} is the
204 volumetric fraction of N₂ in the atmosphere with saturated air. Ar_{EQ} is the water dissolved Ar
205 concentration in equilibrium with the atmosphere at the sediment temperature, Ar_{Tot} is the measured
206 water dissolved Ar concentration for a given sample. N_{2EQ} is the water dissolved N₂ concentration in
207 equilibrium with the atmosphere at the sediment temperature, N_{2Tot} is the measured water dissolved
208 N₂ concentration for a given sample. The eluted masses of mineral N (NO₃⁻ + NO₂⁻ + NH₄⁺), DOC, Cl⁻
209 , SO₄²⁻ and denitrified N ($2 * N_{2Exc}$) were calculated by integrating the measured concentrations respect
210 to the observed leachate volume eluted between each analysed sample and the previous one.

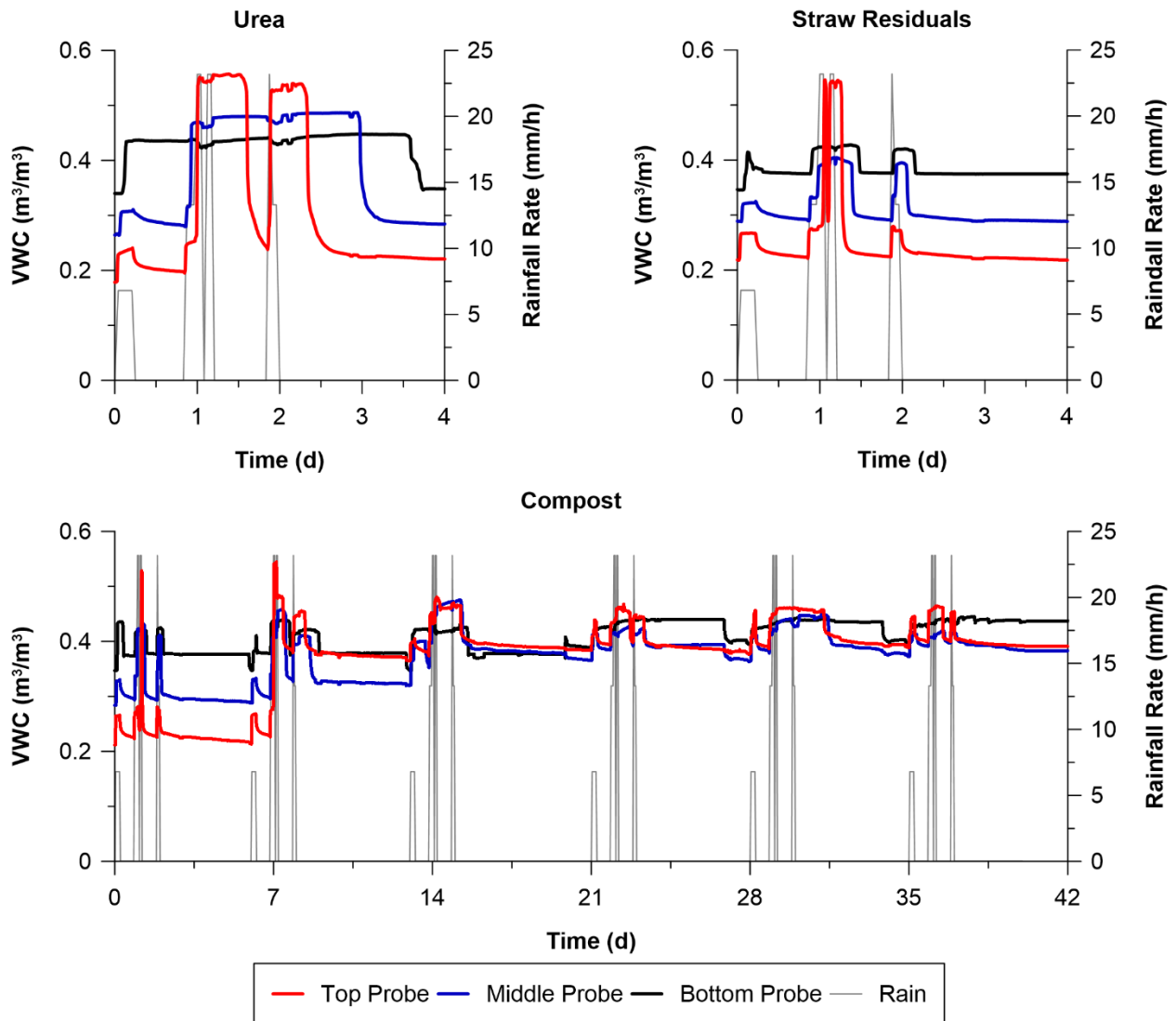
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212 **3. Results and discussion**

213 **3.1. Volumetric Water Content continuous monitoring**

214 The VWC continuous monitoring (Fig.2) highlights a sudden increase due to the simulated intense
215 rainfall events especially in the top probe (located in the topsoil), and a rapid VWC decrease due to
216 porewater drainage. The rapid increase of VWC in the first rainfall spike in all the three monitoring
217 probes was due to preferential flows in macropores, although from the second spike the VWC
218 increased only in the top and middle probe since the bottom probe exhibited values near to saturation
219 ($0.45 \text{ m}^3/\text{m}^3$). These results are consistent with the VWC behaviour observed in the same undisturbed
220 column (Mastrocicco et al., 2019a), obtaining the same VWC saturation values in the three probes
221 even if the previous experiment had an initial VWC near to residual values. In the U experiment a
222 perched water table was visible near the half of the column until the end of the third day, due to nearly
223 complete water saturation of the lower soil horizon during the simulated storm event. The perched
224 water table was then rapidly drawdown due to leaching of porewater from the column. The VWC of
225 the SR experiment showed peaks only during the storm events but with faster VWC decrease due to
226 higher infiltrability of the SR topsoil. The larger infiltrability produced a cumulative amount of 6445
227 mL, while in the U experiment only 5302 mL were leached. The Comp experiment showed different
228 trends respect to the previous ones, in fact during the first elution the VWC was similar to the U and
229 SR experiments, but from the second to the last elution the VWC gradually converged towards similar
230 values over the whole depth of the column. Here the prolonged rainfall caused the nearly full
231 saturation of the soil column, in effect the difference between the VWC of the three probes was
232 minimal at the end of the third elution experiment. Finally, the maximum values recorded in the top
233 probe passed from approximately 0.55 to 0.45 during the Comp experiment, witnessing a porosity
234 reduction in the topsoil. Concomitantly the cumulative leached amount was 6544 mL in the first
235 elution, while in the last one was 4329 mL.

