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

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Highlights

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

Abstract

The presence of crop residues on the soil surface of no-till cropping systems has important consequences on water flows between the atmosphere, litter layer (mulch) and soil. The consequences of rainfall on the transport of soluble C from litter layers are poorly known, despite their importance for soil carbon (C) and nutrient cycling. We quantified relationships among the rain amount and intensity, the water retention by mulches and the soluble C loss from mulches under rainfall. Mulches of residues from mature crops (maize, soybean and rice) and a cover crop (pea) were placed under continuous simulated rains with intensities of 4, 11 and 24 mm h^{-1} for 23 hours, and we measured the water interception dynamics of the mulches and the water and soluble C flows under the mulches. The maximal water contents of the pea, maize and rice mulches did not differ significantly from each other (5.9 to 6.6 g H_2O g^{-1} dry matter), while the soybean mulch retained much less water than the other mulches at 3.5 g H_2O g^{-1} dry matter (DM). The soluble C loss was 9.2 to 23.7 % (4 mm h^{-1}) and 19.3 to 55.2 % (24 mm h^{-1}) depending on the residue type after 7 hours of rain. With similar amounts of received rain (500 mL), the soluble C loss was identical for intensities at 4 and 11 mm h^{-1}, and significantly lower at 24 mm h^{-1}, suggesting inefficient rain transport at the high rain intensity. Finally, this study highlights the importance of better characterizing the physical and water properties of mulches and residue particles because of their significant effects on water and soluble C transport.

Key words (indexing terms)

carbon; crop residue; no-till; rain regime

1. Introduction

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

Although the amount of rainwater that can be intercepted and retained by mulches has received little study, we know that this interception depends mainly on the amount and nature of crop residues (Tuckey, 1970). Previous studies have shown that the maximum water content of these mulches can be modulated according to the crop residue characteristics (Quemada and Cabrera, 2002; Iqbal et al., 2013) and their morphological, anatomical and chemical traits (Garnier and Laurent, 1994). Iqbal et al. (2013) showed for stems of different annual species that the main explanatory characteristic of their maximal ability to retain water was the density of the tissues of the stems (or its inverse, i.e., porosity), whereas chemical characteristics were not directly related to water retention properties. A number of studies have compared the effects of rainfall intensity on the water retention capacity of mulch on the soil surface, mostly on forest systems with leaf litters (e.g., Sato et al., 2004; Schrumpf et al., 2006; Dunkerley, 2015). More recently, the fact that residue mulch constitutes a "hot spot" of biological activity and denitrification has led to interest in the water retention capacity of mulches (Kravchenko et al., 2017) but such study is still rare. To our knowledge, the transport of soluble C or nutrients under the influence of rainfall carried out in an agricultural context are rare (Halvis and Alberts, 1983; Schreiber, 1985; Schreiber and McDowell, 1985; Schreiber, 1999) despite the experimental observation of residue-derived soluble C transport into soil (Coppens et al., 2006; Lee et al., 2014; Iqbal et al. 2015).

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

2. Materials and methods

2.1 Crop residues

Maize (*Zea mays* L.), rice (*Oriza sativa* L.), and soybean (*Glycine max* L.) were harvested at the mature stage, while pea (*Pisum sativum* L.) was harvested at flowering so that its residues represented those of a cover crop. The crop residues were collected in the field in three areas, namely, an area of intensive agriculture in northern France, a family farm in Cerados (Brazil) and upland rice cropping systems in the Central highlands of Madagascar. We used all organs to compose the residues, except for the grains and roots. Samples were dried at 40°C until they reached a constant weight and then were stored in paper pockets. The chemical characteristics of the selected residues were determined prior to the rainfall experiment and are given in Table 1. Briefly a sub-sample of each residue was ground and analysed to determine the chemical and biochemical characteristics via a proximal analysis, thus providing the relative proportion of the so-called "van Soest" fractions of the residue dry matter. The soluble fraction was determined by extraction in hot water (100 °C) for 30 min followed by extraction with a neutral detergent (100 °C) for 60 min. The hemicellulose, cellulose and lignin fractions were subsequently determined via a proximate analysis (Goering and Van Soest 1970). The cold water-soluble fraction of the residues was determined by extraction in deionised water over 30 min at 20 °C (plant material/water ratio 1/100). The total C and N contents of the plant residues were determined via total combustion using an elemental analyser (NA 2000, Fisons Instruments, Milan, Italy).

