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P. Thiébeau, Cyril Girardin, Sylvie Recous

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1 **Water interception and release of soluble carbon by mulches of plant residues under contrasting**
2 **rain intensities**

3

4 Pascal Thiébeau ^a, Cyril Girardin ^b, Sylvie Recous ^{a*}

5

6 ^a Université de Reims Champagne Ardenne, INRAE, FARE laboratory, Reims, France

7 ^b AgroParisTech, INRAE, UMR ECOSYS, Thiverval-Grignon, France

8

9 **Corresponding author:**

10 Sylvie Recous, +33 326 773 583; sylvie.recous@inrae.fr

11

12

13 **Highlights**

- 14 • Soluble C leaching from mulches by rain is an important pathway for soil C cycling
- 15 • Interception of water by mulches depends on the residue type and amount of rain applied
- 16 • Rain leached a large proportion of the initial residue water-soluble C
- 17 • High rainfall intensity was less effective than low intensity at displacing soluble C

18

19 **Abstract**

20 The presence of crop residues on the soil surface of no-till cropping systems has important
21 consequences on water flows between the atmosphere, litter layer (mulch) and soil. The consequences
22 of rainfall on the transport of soluble C from litter layers are poorly known, despite their importance
23 for soil carbon (C) and nutrient cycling. We quantified relationships among the rain amount and
24 intensity, the water retention by mulches and the soluble C loss from mulches under rainfall. Mulches
25 of residues from mature crops (maize, soybean and rice) and a cover crop (pea) were placed under
26 continuous simulated rains with intensities of 4, 11 and 24 mm h⁻¹ for 23 hours, and we measured the
27 water interception dynamics of the mulches and the water and soluble C flows under the mulches. The
28 maximal water contents of the pea, maize and rice mulches did not differ significantly from each other
29 (5.9 to 6.6 g H₂O g⁻¹ dry matter), while the soybean mulch retained much less water than the other
30 mulches at 3.5 g H₂O g⁻¹ dry matter (DM). The soluble C loss was 9.2 to 23.7 % (4 mm h⁻¹) and 19.3
31 to 55.2 % (24 mm h⁻¹) depending on the residue type after 7 hours of rain. With similar amounts of
32 received rain (500 mL), the soluble C loss was identical for intensities at 4 and 11 mm h⁻¹, and
33 significantly lower at 24 mm h⁻¹, suggesting inefficient rain transport at the high rain intensity. Finally,
34 this study highlights the importance of better characterizing the physical and water properties of
35 mulches and residue particles because of their significant effects on water and soluble C transport.

36

37 **Key words** (indexing terms)

38 carbon; crop residue; no-till; rain regime

39

40 **1. Introduction**

41

42 The development of no-till agricultural systems modifies the way crop residues are incorporated
43 back into the soil compared to conventional systems with ploughing. These residues form a layer, or
44 mulch, on the soil surface in no-till systems or are partially incorporated into the first few centimetres
45 of soil with reduced tillage. The presence of crop residues on the soil surface has very significant
46 consequences on water and heat flows between the atmosphere, mulch and soil, as well as on the
47 regulation and stratification of biological activity and organic matter in soil and mulch (Bussière and
48 Cellier, 1994; Baumhardt and Jones, 2002; Fuentès et al., 2012; Dietrich et al., 2019). However, the
49 determinants of water retention by crop residues and the consequences of rainfall on the transport of
50 soluble elements, particularly soluble carbon (C), are much less known, despite their importance for C
51 and nutrient cycling in soils (Lee et al., 2014; Iqbal et al., 2015). In particular, it has been shown that
52 plant litter-derived soluble C may constitute a significant pathway of C stabilization in soil (Cotrufo et
53 al., 2013). Soluble C can account for an important fraction of C in crop residues, varying from
54 approximately 10 to 80 g 100 g⁻¹ total C for main crops and cover crops depending on the degree of
55 maturity and part of the considered plant (Trinsoutrot et al., 2000; Redin et al., 2014).

56 Although the amount of rainwater that can be intercepted and retained by mulches has received
57 little study, we know that this interception depends mainly on the amount and nature of crop residues
58 (Tuckey, 1970). Previous studies have shown that the maximum water content of these mulches can be
59 modulated according to the crop residue characteristics (Quemada and Cabrera, 2002; Iqbal et al.,
60 2013) and their morphological, anatomical and chemical traits (Garnier and Laurent, 1994). Iqbal et al.
61 (2013) showed for stems of different annual species that the main explanatory characteristic of their
62 maximal ability to retain water was the density of the tissues of the stems (or its inverse, i.e., porosity),
63 whereas chemical characteristics were not directly related to water retention properties. A number of
64 studies have compared the effects of rainfall intensity on the water retention capacity of mulch on the
65 soil surface, mostly on forest systems with leaf litters (e.g., Sato et al., 2004; Schrumpf et al., 2006;
66 Dunkerley, 2015). More recently, the fact that residue mulch constitutes a "hot spot" of biological
67 activity and denitrification has led to interest in the water retention capacity of mulches (Kravchenko

68 et al., 2017) but such study is still rare. To our knowledge, the transport of soluble C or nutrients under
69 the influence of rainfall carried out in an agricultural context are rare (Halvis and Alberts, 1983;
70 Schreiber, 1985; Schreiber and McDowell, 1985; Schreiber, 1999) despite the experimental
71 observation of residue-derived soluble C transport into soil (Coppens et al., 2006; Lee et al., 2014;
72 Iqbal et al. 2015).

73 The objective of this work was to understand the relationships among the rain regime (varying by
74 the intensity and amount of water applied), water retention by mulch and soluble C loss from mulch
75 under the influence of rain. Experimentally, mulch residues from four different crops were placed
76 under simulated rains of realistic and contrasting intensities representing the conditions in temperate to
77 tropical climates. We measured the dynamics of water interception by mulches and the leaching of
78 soluble C from the mulch. To facilitate the dynamic and quantitative monitoring of soluble C extracted
79 from the mulch by the rains, we did not place soil under the mulch.

80

81 **2. Materials and methods**

82 *2.1 Crop residues*

83 Maize (*Zea mays* L.), rice (*Oriza sativa* L.), and soybean (*Glycine max* L.) were harvested at the
84 mature stage, while pea (*Pisum sativum* L.) was harvested at flowering so that its residues represented
85 those of a cover crop. The crop residues were collected in the field in three areas, namely, an area of
86 intensive agriculture in northern France, a family farm in Cerasdos (Brazil) and upland rice cropping
87 systems in the Central highlands of Madagascar. We used all organs to compose the residues, except
88 for the grains and roots. Samples were dried at 40°C until they reached a constant weight and then
89 were stored in paper pockets. The chemical characteristics of the selected residues were determined
90 prior to the rainfall experiment and are given in Table 1. Briefly a sub-sample of each residue was
91 ground and analysed to determine the chemical and biochemical characteristics via a proximal analysis,
92 thus providing the relative proportion of the so-called “van Soest” fractions of the residue dry matter.
93 The soluble fraction was determined by extraction in hot water (100 °C) for 30 min followed by
94 extraction with a neutral detergent (100 °C) for 60 min. The hemicellulose, cellulose and lignin
95 fractions were subsequently determined via a proximate analysis (Goering and Van Soest 1970). The

96 cold water-soluble fraction of the residues was determined by extraction in deionised water over 30
97 min at 20 °C (plant material/water ratio 1/100). The total C and N contents of the plant residues were
98 determined via total combustion using an elemental analyser (NA 2000, Fisons Instruments, Milan,
99 Italy).