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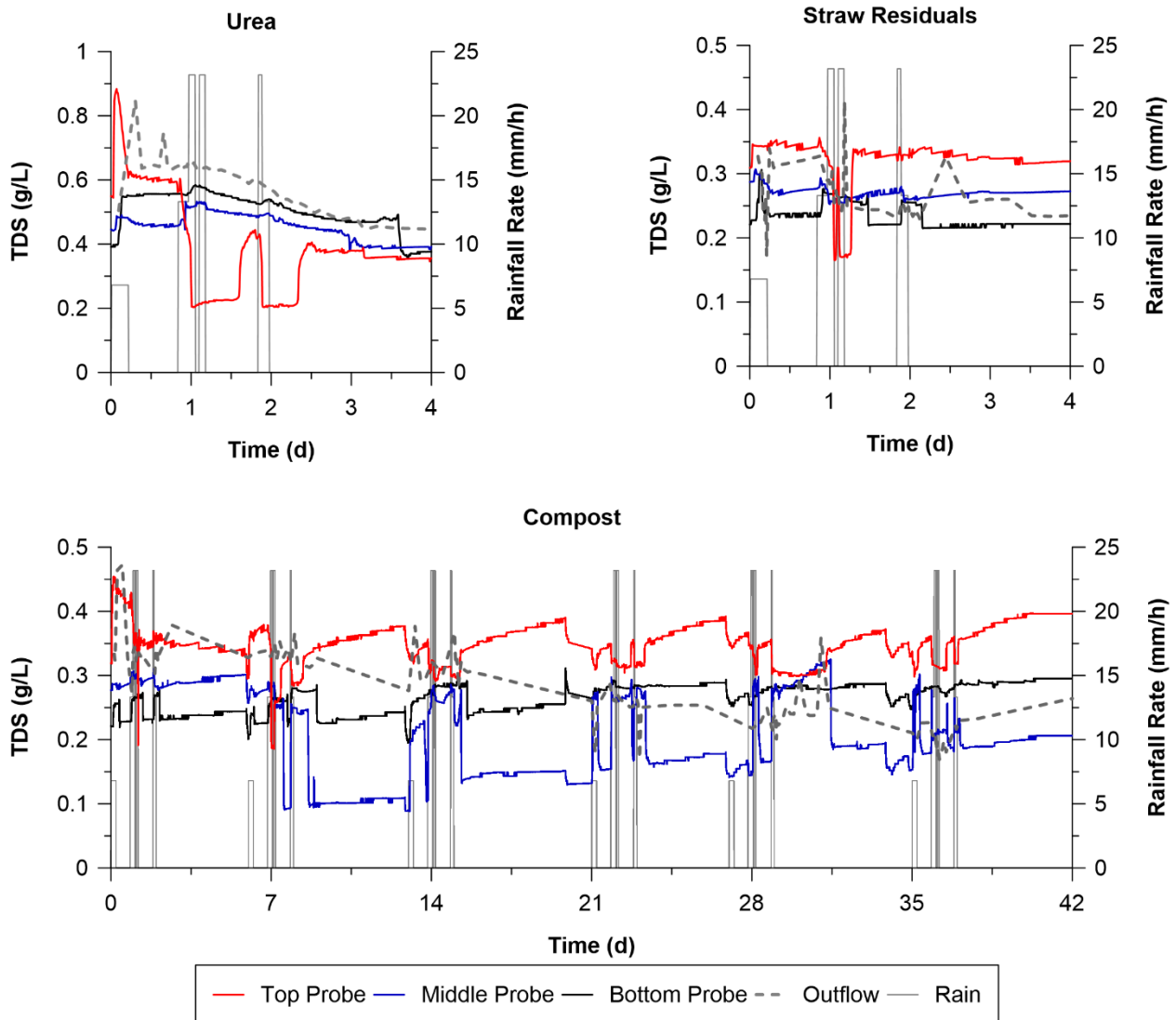
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238 Figure 2: VWC and simulated rainfall during the three laboratory experiments with the addition of
 239 Urea (upper left plot), Straw residuals (upper right plot) and Compost (bottom plot).

240

241 **3.2. TDS continuous monitoring**

242 The results (Fig.3) showed a general TDS reduction in leachate samples during all the experiments.



244

245 Figure 3: TDS and simulated rainfall during the three laboratory experiments with the addition of
 246 Urea (upper left plot), Straw residuals (upper right plot) and Compost (bottom plot). The probes
 247 within the column are shown with different colours, while the TDS at the column's outlet is shown
 248 with a grey dashed line.

249

250 The U experiment presented the highest initial values, with TDS values that reached 0.9 g/L in the
 251 top probe due to urea dissolution. TDS rapidly decreased during the storm events, and gradually
 252 stabilized around to 0.38 g/L in all probes towards the end of the experiment. TDS concentrations
 253 recorded at the column's outflow were similar to the ones recorded in the top probe at the beginning

254 of the experiment and then aligned with those recorded by the middle and bottom probes during the
255 storm events. This is a clear evidence of preferential flow in macropores, as already highlighted in a
256 previous experiment with the same undisturbed column (Mastrocicco et al., 2019a).

257 In the SR experiment, at the beginning TDS was lower than the one recorded in the U test in all
258 probes, this was due to large TDS gradients that often develops during urea fertilizers dissolution and
259 leaching (Castaldelli et al., 2018; Chao et al., 2017). The top probe showed higher values than the
260 other two except during the intense rainfall events, when TDS decreased rapidly. The middle probe
261 showed a behaviour similar to the top one but with a much more smoothed trend. The bottom probe
262 showed lower TDS values respect to the top and middle ones, with an evident increase during the
263 storm events implying fast solutes transport from the topsoil to the column outflow, with constant
264 values towards the end of the SR experiment. This pattern has been recently recognized also in field
265 experiments (Fishkis et al., 2020). TDS concentrations at the column's outflow were always close to
266 the ones registered within the column, with spikes after the storm events that confirm the preferential
267 flow in macropores, as denoted before.

268 The Comp experiment began with same TDS concentrations of the SR experiment. The top probe
269 showed an increase in TDS during the first two rainfall events and a decrease in TDS afterwards. This
270 behaviour was due to the leaching of soluble salts from the Comp after the first rainfall event
271 (Cambier et al., 2014). Conversely, from the third rainfall event onward, the top probe registered a
272 decrement during the elution and an increase in TDS afterwards. This behaviour was due to the
273 desorption of solutes from the Comp at every rainfall event (Sorrenti & Toselli, 2016).

274 At the beginning of the Comp experiment, the TDS trend at the column's outflow was similar to the
275 one recorded in the top probe, while after the third elution TDS gradually decreased towards
276 concentrations in between the ones registered at the middle and bottom probes. This behaviour again
277 witnessed preferential flow in macropores that were gradually diminished by changes in the pore
278 structure of the soil column (see paragraph 3.6).

279

280 **3.3. N speciation, leaching and denitrification**

281 NH_4^+ was very low during the whole duration of the U experiment (Fig.4), consistently with the
282 previous studies where NH_4^+ was completely nitrified in the top 15 cm of soil (Castaldelli et al.,
283 2018). The U experiment recorded much higher NO_3^- concentrations in the leachate samples, than in
284 the SR and Comp experiments. Here, NO_3^- increased after the first rainfall in the first day of the U
285 experiment, reaching a maximum concentration of 520 mg/L; then, NO_3^- gradually decreased due to
286 mixing and dilution with rainwater, reaching a final concentration of 230 mg/L. NO_2^- were low during
287 the initial rainfall events, but started to increase after the second day reaching up to 5 mg/L, suggesting
288 incomplete denitrification for lack of organic substrates. It is interesting to note that NO_2^- were much
289 lower than in a previous experiment (15 mg/L on average) where the same stormwater event was
290 applied at the same column but starting from nearly dry conditions (Mastrocicco et al., 2019a). In
291 fact, it is well known that dry soil conditions hamper bacterial and fungal activity, while the opposite
292 occurs when soil moisture increases (Lund & Goksøyr, 1980).

