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2 **Gradient of decomposition in sugarcane mulches of various thicknesses**

4 Guilherme Dietrich^a, Sylvie Recous^{b*}, Patrick Leal Pinheiro^a, Douglas Adams Weiler^a, Adriane Luiza
Schu^a, Mathias Roberto Leite Rambo^a, Sandro José Giacomini^a

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^a Department of Soils, Federal University of Santa Maria, 97105-900 Santa Maria, RS, Brazil

8 ^b FARE Laboratory, INRA, Université de Reims Champagne-Ardenne, 2 Esplanade R. Garros, 51100
Reims, France

10

*Corresponding author:

12 Sylvie Recous, Tel : +33 (0)326 773 583, E-mail: sylvie.recous@inra.fr

14 **Highlights**

- The vertical decomposition gradient was characterized in mulches of various thicknesses
- 16 • Top mulch layers decomposed similarly, regardless of the thickness of the underlying mulch
- Low mulch layers decomposed faster as the thickness of the overlying mulch increased
- 18 • The decomposition gradient within the mulch was closely correlated with the moisture gradient

20 **Abstract**

Crop residues left on the soil surface as mulch influence many services provided in agrosystems, particularly soil protection, water dynamics and nutrient fluxes. For a given crop, the residue mass influences the mulch thickness, but the effect of thickness on decomposition is not well understood, and decomposition gradients within mulches in the field have not been described. This study aimed to quantify the decomposition of sugarcane straw mulches by varying their mass and thickness and determine the decomposition gradient within the mulches. The experiment was conducted on a first-ratoon sugarcane crop for one year, with 4, 8 and 12 Mg straw dry matter ha⁻¹. Mulches were displayed in 0.16-m² litter boxes and formed by straw layers of equivalent mass, i.e., 4 Mg ha⁻¹, stacked either as a single layer (Low/Top layer), 2 layers (Low and Top layers) or 3 layers (Low, Medium and Top layers) to reconstitute the 3 mulch quantities. We quantified the carbon (C) and nitrogen (N) contents, the chemical composition and the water content of the remaining mulch particles in each layer 10 times within the 360 days. The mulch degradation rates were proportional to the initial amount of straw, the mulch losses representing 75% of its initial C and 46% of its initial N after one year, regardless of the initial mass. Fertilizer-N addition did not change the *k* decomposition rate, with $k=0.0044\text{ d}^{-1}$. However the decomposition rate differed according to the layer position in the mulch, e.g., in the 12 Mg ha⁻¹ treatment $k=0.0064\text{ d}^{-1}$, 0.0046 d^{-1} and 0.0033 d^{-1} for the low, medium and top layers, respectively, indicating that the low layers in contact with the soil decomposed faster than the top layers in contact with the atmosphere, while the medium layers demonstrated intermediate behaviour. The top layers evolved similarly, regardless of mulch thickness, while the lower layers in

40 contact with the soil decomposed more quickly as the overlying straw thickness increased. Regardless
of the thickness and position of a given layer within mulch, the one-year layer C loss was linearly
42 correlated with the average water content of that layer over the year ($y=52.79 - 0.694x$, $R^2=0.991$,
 $P<0.05$). Here, we demonstrate that the dynamics of mulch decomposition is primarily driven by the
44 dynamics of water, which is itself driven by mulch characteristics, rain regime and evaporation.

Keywords: Straw litter layer, carbon decomposition, nitrogen, crop residue water properties, soil-
46 residue contact

48 1. Introduction

No-till in cropping systems are increasingly used worldwide for protecting soil from physical
50 degradation and enhancing soil fertility (Tiecher et al., 2017), and the development of perennial or
semi-perennial crops (miscanthus, sugarcane, etc.) dedicated to bioenergy (Peyrard et al., 2017;
52 Bordonal et al., 2018) leads to the generalization of agricultural situations with crop residue layers,
i.e., mulch, decomposing on the soil surface. Predicting the decomposition rates of crop residue
54 mulches according to system characteristics (crop and rotation types, climatic conditions) is important
because of the crucial services these mulches provide, such as soil cover and protection against erosion
56 and weed growth, water regulation, nutrient recycling, and habitats and resources for soil
communities. Moreover, a better understanding of the decomposition of straw at the soil surface is
58 important because this process determines the fluxes of carbon (C) and nitrogen (N) in the soil and to
the atmosphere via the emission of greenhouse gases (Chen et al., 2013; Pinheiro et al., *accepted*;
60 Vasconcelos et al., 2018).