100 Physical characteristics were also determined. Residue-particle bulk density was calculated
101 using the immersion method in water (Iqbal et al., 2013). Mulch thickness was measured for 4
102 replicates per residue type, with 7 measures per replicate (Thiébeau, 2019). The bulk density of the
103 mulch layers was calculated from the thickness of the layers and the added mass of the residues for
104 each residue type.

105

106 **Insert Figure 1**

107 **Insert Table 1**

108

109 *2.2 Simulated rainfall experiments*

110 A similar residue quantity was used for the 4 types of crops to facilitate the comparison of results, with
111 12.4 g of dry residue, which is equivalent to 0.75 kg dry matter m⁻² of residue, placed as a litter layer
112 (mulch) on a 1 mm nylon mesh in a PVC cylinder that was 14.5 cm in diameter (165 cm²) and four cm
113 in height. This amount of residue corresponded to the usual residue biomass in fields for the main
114 crops (Thiébeau and Recous, 2016; Thiébeau, 2019). The crop residue samples were cut into
115 fragments of two centimetres in length (Fig. 1) to reduce the heterogeneity of composition of the
116 mulches between replicates for each crop species. Indeed, the inherent biological variability in the
117 composition and morphology of plant organs for a given species prevent the replication of 12.4 g of
118 mulches on a 165 cm² surface and do not allow the results to be related to an initial residue
119 composition; thus, the particle size had to be reduced. Thus, the potential natural differences between
120 species were eliminated to some extent. Depending on the residue morphological characteristics and
121 density, the particles formed a layer with an initial thickness of 9.3 ± 0.8 mm for rice, 8.6 ± 1.3 mm for
122 maize, 12.8 ± 1.5 mm for pea and 6.7 ± 1.0 mm for soybean. Therefore, the mulch layers had initial
123 bulk densities of 81 ± 6.4 (rice), 87 ± 11.4 (maize), 59 ± 6.2 (pea) and 112 ± 14.5 kg m⁻³ (soybean).

124 Each experimental treatment consisted of three replicates per residue type (n=4) and per rain
125 intensity (n=3). Drainage buckets were placed under each cylinder to collect the percolated water and
126 were weighed and sampled periodically to characterize the drained water under the litter layer. The
127 experiment was run under controlled temperature conditions at 20 ± 1 °C.

128 The drop-forming rainfall simulator, described earlier by Iqbal et al. (2015), consisted of
129 capillary tubes (inner diameter of 0.5 mm) that were equally distributed over the surface (186 cm²)
130 using 72 needles (0.3 mm diameter x 13 mm long; “BD Microlance 3”; *Becton Dickinson, Fraga,*
131 *Spain*) separated from each other by 16 mm; the simulator released 3906 drops per m² (Fig. 2). The
132 rainfall simulator was fed with a flow of deionized water controlled by a Gamma L electromagnetic
133 pump (*ProMinent, Heidelberg, Germany*). Flow rates were adjusted to predetermined intensity
134 profiles and maintained at a constant value to achieve a constant rainfall intensity. Three rainfall
135 intensities were chosen to simulate different climatic scenarios consistent with the field conditions of
136 the studied crops: i) a low regular rainfall intensity of 4 to 5 mm h⁻¹ representative of temperate
137 climates; ii) an intermediate rainfall intensity of 11 to 12 mm h⁻¹; and iii) a strong rain intensity at 24 to
138 25 mm h⁻¹, representative of the intensity that occurs frequently in tropical conditions.

139

140 **Insert Figure 2**

141

142

143 *2.3 Experimental protocol*

144 The rain experiment was run for 24 hours. First, the rain simulations started one hour before the
145 positioning of the cylinders; then, each cylinder with a mulch layer was placed under one simulator for
146 23 hours. During the first 7 hours of rain, mulch layers and buckets were quickly removed every hour
147 and placed into a pre-weighed tray to record the weight of the water held in the litters and the
148 percolates in the buckets. These data were used to calculate the water interception by the litter and the
149 amount of leached water. Each sieve was immediately returned under the rain simulator until the next
150 measurement. After the homogenization of the bucket water content, an aliquot of water was sampled
151 and frozen until the determination of dissolved organic carbon (DOC). After 22 and 23 hours of

152 continuous rain, sieves and buckets were weighed again, and sub-samples of water were collected.
153 Notably, under the simulated rainfall intensity of 24 mm h⁻¹, a large volume of water had leached
154 through the samples between hour 7 and hour 22 and could not be quantitatively stored, so the above
155 measurement was not conducted.

156

157 2.4 Analysis

158 At the end of experimentation (23 hours), the moist residues were first weighed, and then
159 samples were dried at 40 °C until they reached a constant weight, and the loss of mass was calculated.
160 The maximum water storage capacity (MaxWC) was calculated for each residue type and each rain
161 intensity as the difference in weight between the wet mulch and the mulch dried at 40°C, expressed
162 per g of residue dry matter (DM) at 40 °C. The residues were then dried at 120 °C until constant
163 weight. Minimum water storage capacity (MinWC) was calculated as the difference in weight between
164 the mulch dried at 120 °C and at 40 °C, expressed per g of residue DM at 40 °C (Iqbal et al., 2013). A
165 subsample of each crop residue was ground to a particle size of 80 microns, and the total C and N
166 contents were determined by total combustion using the elemental analyser NA 2000 (*Fisons*
167 *Instruments, Milan, Italy*). The DOC in the leached water was measured with a total organic carbon
168 (TOC) analyser (Shimadzu TOC-5050A, *Shimadzu SAS, Marne la Vallée, France*).

169

170 2.5 Calculations and statistical analysis

171 The characteristics of the interception storage capacity of the different residues as a function
172 of the total rain were calculated using a non-linear equation with two parameters (Iqbal et al., 2013):

$$173 f = a \cdot X^b \quad (1)$$

174 where “a” is the water absorbed by the first mm of rain per g of residue and “b” is the propensity of
175 the residue to retain an additional mm of water until reaching the maximum retention value.