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

Insert Figure 1

Insert Table 1

2.2 Simulated rainfall experiments

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

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

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

Insert Figure 2

2.3 Experimental protocol

The rain experiment was run for 24 hours. First, the rain simulations started one hour before the positioning of the cylinders; then, each cylinder with a mulch layer was placed under one simulator for 23 hours. During the first 7 hours of rain, mulch layers and buckets were quickly removed every hour and placed into a pre-weighed tray to record the weight of the water held in the litters and the percolates in the buckets. These data were used to calculate the water interception by the litter and the amount of leached water. Each sieve was immediately returned under the rain simulator until the next measurement. After the homogenization of the bucket water content, an aliquot of water was sampled and frozen until the determination of dissolved organic carbon (DOC). After 22 and 23 hours of continuous rain, sieves and buckets were weighed again, and sub-samples of water were collected. Notably, under the simulated rainfall intensity of 24 mm h^{-1}, a large volume of water had leached through the samples between hour 7 and hour 22 and could not be quantitatively stored, so the above measurement was not conducted.

2.4 Analysis

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

2.5 Calculations and statistical analysis

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

$f = a.\ X^b$ (1)

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

Statistical analysis was carried out with the Sigma-Plot 12 Statistics programme (*Systat Software, USA*). The significance level chosen in our study was $p < 0.05$. Means were classified in a homogenous group according to the results of ANOVA and the Newman-Keuls test. The statistical model evaluation criteria were the root mean square error (RMSE) and coefficient of determination (R^2) values.

3. Results

3.1 Rainfall assessment

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

3.2 Water interception by crop residues

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

Insert Figure 3

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

The water storage of residue particles measured at the end of the experiment for each residue type and each rain treatment varied depending on the residue type and the cumulative quantity of water received (itself resulting from the rain intensity applied) (Fig. 4A). The rice and maize mulches behaved very similarly, with high water retention under 100 mm of water. The soybean mulch retained much less water than the rice and maize mulches. The pea mulch demonstrated intermediate water retention, with a relatively low but continuous increase in water retention with increasing amounts of rain. The relationships between MaxWC and cumulative rain were well fitted by the non-linear equation with two parameters (Table 2). The water absorbed by the first mm of rain ("*a"* coefficient) varied from 0.3 to 1.5 g H_2O g^{-1} DM, with the lowest value for pea residues. Furthermore, the "*b*" coefficient, which is the propensity of the residue to retain an additional mm of water until reaching the maximum retention value, was quite constant (approximately 0.22) for the soybean, maize and rice residues and was 0.46 for the pea residues. The modelled MaxWC confirmed that pea, maize and rice residues contained large amounts of water, with values that were not significantly different from each other (5.9 to 6.6 g H_2O g^{-1} DM), while soybean retained much less water, with a value of 3.5 g H_2O g^{-1} DM (Table 2). Conversely, the measured MinWC was higher for pea residues (0.06 g H_2O g^{-1} DM) than for the three other residues.

Insert Table 2

Insert Figure 4

3.3 Loss of mulch DM under rain

Pea residues lost much more DM than the three other residues, losing 28.4% of their initial weight under the highest intensity/highest cumulative rain. In contrast, the soybean, maize and rice residues behaved similarly, losing 9.4, 10.7 and 8.3% of their initial weight under the highest rain intensity, respectively, which were not significantly different. (Fig. 4B, supplementary material SM3). This mass loss represented 16.7, 20.5, 31.9 and 29.5% of the initial mass of the "van Soest" soluble fraction for pea, soybean, maize and rice, respectively. The mass loss increased with increasing rain intensity, particularly for pea residues. The N concentration and C:N ratio of the remaining residues measured at the end of the experiment (Supplementary material SM4) showed that leaching affected the residue soluble N as expected. The initial and final C:N ratios did not change significantly for the pea and soybean residues, indicating that the C:N ratio of the residue fraction leached was similar to the C:N of the whole residue, except soybean at 24 mm h^{-1} intensity. For maize, the final C:N ratio increased significantly for the three rain regimes compared to the initial C:N, thus indicating a larger loss of soluble residue-N compared to residue-C. Conversely, the C:N ratio slightly decreased for rice residue but the difference was not significant.