Many studies have shown that the decomposition rate of straw at the soil surface is lower than
62 that of residues incorporated into the soil (Douglas et al., 1980; Schomberg et al., 1994; Coppens et
al., 2006; Curtin et al., 2008). This difference was attributed to the straw undergoing greater and more
64 frequent fluctuations in moisture at the soil surface than within the soil, particularly frequent drying
between rains, combined with a reduced diffusion of nutrients and water from the soil to
66 decomposition sites in the mulch (Christensen, 1986). The soil-residue contact determined by the

characteristics of crop residues (morphology and particle size, mass) and the characteristics of the
68 underlying soil layer (texture, water content, mineral N content) are considered important in driving
decomposition (e.g., Angers and Recous, 1997; Henriksen and Bleland, 2002; Iqbal et al., 2013). The
70 straw mass, together with the residue morphology, is the main factor that determines the proportion of
the mulch that is in contact with the soil. For a given crop residue type, as the residue amount on the
72 soil surface increases, the thickness of the produced mulch increases (Putuhena and Cordery, 1996),
and the proportion of the residues that are in contact with the soil decreases. This was reflected in the
74 fact that under a number of experimental conditions the rate of decomposition decreased with an
increase in the mass of crop residues at the soil surface (e. g. Steiner et al., 1999). These results had led
76 models that simulate the decomposition of straw at the soil surface to consider the degradation of the
mulch to occur from a decomposing layer in contact with the soil fed by an unaltered layer of
78 overlying residues (APSIM Thorburn et al., 2001; CANTIS Findeling et al., 2007). However, a
number of recent studies have changed this perception by showing that mulch decomposition can be
80 proportional to the initial straw mass, within a range of 3 to 12 Mg ha⁻¹ for cover crop mulches
(Acosta et al., 2014; Halde and Entz, 2015), sugarcane (Dietrich et al., 2017), or 5 to 15 Mg ha⁻¹ for
82 rye (Williams et al., 2018). These results are questioning the hypothesis that the undecomposed
proportion of the top layer increases with increasing residue mass. Therefore, it is necessary to
84 improve our understanding of the decomposition processes of residue mulch, particularly how these
decomposition processes are affected by the mass and thickness of mulch.

86 To answer these questions, the objective of this work was to investigate the vertical
heterogeneity of the decomposition process within sugarcane straw mulches with different initial
88 masses, thicknesses, and N availabilities. We investigated the following aspects in field conditions
over one year after sugarcane harvest: i) how decomposition develops at different locations within
90 mulches of varied initial masses, ii) the consequences of mulch features on mulch C and N dynamics
and on the conditions in the soil layer below the mulch, and iii) the factors driving mulch
92 decomposition and the role of the contact between soil and mulch in this decomposition.

94 2. Materials and methods

2.1 Study site

96 The study was located at the Federal University of Santa Maria (29°42'54" S, 53°42'23" W,
approximately 90 m elevation) in the state of Rio Grande do Sul, Brazil. The climate, according to the
98 Köppen classification system, is a type Cfa subtropical humid climate. The mean annual temperature
is 19.3°C; June is the coldest month, with a mean minimum temperature of 9.3°C, and January is the
100 warmest month, with a mean maximum temperature of 30.4°C. The mean annual precipitation is 1660
mm, without a dry season. The soil is classified as Typic Paleudalf according to USDA taxonomy
102 (Soil Survey Staff 2010). Selected soil characteristics (0-20 cm layer) at the beginning of the
experiment were 110 g kg⁻¹ clay, 260 g kg⁻¹ silt, 630 g kg⁻¹ sand, soil bulk density = 1.63 g dm⁻³, pH
104 (water) = 5.4; Mehlich-I P = 33.4 mg dm⁻³, total C = 4.1 g kg⁻¹ and total N = 0.32 g kg⁻¹.

2.2 Main experimental design

106 The experiment was carried out at the first sugarcane ratoon from November 2015 to
November 2016 and began after the harvest of cane plants on November 20, 2015. The sugarcane
108 variety was RB 956911, and the harvest was manual, removing all aboveground biomass (stalk +
leaves + tops) and leaving the soil uncovered. An area was demarcated with 32 plots in 4 lines with
110 1.4 m of spacing between rows and length of 4 m. Each plot had an area of 22.4 m². We used a
randomized complete block design in a factorial scheme of 4x2 with four replicates. The first
112 treatment was the straw quantity treatment, with four amounts of straw on the soil surface: 0, 4, 8 and
12 Mg ha⁻¹ of dry matter (DM). The second treatment was the fertilizer N treatment, with 0 or 100 kg
114 N ha⁻¹ added as urea. The straw was homogeneously distributed by hand on the soil surface, resulting
in 8 treatments (0S, 0S+N, 4S, 4S+N, 8S, 8S+N, 12S, 12S+N). The urea N was applied as granules
116 broadcasted in a single dose on the straw on day 52 after the plant cane harvest.