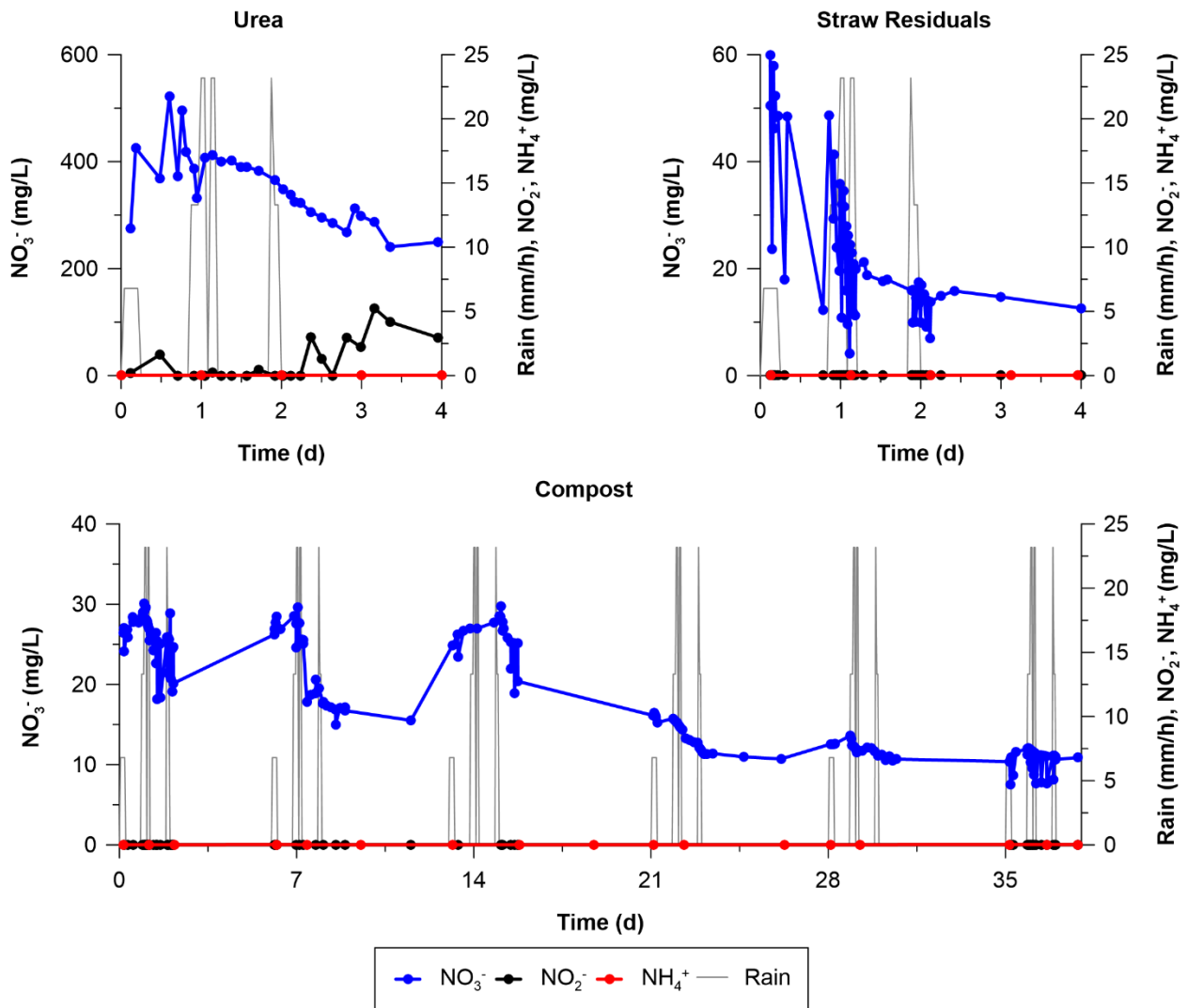
293 In the SR experiment, NO_3^- concentrations were much lower than those measured in the U
294 experiment, since the straw residuals were not rich in NO_3^- . The threshold limit of 50 mg/L (Italian
295 Law Decree 152/2006, 2006) was only exceeded at the beginning of the experiment; then, during
296 storm events, NO_3^- decreased towards a final concentration around 13.5 mg/L; NO_2^- and NH_4^+ were
297 very low or below detection limits.

298 In the Comp experiment the NO_3^- initial concentrations were around 27 mg/L and showed a
299 decreasing trend, apart from some fluctuations during the first three rainfall events. An important
300 aspect which characterised the Comp experiment is that NO_3^- concentrations never exceeded the
301 threshold limit. NO_2^- and NH_4^+ concentrations were very low during the whole duration of the Comp
302 experiment.

303 From a mass balance calculation, the cumulative mineral N released by the U experiment was 151
304 kg-N/ha, while for the SR experiment it was 12.6 kg-N/ha and for the first elution of the Comp

305 experiment it was 15.5 kg-N/ha. In the Comp experiment the cumulative mineral N released by the
306 whole elution (6 storm events) was 48.6 kg-N/ha.

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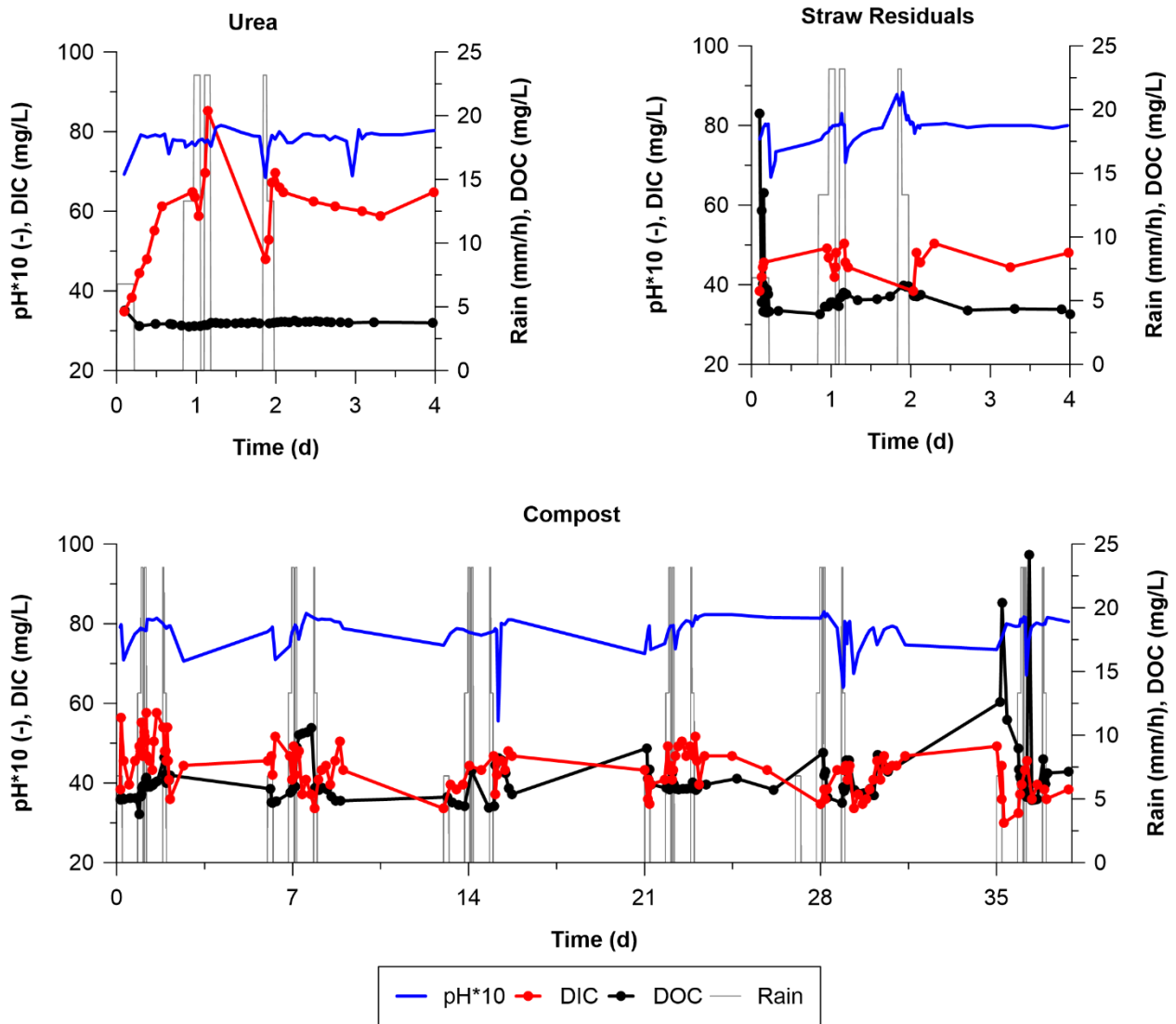


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309 Figure 4: NO_3^- , NO_2^- , NH_4^+ and simulated rainfall during the three laboratory experiments with the
310 addition of Urea (upper left plot), Straw residuals (upper right plot) and Compost (bottom plot).

311

312



313

314 Figure 5: DOC, DIC, pH and simulated rainfall during the three laboratory experiments with the
 315 addition of Urea (upper left plot), Straw residuals (upper right plot) and Compost (bottom plot). Note
 316 that pH values are multiplied by a factor 10 to make it visible in the plots.