3.4 Dynamics of soluble C release

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

Insert Figure 5

The cumulative soluble C leached, calculated from the volume of recovered leached water and its soluble C concentration at each sampling point of the experiment, showed an almost linear increase during the first 7 hours for all residues and rain intensities (Fig. 6). Strikingly, for all residues except for pea, similar amounts of soluble C were removed under the 24 mm h^{-1} and 11 mm h^{-1} intensities until hour 7, with different values at 22 h and 23 h, while the 4 mm h^{-1} intensity removed markedly less soluble C from residues. In terms of the total amount of C released, the residue treatments were ranked as follows: pea > rice = soybean > maize (Fig. 6). However, when the soluble C leached by rain was expressed as a function of the initial water-soluble C (20°C), the ranking of the crop residues was different (Fig. 4C). While approximately 40% of the soluble C was removed by the 4 mm h^{-1} intensity over 23 h for rice, maize and soybean, only 18% of the soluble C was lost from the pea residues. The loss of soluble C increased to 90% for maize and rice at the maximal rate, while it was 53% of the initial water-soluble C for pea and soybean. A comparison of the soluble C losses under the same total amount of water at the three rain intensities (Table 3) can clearly show the effect of rain intensity on C transport. Under a total application of 500 mL of water, the soluble C loss was identical 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} ($P = 0.007$) and 11 mm h^{-1} ($P = 0.005$).

Insert Figure 6
Insert Table 3

4. Discussion

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

The experimental litter mulches used here fell within the lower ranges of bulk density and thickness described under natural conditions, particularly in conservation agriculture systems (Thiébeau, 2019) and natural forest systems (e.g., Dunkerley, 2015). The different mulch thicknesses measured in farmer plots by Thiébeau (2019) varied from 5 mm to 26 mm for residue masses ranging from 0.2 to 1.3 kg DM m^{-2}. Dietrich et al. (2019) measured sugarcane mulch thicknesses varying from 19 mm to 47 mm for residue masses ranging from 0.4 to 1.2 kg DM m^{-2}. Sato et al. (2004), using leaves of *Lithocarpus edulis*, an evergreen stand coppice, obtained a similar mulch thickness range (10-20 mm) for applications of 0.5 to 1 kg DM m^{-2}. Nevertheless, data on the thickness of mulches in agrosystems is still very rare, even in investigations of residue masses that were increased to 5 to 15 Mg maize residue ha^{-1} (Schreiber, 1999).

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

4.1 Water dynamics under simulated rains

Mulches of all four types of crop residues intercepted water, and the interception of water (manifested by the weight gain of the moist mulches) depended on the rainfall regime. The 4 mm h^{-1} rainfall accumulated water more slowly, while the 11 and 24 mm treatments behaved similarly. At the end of the experiment, the MaxWC values (5.9 to 6.6 g H_2O g^{-1} dry residue) obtained for pea, maize and rice were significantly higher than the range (1 to 3 g H_2O g^{-1} dry residue) previously reported by several authors (Kreye et al., 2013; Dunkerley, 2015; Talhelm & Smith, 2018). Soybean mulches retained less water, even at high cumulative rain amounts, than the other three residues, which cannot be explained by the initial differences in the bulk density of these mulches, and we hypothesize that this is due to the high proportion of high-density soybean material and low water retention of soybean pods. Conversely, water interception by the pea mulches showed a very different response to increasing rainfall application compared to that of rice, maize and soybean mulches and exhibited low initial absorption (*a* parameter of the model) and high *b* values, thus reflecting the continual increase in water interception as the amount of water received increased. This response is almost parallel to the observed loss of mass of pea mulches with increasing amounts of water. We assume that the porosity of pea residue tissues, which contain a very high proportion of leachable soluble compounds, increased as the amount of rain received increased, thus promoting increased water retention by the tissues. Iqbal et al. (2013) observed an increase in tissue porosity of maize stems with decomposition in soil, and this finding was translated to an increased MaxWC of these stems. Dunkerley (2015) highlighted the high porosity of mulch, which represented 75% to 95% of the total volume and resulted in the high capacity of the litter layer to intercept and store rainwater. In the present study, pea mulches had lower density than the three other mulch types, thus allowing for higher retention by the mulch itself.