2.3 Straw decomposition microplots

118 A litter box approach was used to monitor straw decomposition (Fig. 1). Air-dried straw was
added into 0.16-m² wooden frames (40-cm length x 40-cm width x 8-cm height) between rows of
120 sugarcane, as described by Dietrich et al. (2017). To evaluate the gradient of decomposition within the
mulch, the mulch was formed by straw layers of 4 Mg ha⁻¹, and we stacked a single layer, 2 layers or 3
122 layers inside the litter box to reconstitute the 3 mulch quantities. The layers were separated by a
malleable 10-mm synthetic mesh with a wide aperture so each layer could subsequently be sampled
124 separately for analysis. The 4 Mg ha⁻¹ treatment (4S) had a single layer, which was, in essence,
simultaneously in contact with the soil (low position: L) and in contact with the atmosphere (top
126 position: T), the layer in this treatment is referred to as 4S L/T. The 8 Mg ha⁻¹ treatment was composed
of two layers, a top layer (8S T) and a low layer (8S L); the 12 Mg ha⁻¹ treatment was composed of
128 three layers, a top layer (12S T), a middle layer (12S M) and a low layer (12S L).

Destructive sampling of litter boxes was performed on days 0, 15, 36, 51, 72, 103, 168, 238,
130 296 and 360 after straw application from November 2015 to November 2016. At each sampling date,
the straw from each layer in each destroyed litter box was collected separately, weighed wet, stored in
132 paper bags and dried in an oven at 40°C. The straw was then separated from adhering soil by dry
cleaning, and a subsample was dried in an oven at 65°C to determine the remaining straw DM. Straw
134 ashes were measured by incinerating 0.4 g in a muffle furnace at 550°C for 3 h. The total C and N
concentrations of the straw were determined using an elemental analyser (FlashEA 1112 model,
136 ThermoFinnigan, Milan, Italy). Straw soluble (SOL), cellulose (CEL), hemicellulose (HEM) and
lignin (LIG) fractions were determined in residues pre-dried at 40°C using the method described by
138 Van Soest (1963). The water-soluble organic C (C_{sw}) and water-soluble total N (N_{sw}) were extracted
using 2 g of chopped plant residue (1 cm) pre-dried at 40°C in 80 mL of water following the
140 methodology described by Schmatz et al. (2017). The C_{sw} and N_{sw} contents were analysed using a
total organic carbon analyser equipped with a kit for N analysis (Shimadzu TOC-LCPH, Shimadzu,
142 Kyoto, Japan). The chemical characteristics of the straw at the beginning of the experiment were as
follows: 228 ±7.5 g kg⁻¹ SOL, 372 ±2.7 g kg⁻¹ CEL, 335 ±5.2 g kg⁻¹ HEM, 65 ±1.6 g kg⁻¹ LIG, 425

144 $\pm 2.7 \text{ g kg}^{-1}$ total C, $8 \pm 0.2 \text{ g kg}^{-1}$ total N, $36.7 \pm 8.5 \text{ g kg}^{-1}$ C_{sw}, $1.2 \pm 0.2 \text{ g kg}^{-1}$ N_{sw} and a C:N ratio of
145 53 ± 1.4 .

146 Mulch thickness was evaluated in four litter boxes randomly selected by treatment (4S, 8S,
147 12S). In each box, nine non-destructive thickness measurements were performed using a graduate
148 ruler. The measurements were performed at 0, 29, 54, 72, 103, 168, 238, 296 and 360 days after straw
addition.

150 *2.4 Soil water content and soil temperature*

Sensors with two 30-cm-long stainless steel rods (FDR CS 616-L, Campbell Scientific, Logan,
152 Utah, US) inserted at 2.5 and 7.5 cm soil depth were used to measure soil moisture. The type T
copper-constantan thermocouple was installed at the same depths to measure soil temperature. Both
154 sensors were installed between sugarcane rows and coupled to a datalogger (CR1000, Campbell
Scientific, Logan, Utah, USA), and measurements were performed at a 10 min sampling interval. The
156 air temperature at 30-cm depth inside of the sugarcane plantation was also evaluated using the same
sensor model. The sensor was covered by a polyvinyl chloride pipe wrapped by asphalt adhesive tape
158 with holes on the sides. Daily air temperature and rainfall data were obtained from an automatic
weather station located 1.7 km away from the experiment site.