317

318 Figure 5 shows DOC, DIC and pH variations in the leachate samples. The U experiment recorded
 319 much lower DOC concentrations than the SR and Comp experiments, moreover the DOC in U
 320 experiment did not vary significantly during the elution, while in SR and Comp, DOC increased
 321 during rainfall events. The constant and low DOC concentrations in U experiment is an indication
 322 that in those experiment only residual DOC was flushed away, while a more labile DOC pool was

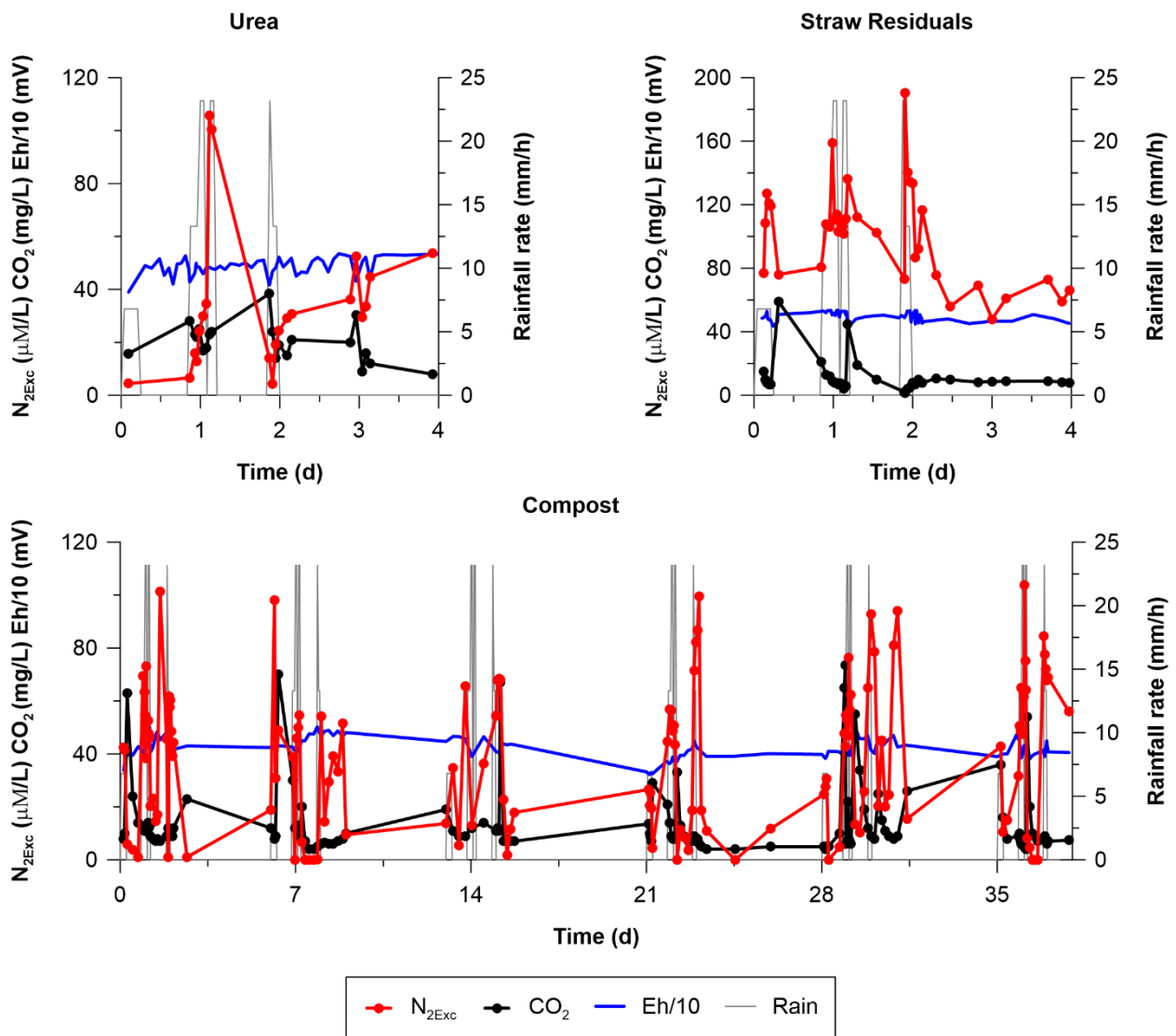
323 probably flushed in the other two experiments, since both SR and Comp can release organic acids
324 when wetted (Krogmann & Woyciechowski, 2000; Liu et al., 2014).

325 DIC variations were of the same order of magnitude in all the experiments due to carbonate
326 dissolution, as witnessed by the alkaline pH respect to the slightly acidic pH of the synthetic rainwater
327 (Table 1). The early breakthrough of rainwater due to preferential flow in macropores is also revealed
328 by negative pH shifts recorded immediately after the rainfalls. From a mass balance calculation, the
329 cumulative DOC released by the U experiment was 7.7 kg-C/ha, while for the SR experiment it was
330 15.1 kg-C/ha and for the first elution of the Comp experiment it was 15.5 kg-C/ha. In the Comp
331 experiment the cumulative DOC released by the whole elution (6 storm events) was 78.6 kg-C/ha,
332 providing a long-term source of leachable DOC.

333 Figure 6 shows N_{2Exc} , CO_2 and Eh variations in the leachate samples. The U experiment recorded
334 lower N_{2Exc} values than in SR and Comp experiments, except for a spike recorded during the rainfall
335 event at day 1. The same spikes of N_{2Exc} were recorded in SR and Comp during rainfall events with
336 a concomitant decrease of dissolved CO_2 , indicating that aerobic respiration diminished when
337 denitrification was boosted, even thou the Eh suggested that oxic spots were prevailing due to mixing
338 with entrapped air, given the unsaturated conditions of the soil. During the last elutions of the Comp
339 experiment the Eh started to slowly decrease, since the near saturated conditions of the column
340 allowed for partial oxygen depletion.

341 Dissolved CH_4 concentrations in leachate samples were always extremely low, in effect CH_4 was
342 never detected despite the low detection limit of MIMS (data not show), so methanogenesis was
343 considered a negligible process along the soil column profile in all the experiments. From a mass
344 balance calculation, the cumulative NO_3^- denitrified in the topsoil of the U experiment was only 1.9
345 kg-N/ha, while in the SR experiment it was 8.7 kg-N/ha and in the first elution of the Comp
346 experiment it was 3.2 kg-N/ha. These low denitrification values are not surprising, since the
347 stormwater events here simulated produced fast percolation rates that usually hinder denitrification
348 capacity due to low contact time with the SOM which is immobile, while only DOC can be used by

349 denitrifying bacteria in such fast flow systems (Mastrocicco et al., 2019a). It must be stressed that
 350 these storm events have been found to recur much more frequently in the last years in the
 351 Mediterranean area and more specifically in the Po river valley (Vezzoli et al., 2015). Coherently
 352 with the above statement, in the Comp experiment the cumulative NO_3^- denitrified by the whole
 353 elution (6 storm events) was 14.5 kg-N/ha, which was lower than the expected 19.2 kg-N/ha value
 354 obtained multiplying the first Comp elution by 6 (storm events). This because the SOM dissolution
 355 rate is expected to rapidly decrease with time given that the most mobile fraction is likely to be flushed
 356 away with the first storm events.
 357



358

359 Figure 6: N_{2Exc} , CO_2 , Eh and simulated rainfall during the three laboratory experiments with the
360 addition of Urea (upper left plot), Straw residuals (upper right plot) and Compost (bottom plot). Note
361 that Eh values are divided by a factor 10 to make it visible in the plots.

362

363 The cumulative masses of DOC, mineral N and denitrified N leached have been summarized in Table
364 2, where it is apparent that the C/N ratio is shifted towards N in the U experiment and consequently
365 only a small percentage of the leached mineral N has been denitrified.