176 Statistical analysis was carried out with the Sigma-Plot 12 Statistics programme (*Systat Software,*
177 *USA*). The significance level chosen in our study was $p < 0.05$. Means were classified in a
178 homogenous group according to the results of ANOVA and the Newman-Keuls test. The statistical

179 model evaluation criteria were the root mean square error (RMSE) and coefficient of determination
180 (R^2) values.

181

182 **3. Results**

183

184 *3.1 Rainfall assessment*

185 The rainfall balance according to rain intensity and residue species showed that the objective of
186 using the three rain intensities was achieved (Supplementary material SM1), with no statistically
187 significant difference between crop treatments for each rain intensity. The cumulative amounts of
188 water provided by the three rainfall regimes during the experiment were 105 ± 1 mm, 266 ± 7 mm and
189 560 ± 3 mm. The water flow, calculated from the bucket weight at each hour, showed the
190 establishment of a regular flow of 72 mL h^{-1} for 4 mm h^{-1} , 190 mL h^{-1} for 11 mm h^{-1} and 400 mL h^{-1}
191 for 24 mm h^{-1} after 4 to 5 hours of rain (Supplementary material SM2).

192

193 *3.2 Water interception by crop residues*

194 From the evolution of the weight of mulches throughout the experiment, we inferred the
195 dynamics of water uptake by the four residues under three rainfall intensities (Fig. 3). However, these
196 uptake values were only “apparent” because the loss of crop residue matter under the rainfall was not
197 determined, except for at the end of the experiment using destructive sampling of the residue layers.

198

199 **Insert Figure 3**

200

201 During the first 7 hours of rain, water uptake kinetics were fast for all residues. The kinetics of
202 the 4 mm h^{-1} rain intensity were markedly lower than those of the 11 and 24 mm h^{-1} rain intensities,
203 which did not differ from each other; this was true for all four types of residues. At the end of the
204 experiment (measurements at +22 and +23 h of continuous rain), the water uptake values under the
205 three rain intensities differentiated from each other for almost all residues, and the residues under the
206 most intense rainfall absorbed the most water ($24 \text{ mm h}^{-1} > 11 \text{ mm h}^{-1} > 4 \text{ mm h}^{-1}$).

207 The water storage of residue particles measured at the end of the experiment for each residue
208 type and each rain treatment varied depending on the residue type and the cumulative quantity of
209 water received (itself resulting from the rain intensity applied) (Fig. 4A). The rice and maize mulches
210 behaved very similarly, with high water retention under 100 mm of water. The soybean mulch retained
211 much less water than the rice and maize mulches. The pea mulch demonstrated intermediate water
212 retention, with a relatively low but continuous increase in water retention with increasing amounts of
213 rain. The relationships between MaxWC and cumulative rain were well fitted by the non-linear
214 equation with two parameters (Table 2). The water absorbed by the first mm of rain (“*a*” coefficient)
215 varied from 0.3 to 1.5 g H₂O g⁻¹ DM, with the lowest value for pea residues. Furthermore, the “*b*”
216 coefficient, which is the propensity of the residue to retain an additional mm of water until reaching
217 the maximum retention value, was quite constant (approximately 0.22) for the soybean, maize and rice
218 residues and was 0.46 for the pea residues. The modelled MaxWC confirmed that pea, maize and rice
219 residues contained large amounts of water, with values that were not significantly different from each
220 other (5.9 to 6.6 g H₂O g⁻¹ DM), while soybean retained much less water, with a value of 3.5 g H₂O g⁻¹
221 DM (Table 2). Conversely, the measured MinWC was higher for pea residues (0.06 g H₂O g⁻¹ DM)
222 than for the three other residues.

223

224 **Insert Table 2**

225 **Insert Figure 4**

226

227 *3.3 Loss of mulch DM under rain*

228 Pea residues lost much more DM than the three other residues, losing 28.4% of their initial
229 weight under the highest intensity/highest cumulative rain. In contrast, the soybean, maize and rice
230 residues behaved similarly, losing 9.4, 10.7 and 8.3% of their initial weight under the highest rain
231 intensity, respectively, which were not significantly different. (Fig. 4B, supplementary material SM3).
232 This mass loss represented 16.7, 20.5, 31.9 and 29.5% of the initial mass of the “van Soest” soluble
233 fraction for pea, soybean, maize and rice, respectively. The mass loss increased with increasing rain
234 intensity, particularly for pea residues. The N concentration and C:N ratio of the remaining residues

235 measured at the end of the experiment (Supplementary material SM4) showed that leaching affected
236 the residue soluble N as expected. The initial and final C:N ratios did not change significantly for the
237 pea and soybean residues, indicating that the C:N ratio of the residue fraction leached was similar to
238 the C:N of the whole residue, except soybean at 24 mm h⁻¹ intensity. For maize, the final C:N ratio
239 increased significantly for the three rain regimes compared to the initial C:N, thus indicating a larger
240 loss of soluble residue-N compared to residue-C. Conversely, the C:N ratio slightly decreased for rice
241 residue but the difference was not significant.

242

243 *3.4 Dynamics of soluble C release*

244 The soluble C concentration of the leached water varied according to residue type, with pea >>
245 soybean > rice > maize, and varied greatly according to rain intensity (Fig. 5). The 11 mm h⁻¹ rain
246 intensity resulted in high soluble C concentrations beginning in the first hour, while the 4 mm h⁻¹ led
247 to concentrations in the same range with a delay in the extraction of soluble C. This delay manifested
248 in an offset concentration peak at hours 3 to 6, except for in rice. For all residues, the soluble C
249 leaching was markedly lower under the 24 mm h⁻¹ regime than under the other two regimes, which
250 suggests that the leaching of soluble C by percolating water was not proportional to the rain intensity.
251 In all cases, except for the case of maize, the concentration of soluble C in the leached water decreased
252 over time and became similar under all treatments and rain intensities during the last time interval (22h
253 - 23 h).

254 **Insert Figure 5**

255

256 The cumulative soluble C leached, calculated from the volume of recovered leached water and
257 its soluble C concentration at each sampling point of the experiment, showed an almost linear increase
258 during the first 7 hours for all residues and rain intensities (Fig. 6). Strikingly, for all residues except
259 for pea, similar amounts of soluble C were removed under the 24 mm h⁻¹ and 11 mm h⁻¹ intensities
260 until hour 7, with different values at 22 h and 23 h, while the 4 mm h⁻¹ intensity removed markedly
261 less soluble C from residues. In terms of the total amount of C released, the residue treatments were
262 ranked as follows: pea > rice = soybean > maize (Fig. 6). However, when the soluble C leached by

263 rain was expressed as a function of the initial water-soluble C (20°C), the ranking of the crop residues
264 was different (Fig. 4C). While approximately 40% of the soluble C was removed by the 4 mm h⁻¹
265 intensity over 23 h for rice, maize and soybean, only 18% of the soluble C was lost from the pea
266 residues. The loss of soluble C increased to 90% for maize and rice at the maximal rate, while it was
267 53% of the initial water-soluble C for pea and soybean. A comparison of the soluble C losses under
268 the same total amount of water at the three rain intensities (Table 3) can clearly show the effect of rain
269 intensity on C transport. Under a total application of 500 mL of water, the soluble C loss was identical
270 at 4 and 11 mm h⁻¹ (P = 0.940) and significantly lower for the 24 mm h⁻¹ intensity relative to 4 mm h⁻¹
271 (P = 0.007) and 11 mm h⁻¹ (P = 0.005).