160 *2.5 Calculations and statistical analysis*

The remaining C and N of the straw at each sampling date were calculated as the remaining
162 mass of each straw layer multiplied by its C and N concentrations (deduced from the ash content). In
treatments 8S and 12S (with and without N), the amounts of C and N remaining were obtained by
164 summing the amounts of C and N in each straw layer. The C remaining in each layer and in the total
mulch over time was described with a simple one-compartment equation according to Plante and
166 Parton (2007):

$$\text{C remaining} = C_0 e^{-kt}$$

168 where C remaining is the mass of the remaining C (Mg C ha^{-1}), C_0 is the straw C pool at time 0 (Mg C ha^{-1}), k is the degradation rate constant (day^{-1}), and t is the time (days).

170 The mean residence time ($t_{1/2}$) of the straw, which corresponds to the time necessary to
degrade half of the initial quantity of mulch, was calculated from k according to Plante and Parton
172 (2007). The LCI (lignocellulose index) was calculated from the CEL, HEM and LIG fractions of
sugarcane straw and corresponds to the relative enrichment of LIG in the plant cell walls (Whittinghill
174 et al., 2012). This index was taken as an indicator of the degradation process of the lignocellulose
substrates.

176 All data were subjected to analysis of variance (ANOVA). The effect of straw quantity or
straw layer, N fertilization and time, and their interaction on mulch decomposition (C and N
178 remaining, SOL, CEL, HEM and LIG remaining and LCI index) and physical (thickness and water
content) variables, were tested. Similarly, we tested the effect of straw quantity or straw layer and N
180 fertilization, and their interaction on decomposition model parameters (C_0 , k and $t_{1/2}$). In the straw
layer data analysis, data from the 4S treatment were included in the statistical analysis. This treatment
182 was considered to have a straw layer representing both L and T straw because the layer was in direct
contact with the soil and the atmosphere simultaneously. The effect of straw quantity, soil depth and
184 time, and their interaction on soil moisture and soil temperature also were tested. When ANOVA
showed significant ($P < 0.05$), the differences between means of treatments were compared by the
186 Tukey test ($P < 0.05$). Relationships between remaining C or N measured at the end of experiment and
the average water content of straw layers in the mulch (T/L, L, M and T) for the three treatments (4S,
188 8S and 12S) over the 360 days of the experiment was fitted.

190 **3. Results**

3.1 Climatic and soil environmental conditions

192 The total annual rainfall was 1519 mm, distributed over 107 events, and the mean air
temperature was 18.4 °C, similar to the historical average (Fig. 2a). The relative air humidity ranged
194 from 39 to 99%, with most values in the 70-90% range (Fig. 2b). As the temperature and moisture at
the 2.5 and 7.5 cm soil depths varied in the same way over time and between treatments, only the 2.5
196 cm soil depth data are shown here (Fig. 2c and 2d). The effect of straw amount on soil temperature

was observed only in the first three months, when the sugarcane canopy had still not completely
198 covered the soil surface (Fig. 2c). The mean soil temperature during this period at 2.5 cm depth
decreased with increasing amounts of straw, as 0S (28.2°C)>4S (27.1°C)>8S (26.4°C) = 12S (26.5°C),
200 indicating an approximately 2°C difference in mean temperature between the highest (12S) and the
lowest (0S) amount of straw. The soil water content responded to daily precipitation and was affected
202 by straw quantity (Fig. 2d). Averaged over the experimental year, the soil volumetric water content
was 0.17 for 0S, 0.19 for 4S, 0.21 for 8S and 0.23 g cm⁻³ for 12S. The soil water content was markedly
204 lower in the treatments with lower straw quantities in the soil surface during periods with a small
amount of rainfall or a short dry period, e.g., from day 46 to 67, day 190 to 217, and day 297 to 320.

206 *3.2 Dynamic of thickness and water retention of mulch*

The initial mulch thickness varied significantly with straw quantity, and, as expected, had a
208 ranking of 12S (4.7 cm)>8S (3.6 cm)>4S (1.9 cm) at day 0 (Fig. 3a). The thickness was not strictly
proportional to the mass, suggesting a layer settling with the larger mass and therefore a higher mulch
210 density for 12S treatment. Then the evolution of mulch thickness was proportional to the initial
thickness in the three straw treatments, with a 32% decrease in thickness at day 29, 50% decrease in
212 thickness at day 103 and 68% decrease in thickness after 360 days. At that time, the mulch was 0.6,
1.2 and 1.5 cm thick for 4S, 8S and 12S, respectively.