366 While in the SR and Comp experiments much greater C/N ratios allow higher percentages of
367 denitrification respect to the leached mineral N after a single stormwater event. The highest denitrified
368 N percentage occurred in the SR experiment, and given that DOC, pH, Eh, and C/N were similar in
369 the SR and Comp experiments, most probably the higher denitrification in SR was due to a higher
370 percentage of labile DOC availability respect to the Comp experiment. This is consistent with results
371 found by Liu et al. (2014) that reviewed 176 published field studies of SR incorporation and
372 calculated an increase in soil active C fraction of 42% on average, although in this study different
373 fractions of DOC were not determined. It must be stressed that in Comp experiment the denitrified N
374 percentage increased from 20.6% to 29.8% after prolonged rainfall events, proofing the long-term
375 action of Comp addition. In fact, according to Xu et al. (2020), the main function of Comp application
376 is the reduction of NO_3^- leaching, and Diez et al. (1997) showed that the Comp application along with
377 intensive irrigation had positive effects on controlling NO_3^- leaching in comparison to other soil
378 conditioners.

379

380 Table 2: Leached masses of DOC, mineral N and denitrified N, C/N and ratio of denitrified N over
381 leached N for the Urea (U), Straw residuals (SR), Compost (Comp) stormwater events and for the 6
382 repeated stormwater events (Comp_{Tot}).

Leached DOC	Leached N	Denitrified N	C/N	Denitrified N/Leached N
-------------	-----------	---------------	-----	-------------------------

	(kg-C/ha)	(kg-N/ha)	(kg-N/ha)	(-)	(%)
U	7.7	151	1.9	0.1	1.3
SR	15.1	12.6	8.7	1.2	69.0
Comp	15.5	15.5	3.2	1.0	20.6
Comp_{Tot}	78.6	48.6	14.5	1.6	29.8

383

384 **3.4. Major dissolved ions**

385 The principal anions present in the leachate samples were Cl^- and SO_4^{2-} (Fig.7). Cl^- is commonly
386 dissolved in natural water, because it isn't adsorbed by the soil (Dev & Bali, 2019) and it is often
387 used as a conservative tracer (Davis et al., 1998).

388 In the U experiment Cl^- rapidly decreased during the elution due to preferential flow in macropores,
389 reaching a minimum of 10 mg/L, and gradually increased afterwards due to micropores contribution.

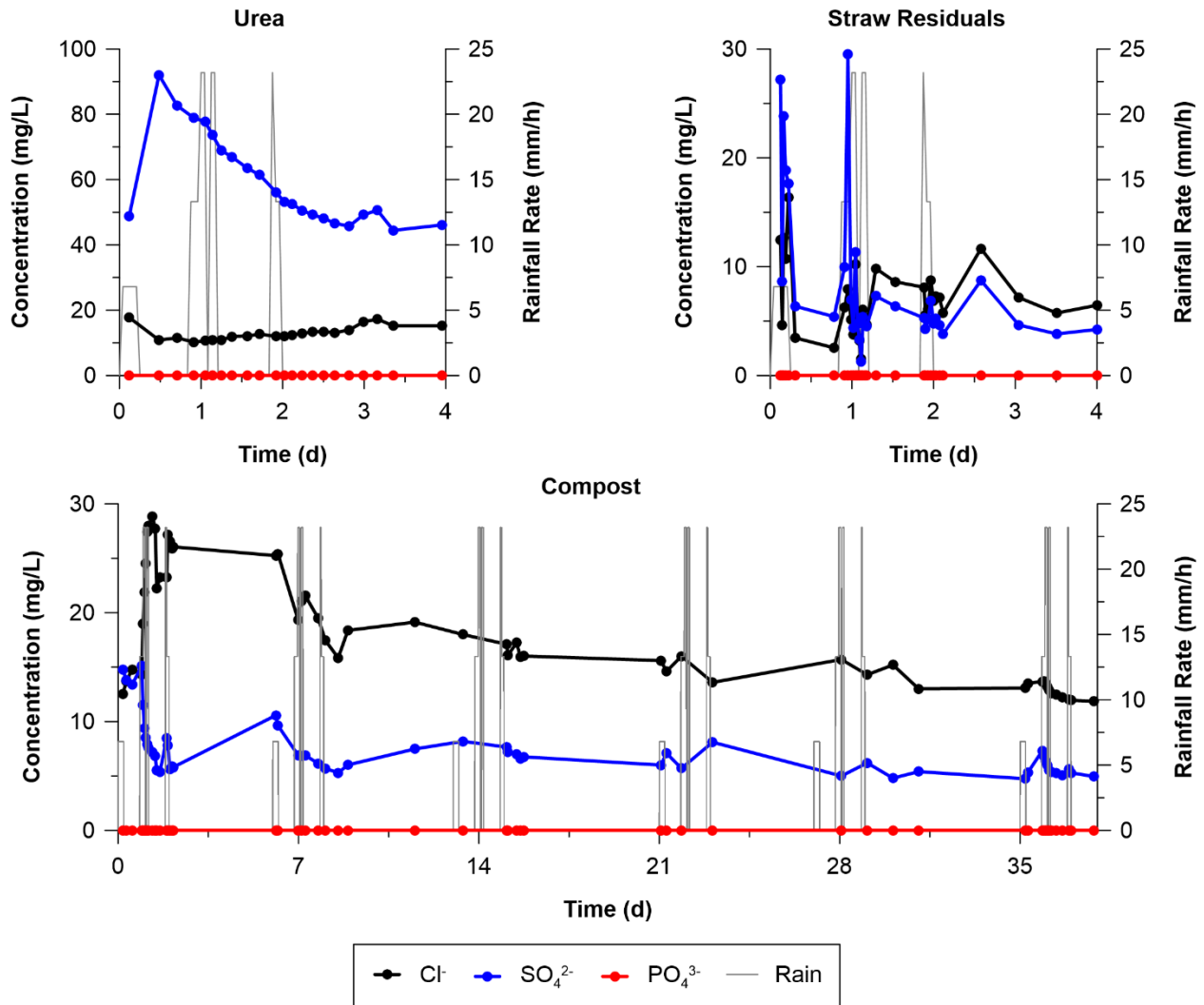
390 In the SR experiment, Cl^- was elevated in the first water samples, with a maximum concentration of
391 16.3 mg/L, and then it decreased with large fluctuations during the rainfall events. In the Comp
392 experiment, Cl^- concentration increased respect to previous experiments, with a maximum
393 concentration of 29 mg/L during the first rainfall event. Then Cl^- gradually decreased until the last
394 storm event (reaching 13 mg/L). The Cl^- mass eluted after the six storm events was 74.9 kg- Cl^- /ha
395 while the Cl^- mass in the Comp was only 2.2 kg- Cl^- /ha and considering that the inflow water (Table
396 1) had very low Cl^- concentrations that contributed with 3.5 kg- Cl^- /ha; this implies that Cl^- was mainly
397 released by dissolution of secondary mineral phases, like halite, which could form during desiccation
398 in soils in micropores (Nachshon et al., 2011) and thus slowly release Cl^- in soil porewater.

399 The trend for SO_4^{2-} was similar to the one recorded for Cl^- in the all experiments. At the beginning of
400 the U experiment, SO_4^{2-} showed high concentrations (with a maximum of 92 mg/L) and remained
401 always higher than Cl^- , even though it gradually decreased reaching a constant value around 46 mg/L.

402 In the SR experiment, SO_4^{2-} concentrations were high during the rainfall events, especially in the
403 second elution when the maximum concentration (30 mg/L) appeared. After that, SO_4^{2-} decreased

404 reaching a constant value around 3 mg/L, which was even lower than Cl⁻ concentration. In the Comp
405 experiment SO₄²⁻ concentrations were lower than Cl⁻ ones and showed a decreasing trend (especially
406 during extreme rainfall events), from 15 mg/L to 4 mg/L. It is worth noting that at the beginning of
407 the Comp experiment, SO₄²⁻ had high initial concentrations and a sudden drop during the first rainfall
408 event, opposite to what has been described for Cl⁻ at the beginning of the Comp experiment, since the
409 SO₄²⁻ concentration in Comp was very low respect to Cl⁻. This again witnesses preferential flow in
410 macropores. The SO₄²⁻ mass eluted after the six storm events was 29.9 kg-SO₄²⁻/ha, while the SO₄²⁻
411 mass in the Comp was minimal (0.2 kg-SO₄²⁻/ha) and the rain water contributed with 6.9 kg-SO₄²⁻
412 /ha; thus SO₄²⁻ was released by dissolution of secondary mineral phases like gypsum. Finally, PO₄³⁻
413 in water samples was considered negligible during the whole duration of the U, SR and Comp
414 experiments since it was always below detection limits.