272 **Insert Figure 6**

273 **Insert Table 3**

274

275 **4. Discussion**

276

277 The objective of this study was to quantify the extent of soluble C leaching from crop residues
278 depending on the nature of the residues and rainfall regime. The four types of residues were chosen
279 because of their agricultural importance and the diversity among their chemical compositions. Pea
280 plants sampled in the vegetative stage as a cover crop had a large soluble fraction compared to rice and
281 maize sampled at maturity, while soybean had intermediate values. Soybean had a high lignin content
282 compared to the other three crops due to the pods in the soybean residue mass (Liu et al., 2015). We
283 acknowledge that the differences in the physical characteristics of the litter layers were partially erased
284 by standardizing the average particle size by hand cutting but this reduction in particle length was
285 crucial for reducing the compositional variability of the mulch replicates, which is inherent to the
286 variability in composition of plant debris. However, the residue particles were not ground but hand
287 cut; therefore, the morphological integrity of the residue particles was not altered.

288 The experimental litter mulches used here fell within the lower ranges of bulk density and
289 thickness described under natural conditions, particularly in conservation agriculture systems
290 (Thiébeau, 2019) and natural forest systems (e.g., Dunkerley, 2015). The different mulch thicknesses
291 measured in farmer plots by Thiébeau (2019) varied from 5 mm to 26 mm for residue masses ranging

292 from 0.2 to 1.3 kg DM m⁻². Dietrich et al. (2019) measured sugarcane mulch thicknesses varying from
293 19 mm to 47 mm for residue masses ranging from 0.4 to 1.2 kg DM m⁻². Sato et al. (2004), using
294 leaves of *Lithocarpus edulis*, an evergreen stand coppice, obtained a similar mulch thickness range
295 (10-20 mm) for applications of 0.5 to 1 kg DM m⁻². Nevertheless, data on the thickness of mulches in
296 agrosystems is still very rare, even in investigations of residue masses that were increased to 5 to 15
297 Mg maize residue ha⁻¹ (Schreiber, 1999).

298 Since the experimental duration was identical for all treatments, treatments with a high rain
299 intensity also corresponded to increased amounts of rain, and the two factors could not be fully
300 distinguished except by comparing treatments with the same amount of water received. In the
301 literature, available studies with simulated rainfall fall within the precipitation intensity range of our
302 study (e.g., 3.6 to 24.2 mm h⁻¹, Sato et al., 2004; 25 mm h⁻¹, Schreiber, 1985). For agricultural
303 situations, the range investigated by Schreiber (1999) was larger (6 to 99 mm h⁻¹) as it aimed at
304 including the simulation of storm events.

305

306 *4.1 Water dynamics under simulated rains*

307 Mulches of all four types of crop residues intercepted water, and the interception of water
308 (manifested by the weight gain of the moist mulches) depended on the rainfall regime. The 4 mm h⁻¹
309 rainfall accumulated water more slowly, while the 11 and 24 mm treatments behaved similarly. At the
310 end of the experiment, the MaxWC values (5.9 to 6.6 g H₂O g⁻¹ dry residue) obtained for pea, maize
311 and rice were significantly higher than the range (1 to 3 g H₂O g⁻¹ dry residue) previously reported by
312 several authors (Kreye et al., 2013; Dunkerley, 2015; Talhelm & Smith, 2018). Soybean mulches
313 retained less water, even at high cumulative rain amounts, than the other three residues, which cannot
314 be explained by the initial differences in the bulk density of these mulches, and we hypothesize that
315 this is due to the high proportion of high-density soybean material and low water retention of soybean
316 pods. Conversely, water interception by the pea mulches showed a very different response to
317 increasing rainfall application compared to that of rice, maize and soybean mulches and exhibited low
318 initial absorption (*a* parameter of the model) and high *b* values, thus reflecting the continual increase
319 in water interception as the amount of water received increased. This response is almost parallel to the

320 observed loss of mass of pea mulches with increasing amounts of water. We assume that the porosity
321 of pea residue tissues, which contain a very high proportion of leachable soluble compounds,
322 increased as the amount of rain received increased, thus promoting increased water retention by the
323 tissues. Iqbal et al. (2013) observed an increase in tissue porosity of maize stems with decomposition
324 in soil, and this finding was translated to an increased MaxWC of these stems. Dunkerley (2015)
325 highlighted the high porosity of mulch, which represented 75% to 95% of the total volume and
326 resulted in the high capacity of the litter layer to intercept and store rainwater. In the present study, pea
327 mulches had lower density than the three other mulch types, thus allowing for higher retention by the
328 mulch itself.

329 In terms of rain interception, the amount of water intercepted by the mulches after 7 hours
330 represented 2 to 4 mm of rain and increased with rain intensity (Supplementary material SM5),
331 confirming findings from Sato et al. (2004), who obtained a comparable range (0.8 to 3 mm rain
332 intercepted), as well as results reported by Dunkerley (2015), while Schreiber (1999) did not find any
333 significant differences between different rain intensities, with 0.7 to 0.9 mm rain intercepted by maize
334 mulches under his experimental conditions.

335 Last, the excess water percolated under the mulch was directly influenced by the rainfall regime
336 ($24 \text{ mm h}^{-1} > 11 \text{ mm h}^{-1} > 4 \text{ mm h}^{-1}$), and this percolate flow stabilized at the 2nd hour of rain. Walsh
337 and Voigt (1977) studied the percolation flows under simulated rain every 30 seconds and found that,
338 at the fine temporal scale, the percolate flow under a fixed rain intensity was not steady, revealing the
339 filling and emptying processes of litter porosity. At our time scale, this was obvious only at the onset
340 of the experiment where the percolate flow increased during the 0-2 h interval and then stabilized.
341 Therefore, the crop residue mulches behaved in a similar manner as forest litter mulches, showing a
342 high water retention capacity varying with crop species, with kinetics and maximum values that
343 depended on the intensity and duration of rainfall. These layers of litter, although intercepting rain,
344 quickly allowed the passage of a flow of solutes, even under the lowest rain duration and intensity
345 tested (e.g., 1 hour at 4 mm h^{-1}).