214 The water content of the sampled mulches varied greatly over the course of the year, ranging
between 10 and 80 g H₂O 100 g⁻¹ DM. The water content varied significantly as a function of straw
216 quantity at some sampling dates (Fig. 3b) and differed according to straw layer position (Fig. 3c and
Fig. S1). Comparing the layer positions for a given treatment, we observed that the water contents in
218 the L layers of 8S and 12S were higher than those in the T layers of 8S and 12S, except for the
samplings performed at days 51, 103 and 238. Comparing different mulch treatments for a given layer
220 position, we observed that generally speaking, the thicker the mulch, the higher the moisture content
of a layer in a given position was. On average over the year, the moisture content of the whole mulch

222 was finally low or negligible for the three quantities of mulch (Fig. 3b), suggesting compensation
226 between the different layers according to thickness.

224 3.3 Dynamic of mulch decomposition

The straw C and N remaining as mulch, expressed as the percentage of the initial straw C or N
226 added, decreased quickly over time but were not influenced by straw quantity, N fertilization or their
interaction (Table S1); therefore, the mean data of the 0N and 100N treatments for each straw
228 treatment are presented here (Fig. 4a and 4b). Notably, approximately half of the straw C and two-
thirds of straw N lost during the 360-day period were lost in the first 36 days, regardless of the initial
230 straw quantity. The straw C and N lost by day 360, averaged for the 12S, 8S and 4S treatments,
amounted to 75 and 46% of the initial C and N, respectively. The C:N ratio of the remaining straw
232 decreased from an initial C:N of 53 to a final C:N of 29, with no significant differences between straw
treatments or between N treatments (Fig. S2).

234 Straw C_{sw} decreased very quickly, and by day 36, only 14, 12 and 19% of the initial C_{sw}
remained in the 4S, 8S and 12S treatments, respectively, with significant transient differences between
236 treatments (Fig. 4c). Straw N_{sw} decreased more slowly until day 72 and then remained stable until the
end of the experiment (Fig. 4d). The chemical composition of the straw particles changed over time,
238 with, at day 360, a relative increase in HEM and LIG and a strong decrease in CEL, while the SOL
fraction remained stable (Fig. S2). This final composition was not influenced by straw quantity, N
240 application or their interaction ($P > 0.05$) (Table S1). The C₀ straw pools calculated with the one-
compartment equation was, as expected, close to the initial straw quantities, representing 1.47 Mg ha⁻¹
242 (4S), 2.99 Mg ha⁻¹ (8S) and 4.45 Mg ha⁻¹ (12S) (Table 1). The straw quantity and N addition did not
change the k decomposition rates, with on average $k = 0.0044$ and $t_{1/2} = 158$ days.

244 3.4 Effect of straw layer position on decomposition

3.4.1. C and N evolution in the mulch layers

246 The dynamics of straw C and N in the various mulch layers were significantly influenced by
the position of the straw layers within the mulch ($P < 0.001$) but were not significantly influenced by N

248 fertilization or the interaction between straw layer position and N fertilization ($P>0.05$) (Table S2);
therefore, the means of the two N treatments are presented here (Fig. 5). In treatment 12S (Fig. 5a), the
250 dynamics were characterized by a rapid decrease in straw C that was similar among all layer positions
(0-36 days), followed by a slower decrease, during which the decomposition of 12 L>12M>12T. The
252 same pattern of decomposition was also observed in the 8S treatment, with layer 8 L>layer 8T (Fig.
5c). Comparing the C loss of the top layers across the three straw treatments (4S L/T vs. 8S T vs. 12S
254 T), we observed that the dynamics were very similar, except for at two dates, which demonstrated a
transient difference that subsequently disappeared (Fig. 5e). The same comparison among low layers
256 (4S L/T vs. 8S L vs. 12S L) showed that the 4S L/T layer decomposed less rapidly and had
significantly less decomposition over the final two sampling dates than the 8S L and 12S L layers (Fig.
258 5g). As expected, the decomposition parameters of the adjusted model were significantly different
only for mulch layer position (Table 1): the highest and lowest decomposition k rates were observed in
260 the L and T layers, respectively.

The straw N kinetics followed the same pattern for each layer position (Fig. 5b,d,f,h). The
262 dynamics were characterized by a rapid decrease in straw N (0-36 days) that was similar among all
layer positions, followed by a slower decrease up to day 103, after which the remaining N values were
264 relatively stable until day 360. Differences in the remaining N among the straw layers were observed
mainly from day 238 in the 12S (T>M>L) and 8S (T>L) mulch. The N remaining in the mulch at the
266 end of the experiment also differed between the low layers, with 4S L/T>12S L.