415



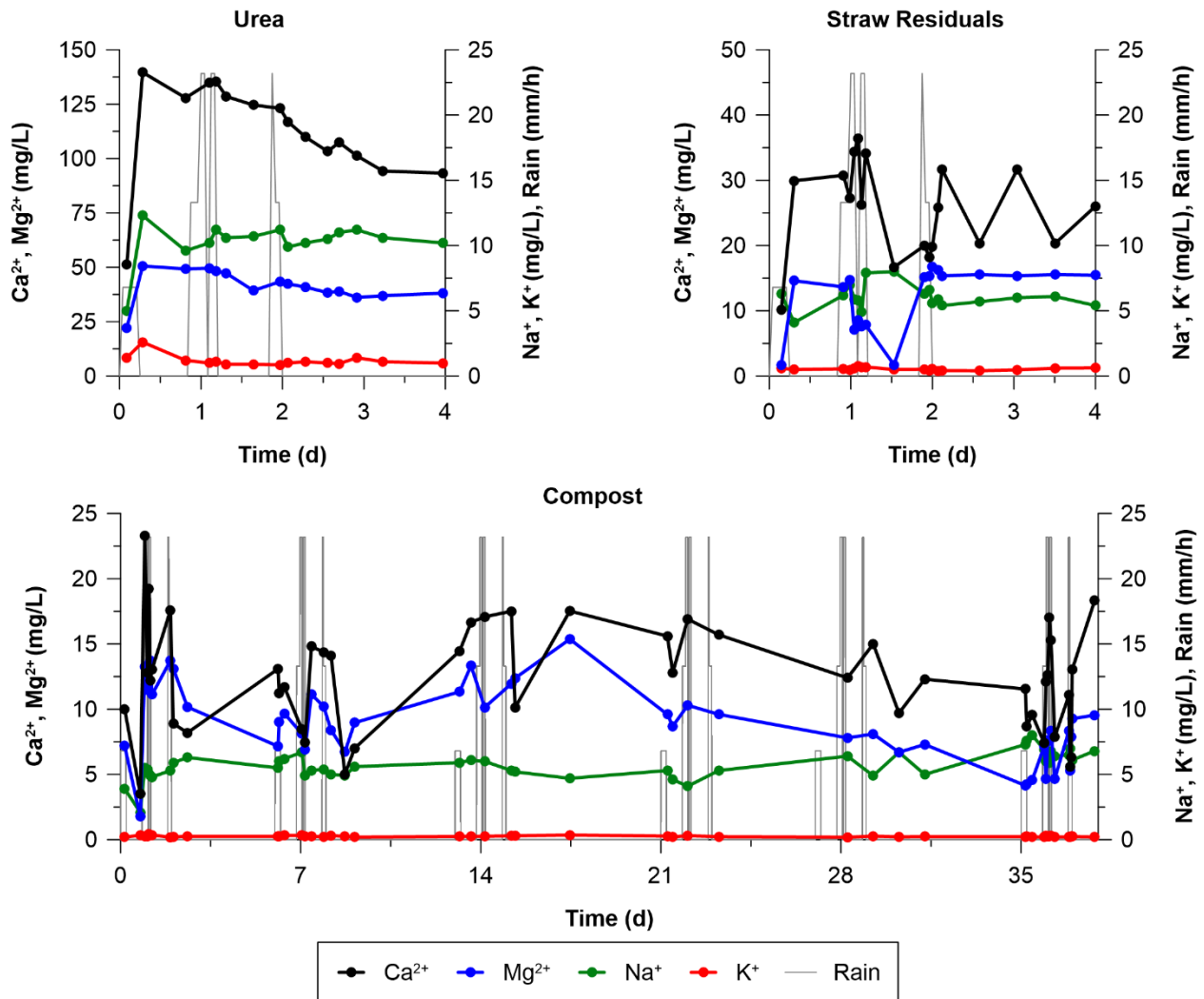
416

417 Figure 7: Cl⁻, SO₄²⁻, PO₄³⁻ and simulated rainfall during the three laboratory experiments with the
 418 addition of Urea (upper left plot), Straw residuals (upper right plot) and Compost (bottom plot).

419

420 The principal cations present in the leachate samples were Ca²⁺ and Mg²⁺ (Fig.8). Both Ca²⁺ and Mg²⁺
 421 trends were similar, especially in the U experiment, with Ca²⁺ showing higher concentrations than
 422 Mg²⁺. This may be due to Ca²⁺ release in the topsoil to buffer the acidity formed by nitrification
 423 reactions (Chao et al., 2017). Ca²⁺ content in the U leaching samples decreased during the
 424 experiments, while Mg²⁺ had only a gradual decrement. In the U experiment, Na⁺ was almost constant
 425 over the whole experiment, with an average concentration of 10.6 mg/L. The behaviour of major
 426 cations is congruent with the displacement of the initial TDS spike (see Fig.3) induced by urea
 427 hydrolysis. In the SR experiment, both Ca²⁺ and Mg²⁺ showed a lower initial concentration than the

428 one recorded for the U experiment, with an initial concentration of 10 mg/L for Ca^{2+} and 1.7 mg/L
429 for Mg^{2+} . Their trends showed an increment until the end of the second rainfall event, a rapid decrease
430 between day 1 and 2, again an increase with the last event and then it became constant. In the SR
431 experiment, Na^+ showed a smooth increase during the rainfall event, with an average concentration
432 of 7.8 mg/L. In the Comp experiment, Ca^{2+} and Mg^{2+} had the same trend with slightly lower
433 concentrations than the SR experiment. During the Comp experiment, elevated concentrations of Ca^{2+}
434 and Mg^{2+} were recorded in leachate samples in coincidence with the storm events, while Na^+
435 remained nearly constant throughout the different elutions except for a slight increase in the last one,
436 from 3.7 mg/L up to 7.2 mg/L. The displacement of divalent cations (Ca^{2+} and Mg^{2+}) followed by
437 monovalent (Na^+) was due to the chromatographic effect triggered by the moderate cation exchange
438 capacity of these soils (Castaldelli et al., 2018). This effect was not evident in the U and SR
439 experiments since it may need many pore volumes to produce appreciable variations in leachate
440 samples, as shown by Mastrocicco et al. (2011) with similar soils in water saturated conditions.
441 Finally, K^+ concentrations could be considered negligible during the whole duration of the U, SR and
442 Comp experiments.



444

445 Figure 8: Ca^{2+} , Mg^{2+} , Na^+ , K^+ and simulated rainfall during the three laboratory experiments with the
 446 addition of Urea (upper left plot), Straw residuals (upper right plot) and Compost (bottom plot).