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

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

4.2 Effect of rain on residue C leaching

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

Expressed as a function of the initial water-soluble C pool, the cumulative loss of soluble C, at 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, 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 water-soluble C. This finding indicates that although the cumulative quantities of water received in 23 h were unrealistic at high intensities (totalling more than 550 mm), there was a near-complete soluble C leaching potential, which can occur in the context of very heavy rainfall events and/or with successive but frequent rainfall over time. Schreiber (1999) investigated maize residues placed under simulated rain and observed that 0.5 to 1% of the total soluble C was leached with 25 mm of rain applied at different intensities, i.e., in the range of values obtained in the early phase of our study. The differences in the loss of DM and water-soluble C resulted from other nutrients (as suggested by the final C:N ratio of leached residues in the present study), particularly soluble organic and inorganic N, being leached down with water, and this was most likely the case for pea residues rich in nitrogen, thus explaining the large difference observed between % soluble DM and % soluble C lost under rain.

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

5. Conclusions

Rainfall washed away significant quantities of soluble C from plant residue mulches, and the results depended on the nature of the residues and the duration of the rainfall and its intensity. As expected, the soluble pool and soluble C leaching was increased for pea residues, which have a high initial proportion of soluble compounds, because they were collected in the vegetative stage to mimic cover crop residue. C leaching also increased with increasing rainfall intensity from 4 to 11 mm h^{-1} and then decreased at 24 mm h^{-1}, suggesting a maximum intensity threshold, after which the water would percolate through the mulch without leaching more soluble C. The magnitude of the observed fluxes suggests that crop-soil models should incorporate soluble C transport from mulches to soils by rainfall, which is not, to our knowledge, rarely the case. This work was performed using a single standardized particle size and a single mass for each species; however, the effect of rain on C loss for mulches of residues of different particle sizes or different masses should be better understood because these factors can be modified by management. Lastly, this study emphasized the importance of better characterizing the physical properties (thickness, density, and water properties) of mulches and residue particles in the future to better understand their interactions with water dynamics, which is a key factor of mulch decomposition and the environmental impacts of residue management.

Acknowledgements

This work was supported by INRAE (French National Research Institute for Agriculture, Food and Environment) and ANR (National Research Agency), the PEPITES project (ANR-08-STRA-10). We thank Olivier Delfosse and Gonzague Alavoine for their technical assistance with crop residue chemical characterization; Dr S. J. Giacomini and Dr B. Chabbert for their helpful comments on an earlier version of this manuscript; and two anonymous referees for their comments that contributed to improving this work.

Conflict of Interest Statement

The authors have no conflict of interest to declare

Authorship

Study concept and design: SR and PT; Acquisition and statistical analysis of the data: PT and CG; Writing of the manuscript: PT, CG, and SR. Obtained funding and performed study supervision: SR

Data availability statement

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

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Figure captions

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

Figure 2: Rain simulator and leachate collection experimental design

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

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

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

Figure 6: Cumulative 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 means of 3 replicates (± standard error).