3.4.2. *Changes in chemical composition*

268 The chemical composition of the straw layers, i.e., the straw C:N ratio and chemical
composition expressed by the LCI, taken as an indicator of the decomposition process, varied over
270 time for all layer positions and depended on the position of layers in the mulch (Fig. 6 and Fig. S3).
Considering the 12S treatment as an example, we observed that the pattern of evolution of the C:N
272 ratio was similar among the three layers, but in general, the C:N decrease was more pronounced for
low layers, with 12S L<12S M<12ST (Fig. 6a). The LCI increased from 0.08 to 0.17 over time for all

274 layers and was significantly different between layers at different positions until day 168 (e.g., 12L =
12 M>12T), but no difference persisted at day 360 (Fig. 6b).

276 3.4.3. Relationships with straw water content

The C and N remaining at day 360 in the L, M, T or L/T straw layers were significantly and
278 linearly related to the average moisture content of these layers sampled over the year, regardless of the
position of the layer within the mulch and the mulch quantity (Fig. 7). This relationship was also
280 found when using the degradation constant k , which reflects all decomposition kinetics, with $k=$
 $0.0001x - 0.0005$ ($R^2=0.882$, $P<0.05$).

282

4. Discussion

284 4.1. Effect of mulch mass and thickness on mulch decomposition

A main hypothesis, based on recent published work, was that increasing the mass of mulch
286 residues at the soil surface does not affect the decomposition rate of these mulches (Acosta et al.,
2014; Halde and Entz, 2016; Dietrich et al., 2017). This situation was reflected in the present study
288 with 3 amounts of sugarcane straw initially placed on the soil surface, which increased the initial
mulch thickness (12S>8S>4S). We confirmed that the straw C and -N dynamics and calculated
290 decomposition rates of the mulches were similar, regardless of the initial quantity of straw and
whether they received 100 kg of fertilizer N 52 days after straw application. This result signifies that,
292 although the proportion of the total mass in contact with the soil decreased as the mass increased, the
decomposition was not modified. In fact, the initial thickness of the mulch varied from 1.9 cm to 4.7
294 cm, which is not a great difference. This may be due to our experimental system, which, although
using hand-cut straw particles of a realistic decimetre length, minimized the thickness by "stacking"
296 the straw in layers. In the field, mulches can be thicker but less dense. Meier et al. (2006) observed an
initial sugarcane mulch thickness of about 11 cm for a 10 Mg ha⁻¹ mulch mass, decreasing rapidly in
298 one year. Stott et al. (1990) measured that the initial wheat straw layer thickness ranged from 12 and
20 cm. Although mulch thickness is a parameter important for both the interpretation and the

300 modelling of mulch decomposition, data are still very rare. These results suggest that neither microbial
colonization nor N availability were limiting factors of decomposition for the thickest mulches, which
302 invalidates the hypothesis that soil-straw contact plays a major role as a key driver of mulch
decomposition (Coppens et al., 2007; Thorburn et al., 2001). The initial thickness of the mulch was
304 not proportional to the mass, due to a settling of the mulch with increasing weight of the residues. It
should also be noted that the decrease was not linear over time, probably due to the effect of two
306 combined factors, an initial possible and rather rapid settling under the influence of rainfall, combined
with a more regular decrease under the effect of decomposition. It is noteworthy that the decrease in
308 thickness was proportional to the initial thickness, reflecting the observed proportionality of the
decomposition rate with the initial mass.

310 Strikingly, the N dynamics in mulch differed substantially from the C dynamics in mulch.
After a synchronized, rapid C and N net loss at the beginning of decomposition, the N in the mulch
312 remained stable while decomposition continued, and adding N onto the mulch in fertilized plots did
not modify this dynamic. Sousa Jr et al. (2017) also observed little and transient effect of adding
314 vinasse onto sugarcane mulch on decomposition rate. These results suggest the efficient use of straw N
and recycling of microbial N by decomposers growing on the straw and that the availability of N to
316 decomposers was not a limiting factor of decomposition, even with increased mulch masses and
thicknesses and a lack of mineral N in the soil under the mulches in non-fertilized plot (Pinheiro et al.,
318 *accepted*). Some work has also highlighted the possibility of a significant contribution of asymbiotic
N-fixation during decomposition of sugarcane litter. Lincoln and Vitousek (2016) calculated that the
320 asymbiotic N fixed represented 17 to 40% of the N present in the litter. They pointed out that the
potential N-fixation per unit litter depended on the thickness of the litter with an optimum for a 5cm-
322 thick litter. This amount of fixed N could represent from 5 to 39 kg N ha⁻¹ year⁻¹ depending on the
conditions tested. Patriquin (1982) earlier found that 10 to 30 kg N ha⁻¹ were potentially fixed during
324 sugarcane litter decomposition. The possible contribution of non-symbiotic fixation to mulch N
dynamics would merit further investigation, as it appears to be quantitatively important. The relatively
326 high C:N ratio of sugarcane straw suggests also that fungi may be the main group of microorganisms

involved in decomposition, particularly for the upper layers of the mulch, due to their ability to
328 translocate N from the soil through the hypha network to substrates that are recalcitrant or poor in N
(Frey et al., 2000).