447

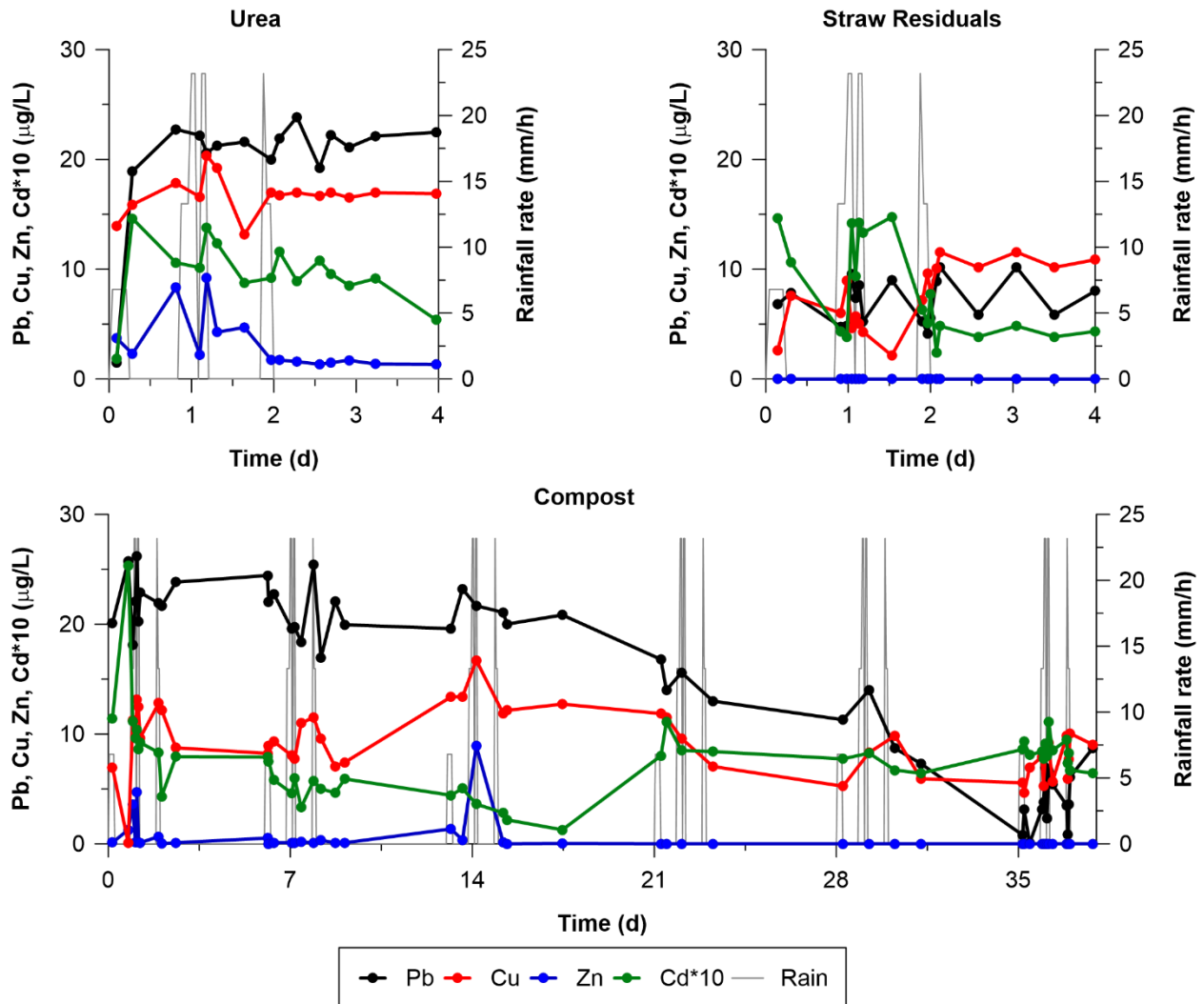
448 3.5. Heavy metals leaching

449 Figure 9 shows that Pb and Cu were the main heavy metals present in leachate water samples. Pb
 450 exceeded the WHO threshold limit ($10 \mu\text{g/L}$) during the whole duration of the U experiment, with an
 451 average concentration of $22.1 \mu\text{g/L}$, and also during the first three rainfall events in the Comp
 452 experiment, with an average concentration of $20.0 \mu\text{g/L}$. At the end of the Comp experiment, Pb
 453 significantly decreased, with an average concentration of $5.1 \mu\text{g/L}$. In the SR experiment, Pb was
 454 always below the WHO threshold limit.

455 Cu followed similar trends to the ones recorded for Pb both in the U and Comp experiments, but
456 always showed concentrations below the WHO threshold limit (20 µg/L). In the SR experiments, Cu
457 showed an anomalous pattern, with low concentrations at the beginning of the experiment which
458 suddenly increase during rainfall events and remained constant, with high values, until the end of the
459 experiment. The SR experiments is the only one having Cu higher than the other analysed compounds.
460 Cd and Zn didn't exceed WHO threshold limits (5 and 2000 µg/L, respectively) in all experiments;
461 moreover, Cd results were very low, since they have been multiplied by a factor 10 to be shown in
462 Figure 9. Zn appeared in water samples of the U experiment, occasionally in the Comp experiment,
463 and it is not present in the SR experiment. In the U experiment concentrations were higher during the
464 second elution, with a maximum content of 9.0 µg/L; instead, in the Comp experiment Zn was present
465 only during the first and the third storm events, in which concentrations were 3.1 µg/L and 2.0 µg/L,
466 respectively.

467 Cd trend reflected Cu one in the U experiment, but Cd concentrations continued to decrease until the
468 end of experiment. Conversely, in the SR experiment, Cd pattern was opposite to the Cu one. In the
469 Comp experiment, Cd showed maximum concentrations (2.5 µg/L) at the beginning of the
470 experiment, then decreased from the first to the third rainfall event and then it increased again in the
471 last three elutions. A Zn spike is also present at day 14, possibly released by Comp, although the
472 concentration was low.

473



474

475 Figure 9: Pb, Cu, Zn, Cd and simulated rainfall during the three laboratory experiments with the
 476 addition of Urea (upper left plot), Straw residuals (upper right plot) and Compost (bottom plot). Note
 477 that Cd concentrations are multiplied by a factor 10.

478

479

480

481

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483

484 Table 3: Summary of the aqua regia extraction tests carried out on soil samples compared with Italian
 485 legislative thresholds (Italian Law Decree 152/2006, 2006).

	Cu	Cd	Ni	Pb	Zn
	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
Italian Legislative Limits	120	2.0	120	100	150
Topsoil	73.4	1.2	114.0	24.9	106.2
Soil at -25 cm	71.4	1.0	108.3	21.0	103.5
Soil at -50 cm	74.9	0.9	114.1	22.9	105.4

486

487

488 Heavy metals in the lower portion of the Po river valley can derive from anthropogenic pollutants or
489 may have a geogenic origin (Di Giuseppe et al., 2014). The sediments of the Po river are rich in Cr
490 and Ni, related to Ophiolite rocks weathering in the hydrological basin, but they are not particularly
491 rich in Pb (Amorosi, 2012; Bianchini et al., 2012) and the heavy metals soil characterization at the
492 beginning of the experiment highlighted concentrations below Italian Legislative Limits (Table 3).
493 So Pb could be derived from anthropogenic activities, like the application of fertilizers onto
494 agricultural fields that could be a direct source of Pb or could have triggered reactions promoting its
495 mobilization (Atafar et al., 2010). Giusquiani et al. (1995) demonstrated that Comp application could
496 cause Pb leaching, and in agreement with their findings elevated Pb concentrations appeared in the
497 leachate at the beginning of the Comp experiment, even though the Pb content in the applied Comp
498 was extremely low (Table 1). Thus, the Pb mobilization was due to reactions triggered by the Comp
499 addition. Likewise, the leachate obtained from the U experiment had an elevated content of Pb while
500 its content in the applied U was extremely low (Table 1). Thus, the Pb mobilization was due to
501 reactions triggered by U addition and not by the U impurities. Finally, it should be stressed that all
502 the heavy metals here monitored were well below the EPA quality water standards for agricultural
503 purposes (EPA, 2017).

504

505 **3.6. Modification of the soil hydraulic properties due to compost incorporation**

506 The ratio of salinity to sodicity determines the effects of salts and Na^+ on soils: salinity promotes soil
507 flocculation while sodicity promotes soil dispersion (Warrence et al., 2002). The combination of
508 salinity and sodicity of soils is measured by the swelling factor (SF), which predicts whether sodium-
509 induced dispersion or salinity-induced flocculation will affect soil physical properties.

510 The calculated SF of 0.28, with a combination of ESP equal to 30 and salinity equal to 2 meq/L,
511 indicates that dispersion is likely to occur within the Comp soil column.

512 Another approach to estimate the effects of salinity and namely Sodium Adsorption Ratio (SAR) on
513 soil physical properties is to assess the potential impacts of various irrigation water qualities on
514 infiltration rates. For example, at SAR equal to 15, a severe reduction in infiltration will occur with
515 an EC equal to 1 dS/m; an EC of 2.5 dS/m or less results in a slight to moderate reduction in infiltration
516 and at EC greater than 2.5 dS/m, there will likely not be a reduction in infiltration.