Figure 1

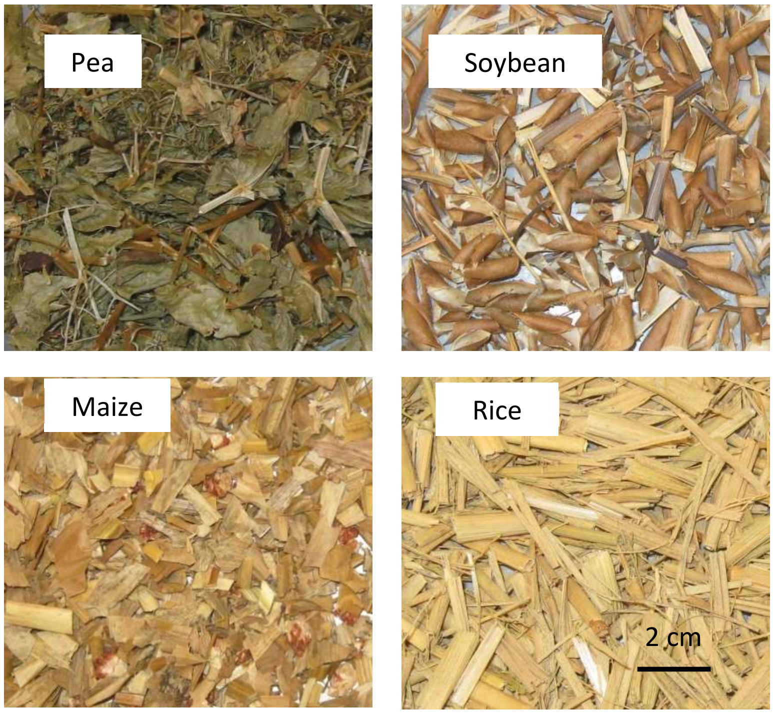


Figure 2

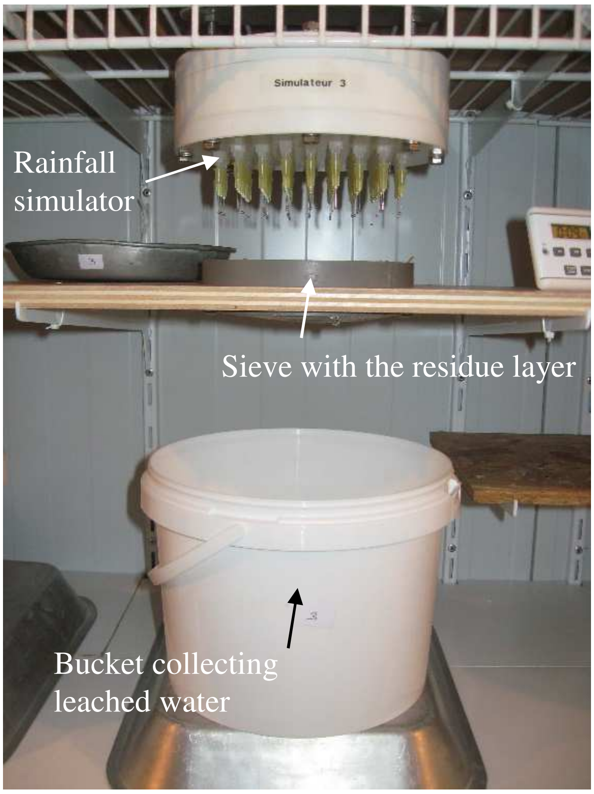
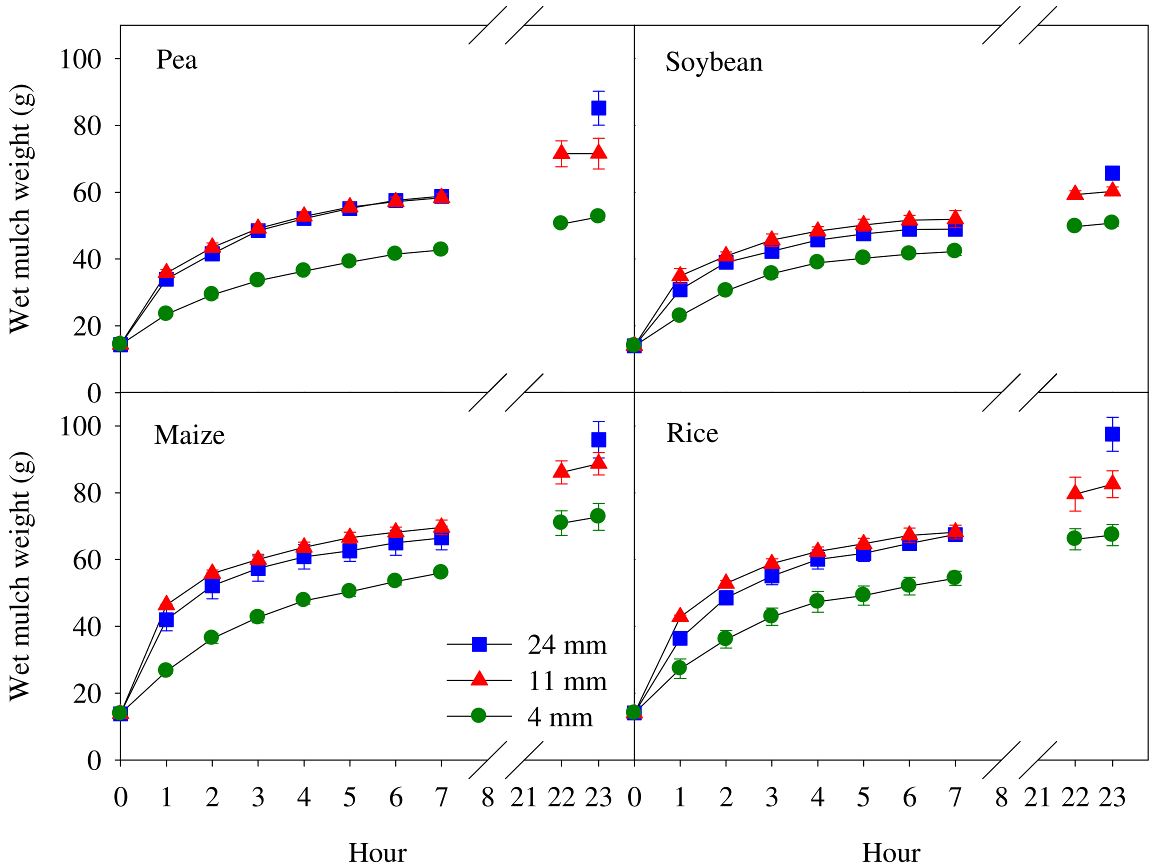