330 The amount of straw on the soil surface also affected soil temperature and moisture and had a
substantial effect on the straw water content. Previous studies demonstrated that mulch moisture is
332 driven by the water retention characteristics of residue particles and by rain and evaporation regimes
(Lee et al., 2014; Iqbal et al., 2015). Few studies have evaluated the interaction between different
334 amounts of straw and soil moisture (Cook et al., 2006). Our results clearly showed an increase in soil
moisture with increasing straw masses on the soil surface, mainly in periods with low rainfall, when
336 thicker mulch prevented soil water evaporation more effectively, confirming other studies (Sousa Jr et
al. (2017). This is because the straw on the surface acts as a physical barrier to the transfer of heat and
338 water to the atmosphere (Fuchs and Hadas, 2011). Despite rain water being retained by mulches, soil
without mulch remained drier than soils covered by mulches. This is due to the fact that the increased
340 evaporation of soil not covered by mulch (0S) was not offset by the higher amount of water reaching
soil after the rains in such situation. It is understandable that this effect depends on several factors, not
342 only on the intensity and frequency of rainfall, but also on the proportion of mulch-covered area and
the characteristics of the mulch, and may vary according to agricultural and climatic conditions.

344 *4.2. Water and decomposition gradients within the mulch*

The amount of straw on the soil surface not only affected the overall soil and straw moisture
346 but also created a moisture gradient within the mulch. Sampling straw layers in different positions in
the mulch showed that the layers in contact with the soil in the thicker mulch (8S L and 12S L) were
348 almost always wetter during the year than the more distant layers (8S T, 12S M and 12S T), which
were exposed to solar radiation and wind. The higher moisture of the layers in contact with the soil
350 was mainly due to the lower water loss by evaporation but may also be due to the absorption of water
from soil by the straw in a phenomenon defined as the “sponge effect” (Kravchenko et al. 2017).

352 These moisture conditions favour high microbial activities and faster decomposition at the soil-mulch
interface.

354 The kinetics of straw C and N for each layer position and each mulch mass treatment indicated
that all layers decomposed, even at the top of the thicker mulch (12S T), which was the most distant
356 layer from the soil and that the decomposition of the top layers started as quickly as the decomposition
of the other layers. This suggests that part of the initial fast C and N losses could be due to the
358 leaching of soluble compounds under rain. However, the change in the chemical composition of mulch
over time, expressed here by the LCI index, occurred in all straw layers, regardless of position. The
360 LCI corresponds to the relative enrichment of LIG in the plant cell walls of the residues (Whittinghill
et al., 2012) because structural components such as CEL and HEM are more easily decomposed than
362 LIG (Berg and McClaugherty, 2014). This confirms that the C or N loss of the top layers was not
simply due to the possible physical transport of straw particles from an upper layer to a lower layer
364 during experimental handling or by rain leaching; rather, remaining particles of each layer underwent
decomposition. The high LCI value of the low 12S layer (12S L) also confirms that decomposition
366 advanced more in this layer than in the other straw layers.

We observed that the top layers behaved similarly (12S T= 8S T= 4S L/T), while the
368 decomposition speed of the low layers increased as the overlying mulch thickness increased (12S
L>8S L>4S L/T). This pattern indicates that the top layers were under similar control of humectation-
370 desiccation cycles, driven by climate, while the low layers differentiated from each other by the
thickness of the overlying mulch, which in turn influenced the low-layer moisture. These findings are
372 very well supported by the strong relationships between the amount of straw C or N remaining after
360 days (or the k degradation constant) and the mean straw moisture in each layer, irrespective of
374 layer position and the mulch thickness. We conclude that a mulch system of various thicknesses is
driven primarily by water dynamics, which is under the control of water retention-evaporation by the
376 straw particles. The moisture gradient in the mulch depended on mulch thickness and determined
decomposition gradient, which finally defined the decomposition rate of the whole mulch. This raises
378 the question of understanding how the observed differences between layers perfectly balance in order

not to be able to find any difference in decomposition rate between mulches of different thicknesses.