517 The variation of the soil hydraulic properties between the initial and final conditions (Table 4) in the
518 Comp experiment highlights the impact of the application of compost as soil conditioner on the soil
519 column after intensive and prolonged rainfall events. θ_{33} and θ_{1500} were calculated according to Rawls
520 et al. (2003), and they were found to be constant from the beginning to the end of experiment. On the
521 other hand, total porosity (Φ_{tot}), that is the ratio between the volume of the soil's pores and the total
522 volume of the column, decreased from 0.55 to 0.47 in the top 15 cm of the column, confirming that
523 empty pores were reduced because of the swelling effect induced by the application of the compost
524 to the topsoil; in the remaining part of the column this effect was not so evident (from 0.46 to 0.45),
525 nevertheless, when considering the weighted average on the whole column the reduction of the total
526 porosity was still evident (from 0.51 to 0.48). At the beginning of the Comp experiment the Available
527 Water Content (AWC), that is the difference between θ_{33} and θ_{1500} expressed as a percentage of Φ_{tot} ,
528 was equal to 28% in the topsoil while at the end of the Comp experiment it was equal to 33%, so 5%
529 higher than initial condition thus improving the hydraulic properties of the topsoil. Contrary, the
530 percentage of gravitational water ($\text{H}_2\text{O}_{\text{grav}}$) within the Φ_{tot} in the topsoil, decreased from 36% to 24%
531 after the compost application. This could also be considered a positive effect if the percolation of

532 harmful species is believed to be an issue in the considered agricultural field. In the remaining part
 533 of the column H_2O_{grav} decreased from 24% to 22%, while the weighted average of H_2O_{grav} on the
 534 whole column substantially changed from 27% to 23%.

535

536 Table 4: Soil hydraulic properties at the beginning of the experiment and after the compost addition
 537 in the topsoil of the column.

INITIAL CONDITION							
Parameters*	Φ_{tot} (-)	Θ_{33} (-)	Θ_{1500} (-)	AWC (% Φ_{tot})	H_2O_{grav} (% Φ_{tot})	H_2O_{ret} (% Φ_{tot})	ρ_b (gr/cm^3)
TOPSOIL (15 cm)	0.55	0.35	0.20	28	36	36	1.30
SOIL (40 cm)	0.46	0.35	0.20	33	24	43	1.40
WHOLE COLUMN (55 cm)	0.51	0.35	0.20	32	27	41	1.44
FINAL CONDITION (after compost application)							
TOPSOIL (15 cm)	0.47	0.35	0.20	33	24	43	1.38
SOIL (40 cm)	0.45	0.35	0.20	34	22	44	1.47
WHOLE COLUMN (55 cm)	0.48	0.35	0.20	33	23	44	1.52

538 *Total porosity (Φ_{tot}); field capacity (Θ_{33}); permanent wilting point (Θ_{1500}); available water content
 539 (AWC) as a % of Φ_{tot} ; gravitational water (H_2O_{grav}) as a % of Φ_{tot} ; retention water (H_2O_{ret}) as a % of
 540 Φ_{tot} ; dry bulk density (ρ_b).

541

542 Obviously, the retention water (H_2O_{ret}) increased after the compost application on the topsoil, from
 543 36% to 43%. Conversely to what considered for H_2O_{grav} reduction, the increase in H_2O_{ret} could have
 544 negative effects on agricultural fields since it may induce waterlogged conditions that are known to
 545 be detrimental for most crops. In the remaining part of the column H_2O_{ret} increased from 43% to 44%,
 546 while the weighted average of H_2O_{ret} on the whole column changed from 41% to 44%.

547 Finally, ρ_b which is the ratio between the weight of dry soil and the total soil volume slightly increased
548 after the compost application, both in the topsoil and in the remaining part of the column, because of
549 the swelling effect (see next paragraph for further explanation).

550

551 **3.7. Clay swelling due to compost incorporation**

552 In this study, it was observed that clay swelling occurred as a consequence of the prolonged simulated
553 rainfall only after the use of compost as amendment on the soil column. In fact, the forces that bind
554 clay particles together are disrupted when too many Na^+ ions come between them. When this
555 separation occurs the clay particles expand, causing swelling and soil dispersion.



556

557 Figure 10: Soil column at initial (left picture) and final (right picture) conditions, after the clay's
558 swelling due to the compost addition in the topsoil.

559

560 Even though this phenomenon is certainly related to the increment of VWC (it appeared for the first
561 time during the third elution in the Comp experiment), it is most probably driven by the high Na^+
562 content of the compost applied (approximately 450 mg/kg), because the elevated content of this

563 monovalent cation usually influences soil structure, polarizing clay particles favouring their
564 dispersion (Fig.10).

565 Moreover, the applied compost was not so rich in Ca^{2+} and Mg^{2+} (44 and 17 mg/kg, respectively),
566 giving a SAR of about 15, which also suggests the possible occurrence of clay swelling, since this
567 phenomenon is highly probable above a SAR of 13 (Choudhary & Kharche, 2018).

568 The clay swelling observed for the Comp experiment, had a detrimental effect on the infiltration
569 capacity of the soil column as confirmed by the model proposed by Hanson et al. (1999). As already
570 mentioned in a previous paragraph, Comp incorporation influenced soil structure and properties,
571 especially ρ_b and porosity. Different to previous studies (Paradelo et al., 2019), in this study the
572 application of compost caused porosity's decrease and the raise of ρ_b after the experiment (Giusquiani
573 et al., 1995; Zhao et al., 2012). The main cause of porosity's reduction was clay's swelling (qualitative
574 analyses showed in Fig.10), which was due to the raise of VWC and to the elevated Na^+ content in
575 the amendment (Table 1). This side effect explained the elevated content of $\text{H}_2\text{O}_{\text{ret}}$ after the compost
576 application (see Table 4) and the rise of Na^+ content in the leachate, while ions as Ca^{2+} and Mg^{2+}
577 decreased (see Fig.8). The decrease of porosity influenced also AWC (Celik et al., 2004), which
578 increased after the use of compost. However, the increment of AWC could also be justified by the
579 increase of DOC during the Comp experiment (Ramos, 2017).

580

581 **4. Conclusions**

582 This study describes the effects of straw residuals and compost respect to urea, in reducing nitrate
583 losses from agricultural field situated in vulnerable zones of the province of Ferrara, which may be
584 subject to extreme rainfall events. The results of the laboratory's column experiments show that straw
585 residuals and compost incorporation could decrease nitrate leaching towards groundwater by
586 increasing the denitrification capacity. On the other hand, the treatment with urea showed incomplete
587 denitrification, mostly related to the lack of labile organic substrates, rather than to other inhibitor
588 effects as pH and Eh changes. Furthermore, the results showed that the compost addition modified

589 the physical and hydraulic properties of the soil, because of the elevated sodium content of the
590 employed compost, leading to clay's swelling, which negatively affected water retention and
591 infiltration rate. Thus, an issue to be considered when applying compost to agricultural land is the
592 chance to induce waterlogged conditions if prolonged rainfall events occur. Moreover, further
593 experiments should be conducted with loamy textures soils and different rainfall intensities to widen
594 the obtained results. The main limitations of this study are: (i) three or more undisturbed soil cores
595 should have been used to provide more insights on the statistical representativeness of the obtained
596 results and (ii) the lack of sampling ports within the soil column limited the quantification of the most
597 reactive soil horizons.

598 Despite the above mentioned limitations, some general conclusions can be drawn: the use of organic
599 conditioners, like straw residuals and compost, have positive impacts on agricultural fields, like the
600 dissolution of labile organic carbon which, by fuelling denitrification, may prevent nitrate migration
601 to shallow groundwater; this without a significant mobilization of potentially toxic elements, such
602 as lead, which was detected at low concentrations only in the initial stage of the compost experiment.

603

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614 Project Ferrara Nitrates - Agricultural techniques to prevent nitrates pollution and for the organic

615 matter conservation (<https://ec.europa.eu/eip/agriculture/en/find-connect/projects/nitrati-ferrara->
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