Simulateur 3
Rainfall simulator
Sieve with the residue layer
Bucket collecting leached water

FIGURE 3



Pea
Soybean
Maize
Rice
Wet mulch weight (g)
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
21
22
23
Hour
24 mm
11 mm
4 mm

FIGURE 4:

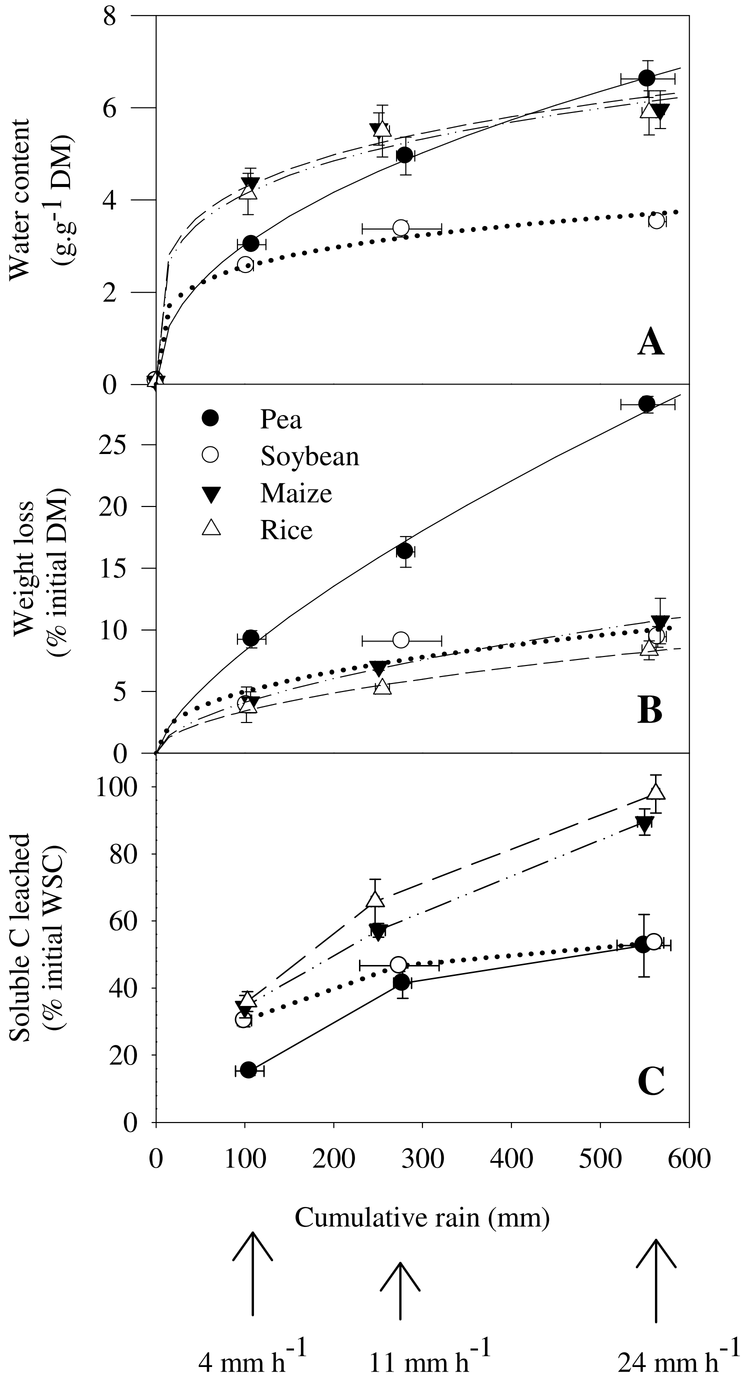

8
6
4
2
0
Water content
(g.g-1 DM)
A
Pea
Soybean
Maize
Rice
25
20
15
10
5
0
Weight loss
(% initial DM)
B
100
80
60
40
20
0
Soluble C leached
(% initial WSC)
C
0
100
200
300
400
500
600
Cumulative rain (mm)
4 mm h-1
11 mm h-1
24 mm h-1