346

347

348 *4.2 Effect of rain on residue C leaching*

349 Along with water, soluble C was washed away for all residues and at all rainfall regimes as
350 expected. The loss of mass and C could only be attributed to the effect of rain because the loss of mass
351 by microbial decomposition can be considered negligible within one day (Trinsoutrot et al., 2000).
352 After 23 hours, the measured DM loss under rain varied significantly with residue type and was much
353 higher for the pea residue than for the other residues, which can be explained by the higher initial size
354 of the soluble fraction of pea residue (representing 55% of the initial DM). However, expressed as a
355 proportion of the initial soluble fraction, pea residues lost only 16% of the mass of the soluble pool,
356 while maize and rice lost approximately 30% of their soluble pool, suggesting that the soluble
357 compounds were less accessible to water leaching in the pea residue than in the other residues. Few
358 data are available on the transport of soluble fractions under the influence of rainfall. Uselman et al.
359 (2012) showed the high variability of the quantities involved from forest litter (leaves, branches, roots).
360 Coppens et al. (2006) measured a very transient peak of soluble C accumulation in the soil solution
361 after rain applied to mulch.

362 Expressed as a function of the initial water-soluble C pool, the cumulative loss of soluble C, at
363 $t = 7$ h, represented 9.2 to 23.7 % (4 mm h^{-1}) and 19.3 to 55.2 % soluble C (24 mm h^{-1}). After 23 hours,
364 the loss of soluble C represented 15.2-36.0 % (4 mm h^{-1}) to 52.6-97.9% (24 mm h^{-1}) of the initial
365 water-soluble C. This finding indicates that although the cumulative quantities of water received in 23
366 h were unrealistic at high intensities (totalling more than 550 mm), there was a near-complete soluble
367 C leaching potential, which can occur in the context of very heavy rainfall events and/or with
368 successive but frequent rainfall over time. Schreiber (1999) investigated maize residues placed under
369 simulated rain and observed that 0.5 to 1% of the total soluble C was leached with 25 mm of rain
370 applied at different intensities, i.e., in the range of values obtained in the early phase of our study. The
371 differences in the loss of DM and water-soluble C resulted from other nutrients (as suggested by the
372 final C:N ratio of leached residues in the present study), particularly soluble organic and inorganic N,
373 being leached down with water, and this was most likely the case for pea residues rich in nitrogen,
374 thus explaining the large difference observed between % soluble DM and % soluble C lost under rain.

375 The hourly monitoring of the C concentration of the leached water revealed that the 24 mm h⁻¹
376 intensity had a higher water flow but a much lower C concentration than the 11 mm h⁻¹ intensity,
377 which is indicative of a higher soluble C dilution. This is also highlighted by the amounts of leached
378 soluble C collected, which were almost identical for the two highest intensities throughout the kinetics
379 of all residue types except for soybean. The dilution of leachates under a higher rain intensity was
380 previously shown by Schreiber (1999) in the range 6 to 99 mm h⁻¹ rain applied to 10 Mg ha⁻¹ of maize
381 residues. Thus, at high rain intensities, not all the rain efficiently leached down the soluble fraction of
382 the residue; therefore, there is a rain intensity threshold below which soluble C is not completely
383 entrained and beyond which water can pass through the mulch without entraining more soluble
384 compounds. This hypothesis is also supported by the observed increase in the C concentration of the
385 leached water during the 0-4 h period (for all residues except rice), which then decreased slightly,
386 under the 4 mm h⁻¹ rainfall intensity. This finding suggests that at a low rain intensity, a longer contact
387 time between the rainfall and the residue before the beginning of leaching allowed for the
388 displacement of soluble C, as observed by Schreiber (1999).

389

390 **5. Conclusions**

391

392 Rainfall washed away significant quantities of soluble C from plant residue mulches, and the
393 results depended on the nature of the residues and the duration of the rainfall and its intensity. As
394 expected, the soluble pool and soluble C leaching was increased for pea residues, which have a high
395 initial proportion of soluble compounds, because they were collected in the vegetative stage to mimic
396 cover crop residue. C leaching also increased with increasing rainfall intensity from 4 to 11 mm h⁻¹
397 and then decreased at 24 mm h⁻¹, suggesting a maximum intensity threshold, after which the water
398 would percolate through the mulch without leaching more soluble C. The magnitude of the observed
399 fluxes suggests that crop-soil models should incorporate soluble C transport from mulches to soils by
400 rainfall, which is not, to our knowledge, rarely the case. This work was performed using a single
401 standardized particle size and a single mass for each species; however, the effect of rain on C loss for
402 mulches of residues of different particle sizes or different masses should be better understood because

403 these factors can be modified by management. Lastly, this study emphasized the importance of better
404 characterizing the physical properties (thickness, density, and water properties) of mulches and residue
405 particles in the future to better understand their interactions with water dynamics, which is a key factor
406 of mulch decomposition and the environmental impacts of residue management.

407

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409

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416

417

418 **Conflict of Interest Statement**

419 The authors have no conflict of interest to declare

420

421 **Authorship**

422 Study concept and design: SR and PT; Acquisition and statistical analysis of the data: PT and CG;

423 Writing of the manuscript: PT, CG, and SR. Obtained funding and performed study supervision: SR

424

425 **Data availability statement**

426 The data that support the findings of this study are available at Data INRAE,
427 <https://doi.org/10.15454/KQS5EK>

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519

520 **Figure captions**

521 **Figure 1:** Mulches composed of pea, soybean, maize and rice residue particles

522 **Figure 2:** Rain simulator and leachate collection experimental design

523 **Figure 3:** Inferred evolution of the wet mulch weight (g /mulch) for pea, soybean, maize and rice
524 residues under rain intensities of 4, 11 or 24 mm h⁻¹. Values are the means of 3 replicates with their
525 standard errors.

526 **Figure 4:** Mulch water content (A), weight loss (B) and leached soluble C (C) of pea, soybean, maize
527 and rice mulches measured after 23 hours of rain and expressed against the total rain received for 4, 11
528 and 24 mm h⁻¹ rain intensities. Soluble C is expressed as the % of the initial water-soluble C at 20°C
529 (WSC). Values are the mean ± standard error (n=3).

530 **Figure 5** Soluble C concentration of the leached water under different rain intensities (4, 11 and 24
531 mm h⁻¹) for the 4 crop residues. Values are the means of 3 replicates per treatment and per date (±
532 standard error).

533 **Figure 6:** Cumulative soluble C in the leached water (mg/sample) as a function of rain intensity (4, 11
534 and 24 mm h⁻¹) for the 4 crop residues. Values are the means of 3 replicates (± standard error).