FIGURE 5

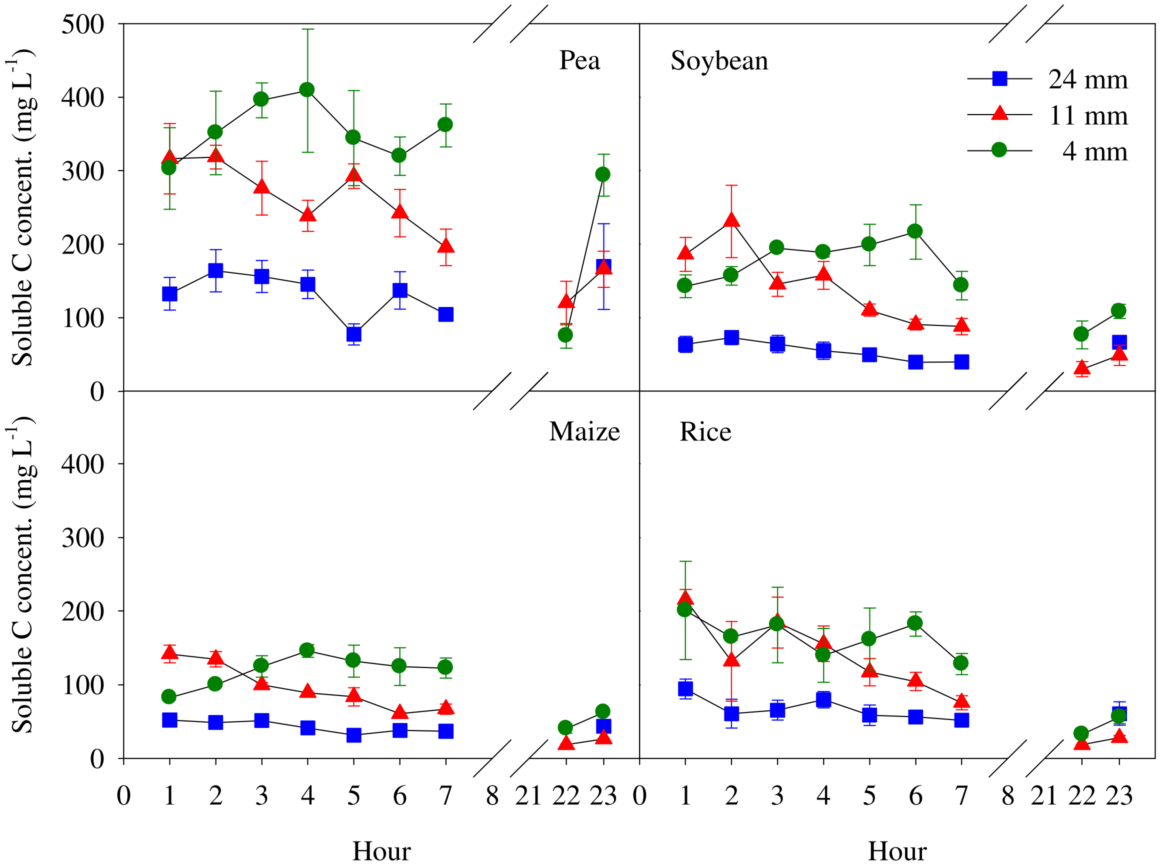

Pea
Soybean
Maize
Rice
24 mm
11 mm
4 mm
Soluble C concent. (mg L-1)
Hour
0
100
200
300
400
500
1
2
3
4
5
6
7
8
21
22
23

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 (± Standard Error)