Figure 1

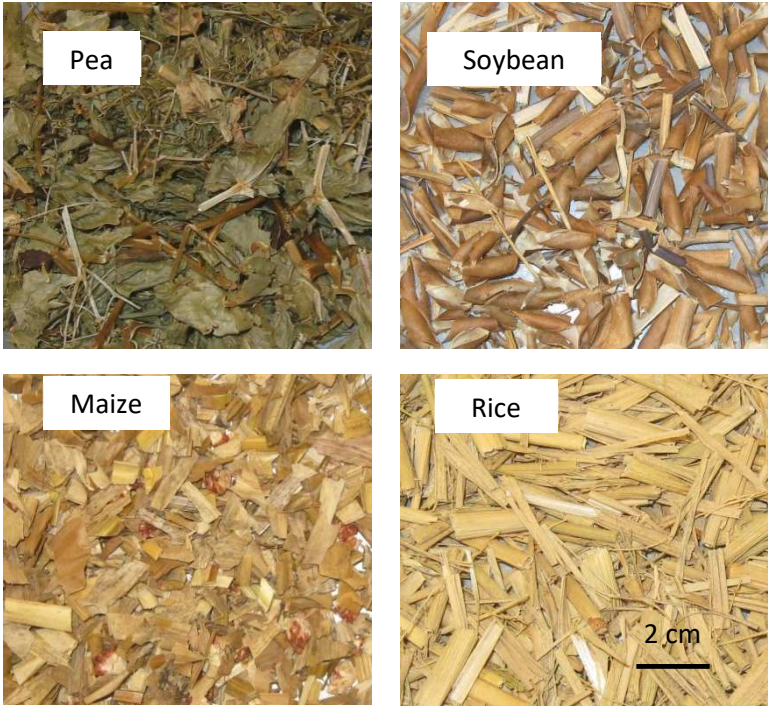


Figure 2

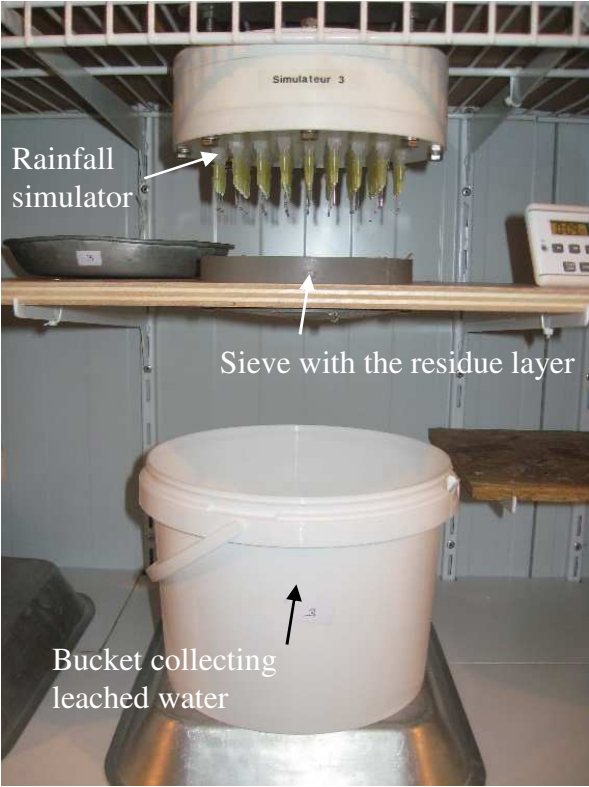


FIGURE 3

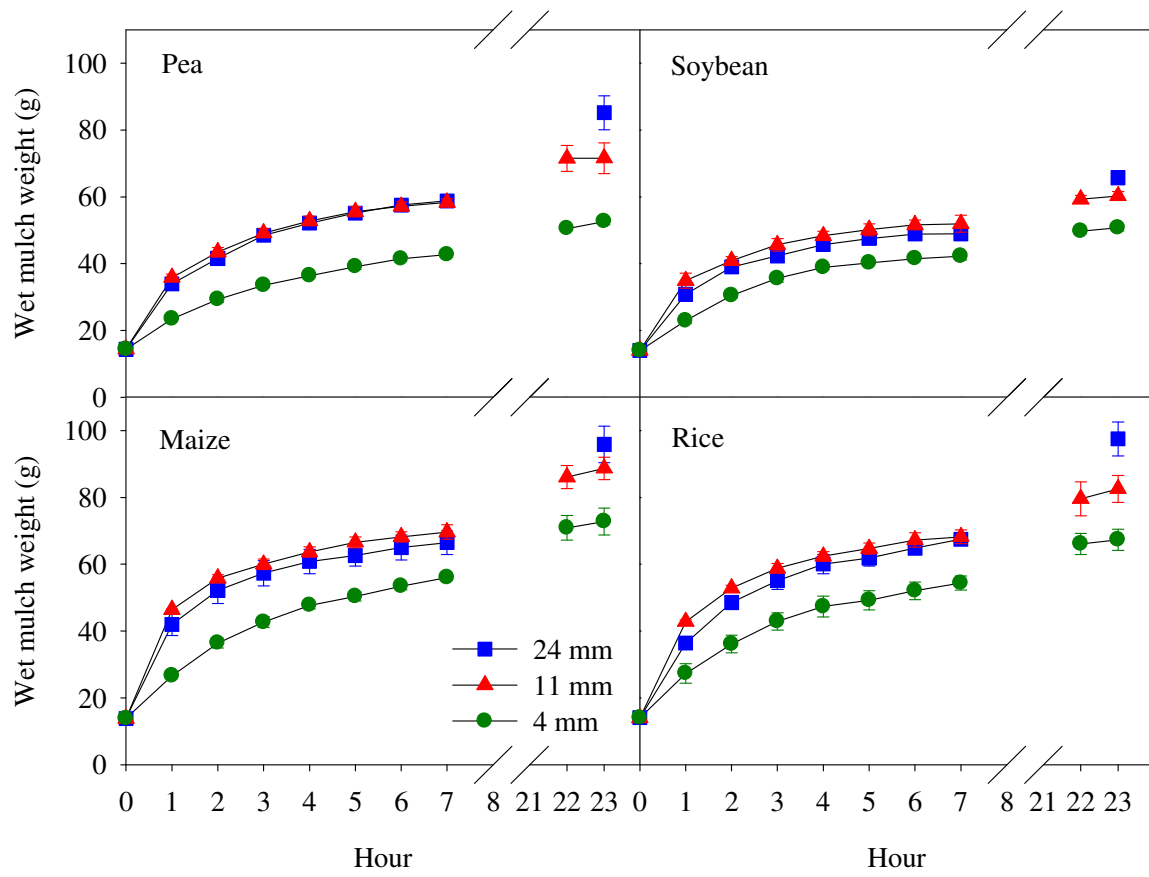


FIGURE 4:

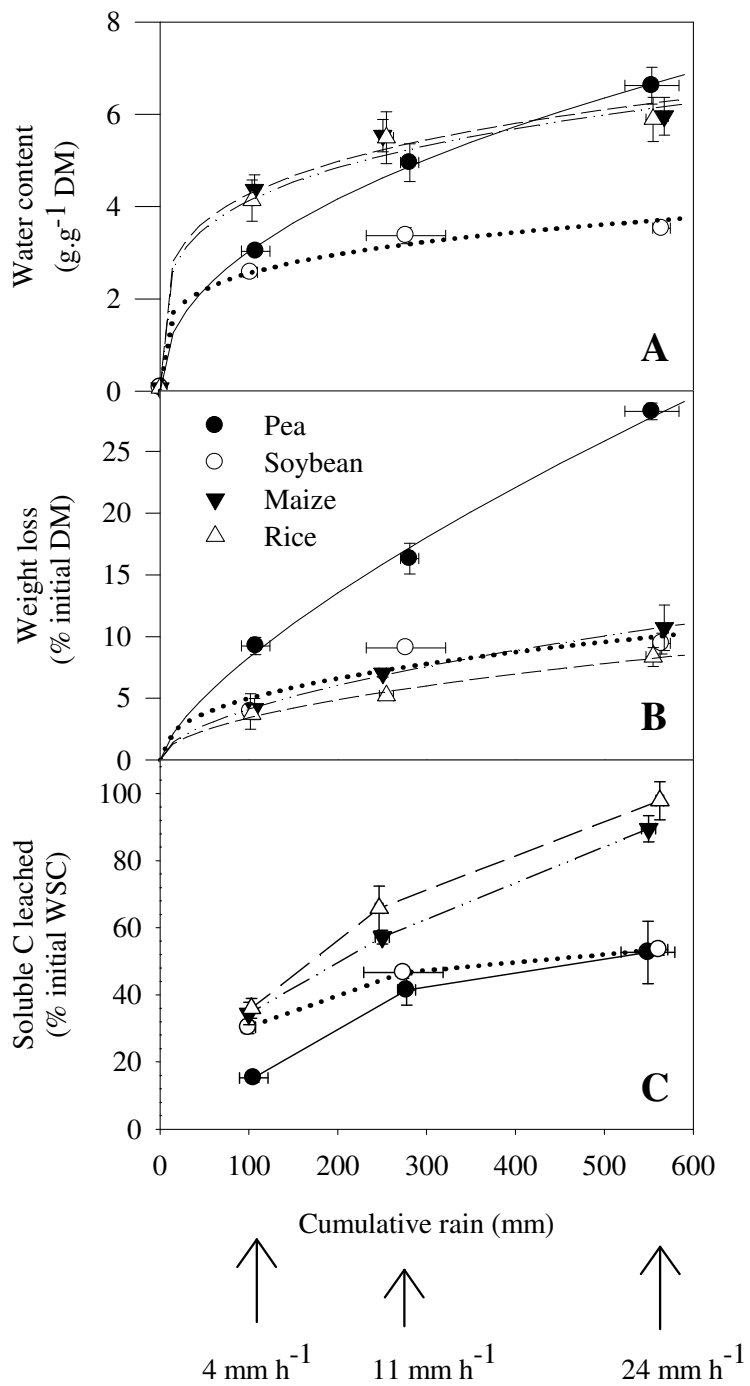


FIGURE 5

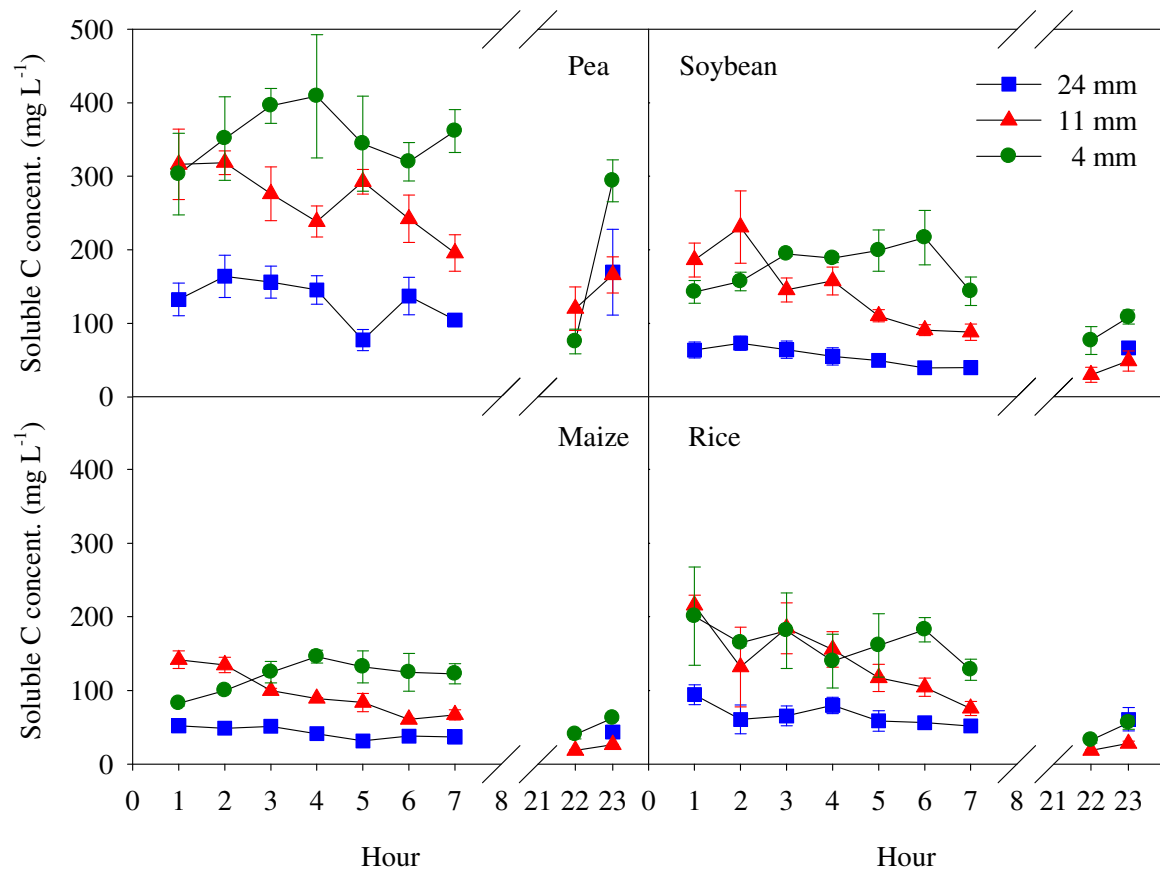


FIGURE 6: Cumulated soluble C in the leached water (mg / sample) as a function of rain intensity (4, 11 and 24 mm h⁻¹), for the 4 crop residues. Values are the mean of 3 replicates (\pm Standard Error)