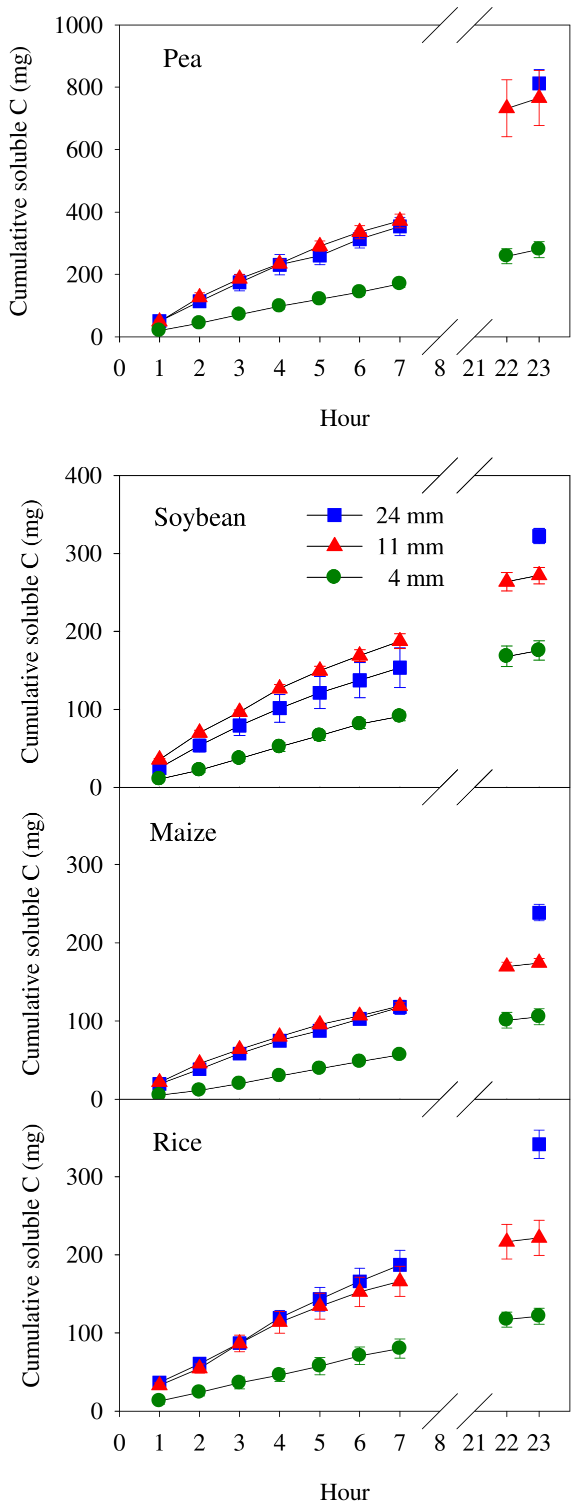


Table 1: Initial chemical characteristics of the pea, soybean, maize and rice residues. Values are the mean of 3 replicates (± standard error of the mean) for chemical analysis and 8 replicates for measurement of bulk density of particles.

Residue :	Pea	Soybean	Maize	Rice
Total C *(g/kg)*	449.8 ±2.8	448.3 ±4.0	431.8 ±2.7	393.2 ±3.8
Total N *(g/kg)*	30.6 ±0.2	6.1 ±0.1	5.6 ±0.2	4.1 ±0.1
C : N ratio	14.7 ±0.1	73.5 ±1.5	77.1 ±3.0	95.9 ±1.6
Water soluble C at 20°C *(g/kg)*	141.0 ±4.0	45.0 ±1.0	24.0 ±1.0	26.0 ±1.0
Van Soest fractions *(g/kg)*				
Soluble[1]	555.0 ±2.0	295.7 ±10.2	168.0 ±0.7	228.0 ±0.9
Hemicellulose	174.6 ±0.5	207.5 ±2.2	361.6 ±0.7	324.4 ±1.3
Cellulose	231.0 ±0.9	385.6 ±6.9	423.9 ±1.8	411.3 ±1.9
Lignin	39.4 ±0.6	111.2 ±1.5	46.4 ±0.5	36.3 ±0.3
Particle Bulk density (kg/m^3)	29.3 ±1.0	47.9 ±1.9	25.0 ±1.3	21.3 ±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: $f = a.\ X^b$ *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_2O g^{-1} DM)*	MaxWC *(g H_2O 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}		
	Time	Soluble C leached		Time	Soluble C leached		Time	Soluble C leached	
Residue	*min*	*mg*	*% initial*	*min*	*mg*	*% initial*	*min*	*mg*	*% initial*
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 $p<0.05$