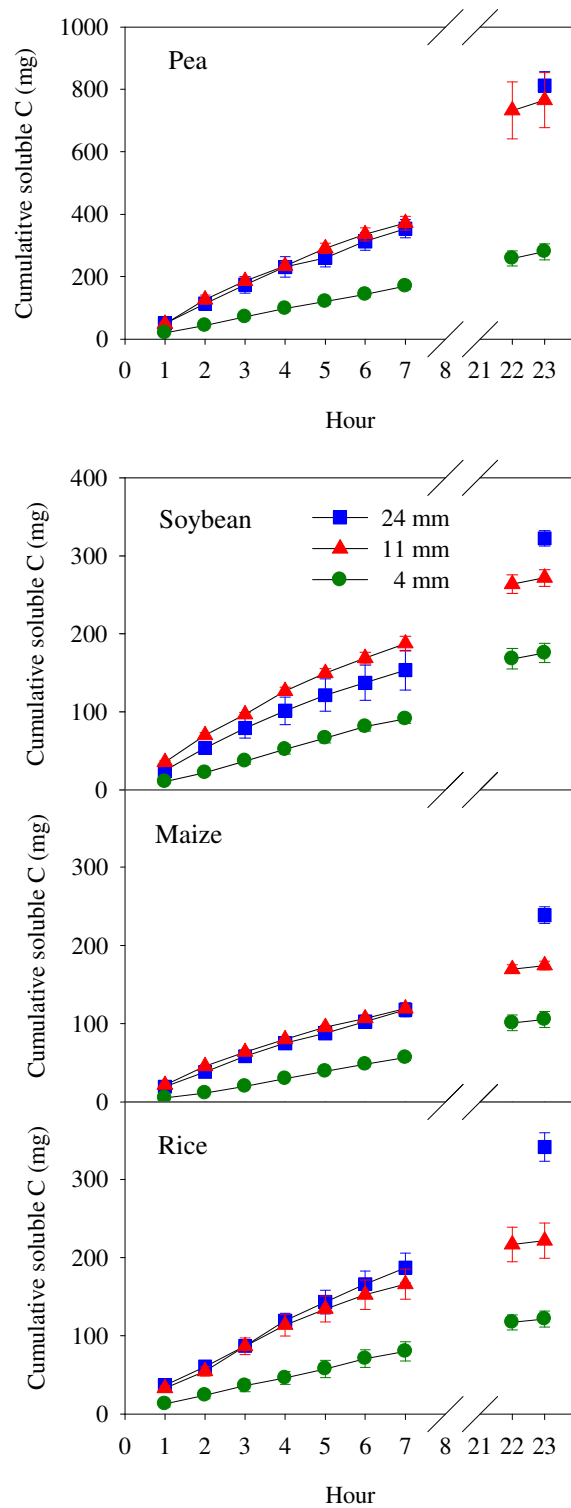


Table 1: Initial chemical characteristics of the pea, soybean, maize and rice residues. Values are the mean of 3 replicates (\pm standard error of the mean) for chemical analysis and 8 replicates for measurement of bulk density of particles.

Residue :	Pea	Soybean	Maize	Rice
Total C (g/kg)	449.8 \pm 2.8	448.3 \pm 4.0	431.8 \pm 2.7	393.2 \pm 3.8
Total N (g/kg)	30.6 \pm 0.2	6.1 \pm 0.1	5.6 \pm 0.2	4.1 \pm 0.1
C : N ratio	14.7 \pm 0.1	73.5 \pm 1.5	77.1 \pm 3.0	95.9 \pm 1.6
Water soluble C at 20°C (g/kg)	141.0 \pm 4.0	45.0 \pm 1.0	24.0 \pm 1.0	26.0 \pm 1.0
Van Soest fractions (g/kg)				
Soluble ¹	555.0 \pm 2.0	295.7 \pm 10.2	168.0 \pm 0.7	228.0 \pm 0.9
Hemicellulose	174.6 \pm 0.5	207.5 \pm 2.2	361.6 \pm 0.7	324.4 \pm 1.3
Cellulose	231.0 \pm 0.9	385.6 \pm 6.9	423.9 \pm 1.8	411.3 \pm 1.9
Lignin	39.4 \pm 0.6	111.2 \pm 1.5	46.4 \pm 0.5	36.3 \pm 0.3
Particle Bulk density (kg/m ³)	29.3 \pm 1.0	47.9 \pm 1.9	25.0 \pm 1.3	21.3 \pm 0.9

¹ Van Soest soluble fraction includes water soluble C

TABLE 2: MinWC and MaxWC of crop residues measured at the end of the experiment (after 23 hours of rain). Values are the mean of 3 replicates with the standard error and are classified in homogeneous groups according to the ANOVA results ($p < 0.05$).

Estimated parameters of the model: $f = a \cdot X^b$ fitted to the water kinetics of the experimental data where “a” is the water absorbed by the first mm of rain/g residue, and “b” is the propensity of the residue to retain an additional mm of water until reaching the maximum retention value.

Residue	MinWC (g H ₂ O g ⁻¹ DM)	MaxWC (g H ₂ O g ⁻¹ DM)	a (g g ⁻¹)	b	R ²	RMSE
Pea	0.067 ±0.001 ^b	6.62 ±0.40 ^b	0.364	0.460	0.973***	0.415
Soybean	0.043 ±0.002 ^a	3.53 ±0.04 ^a	0.950	0.215	0.985***	0.176
Maize	0.038 ±0.002 ^a	5.96 ±0.41 ^b	1.544	0.221	0.963***	0.481
Rice	0.041 ±0.001 ^a	5.89 ±0.48 ^b	1.426	0.231	0.937***	0.630

*** $P < 0.001$

TABLE 3 Soluble C extracted by the first 500 mL of precipitated water for pea, soybean, maize and rice residues under rain of 4, 11 or 24 mm h⁻¹ intensities. Values are the mean of 3 replicates with their standard error. The exact duration of rain application (in minutes) needed to reach 500 mL cumulated rain was calculated by intrapolation between two sampling dates for each rain intensity and residue type.

Rain intensity	4 mm h ⁻¹			11 mm h ⁻¹			24 mm h ⁻¹		
Residue	Time <i>min</i>	Soluble C leached		Time <i>min</i>	Soluble C leached		Time <i>min</i>	Soluble C leached	
		<i>mg</i>	<i>% initial</i>		<i>mg</i>	<i>% initial</i>		<i>mg</i>	<i>% initial</i>
Pea	421	169.6±10.6 a,A	23.0	146	152.2±13.8 a,A	20.6	78	69.7±11.8 a,B	9.4
Soybean	403	88.1±5.8 b,A	38.3	166	90.4±2.7 b,A	38.9	77	32.9±5.4 b,B	14.2
Maize	442	57.8±3.7 b,A	44.6	175	62.3±1.6 b,A	48.3	80	25.6±3.9 b,B	19.8
Rice	430	80.6±12.2 b,A	59.2	182	87.7±10.7 b,A	64.5	77	43.4±5.6 b,B	31.8

P (rain intensity) = A, B p<0.01

P (crop residue type) = a, b p<0.05