380 Our assumption is that, in our experimental conditions (climate, range of DM), the higher
decomposition rates of the low layers in thick mulches compensated for the large mass of these thick
382 mulches not in direct contact with the soil. This “compensation” hypothesis is also supported by our
results of water content of whole mulches (measured 9 times during the year), showing that although a
384 gradient was established within the mulches, and transient differences appeared between mulches of
increasing thickness, on average there were little or no differences in water content of the mulches
386 regardless of their initial mass. These results confirm the hypothesis of Dietrich et al. (2017) that
increasing mulch quantity has an antagonistic effect, increasing the proportion of straw less wet and
388 not in direct contact with the soil but improving the environmental conditions of decomposition of the
mulch at the soil-mulch interface. Williams et al. (2018), measuring the decomposition of varied
390 quantities of surface rye straw, also obtained similar decomposition rates in the range of 5 to 15 Mg
ha⁻¹. Conversely, Vasconcelos et al. (2018) and Sousa Jr et al. (2017), investigating sugarcane, showed
392 that the decomposition rate increased with the amount of straw in the range 3-14 Mg DM ha⁻¹,
suggesting that the positive effect of increased moisture prevailed in thicker mulches. However, the
394 thickness and density of the mulches were not available in these studies; therefore, it is not possible to
interpret the differences with our results. Thus, further research is needed to establish the mulch
396 thickness range and rain patterns for which these results are valid and, in particular, better understand
how the dynamics of mulch layers that are thicker than those explored here and in the literature could
398 modify the above conclusions. It is expected that these results will strongly depend on climatic
conditions and will particularly be affected by interactions between mulch properties and thickness
400 and water dynamics in dry periods.

4.3. Consequences for much conceptual modelling

402 Many modules developed in several simulation models (i.e., APSIM, Thorburn et al., 2001;
PASTIS, Findeling et al., 2007) represent residue mulch composed of two layers; one of these layers is
404 in contact with the soil, undergoing decomposition with moisture, available N and microbial biomass

processes influenced by the underlying soil layer, and the other layer is undecomposed straw, which
406 "feeds" the lower layer as it empties. Moreover, in the model proposed by Findeling et al. (2007), the
water dynamics of mulch are simulated by considering the whole mass of straw that forms the mulch
408 to present the same moisture content. Our results demonstrated that upper mulch layers, which are not
in direct contact with the soil (exposed to air), also decompose and that there is a gradient of moisture
410 and decomposition (and probably temperature, although we did not measure this factor) throughout the
mulch volume. These findings suggest the need for more sophisticated models dedicated to the
412 simulation of mulch evolution, by considering the whole straw layer to be decomposing, albeit with a
gradient, and with an accurate estimation of the mulch water content over time, including knowledge
414 about water interception, retention and leaching for various crop residues (Iqbal et al. 2013; Sato et al.
2004).

416

5. Conclusions

418 By varying mulch thickness under similar climatic conditions, we demonstrated that not only
the mulch in contact with the soil but also the whole mulch decomposed, starting quickly after the
420 residues were deposited on the soil, with a vertical gradient of decomposition closely linked to the
moisture gradient. The moisture gradient of the mulch, which is under the control of humectation
422 (rain) and desiccation (evaporation) and depends on thickness, drives decomposition; therefore, it is
important to correctly model water properties of crop residues and water transport between soil, mulch
424 and atmosphere. Our results indicated the importance of soil-residue layer contact properties in driving
mulch decomposition. We also showed that, despite heterogeneity within the mulch, decomposition
426 was proportional to the initial amount of mulch mass for the studied crop. For the present range of
straw masses, as mulch thickness increased, the moisture and decomposition rate of the underlying
428 layers increased compensating for the increase in the fraction of mulch more distant from the soil and
drier. Considering the importance of these results for the dynamics of nutrient recycling and release in
430 non-tilled agrosystems, the ability of mulch decomposers to efficiently recycle N and the dynamics of
microbial colonization within the mulch should receive more attention. Finally, the accurate prediction

432 of water dynamics in soil-mulch systems is crucial because these systems act as hot spots for many
processes, particularly gas emissions (NH₃, N₂ and N₂O), which are under the control of moisture
434 conditions.

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442
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Figure Captions

560 **Fig. 1.** Schematic layout of the field plots demonstrating the locations of soil water content and soil
temperature sensors (2.5 and 7.5 cm depth) and the litter boxes, with emphasis on the different straw
562 layers (L: low, M: middle and T: top) forming the three quantities of straw (4S: 4 Mg ha⁻¹, 8S: Mg ha⁻¹
and 12S: 12 Mg ha⁻¹).

564 **Fig. 2.** Precipitation and air temperature (a), relative humidity (b), soil temperature (c) and soil
moisture (d) at 2.5 cm depth for four quantities of straw (0S, 4S, 8S and 12S, i.e., 0, 4, 8 and 12 Mg
566 ha⁻¹, respectively) over the 360 days of the experiment.

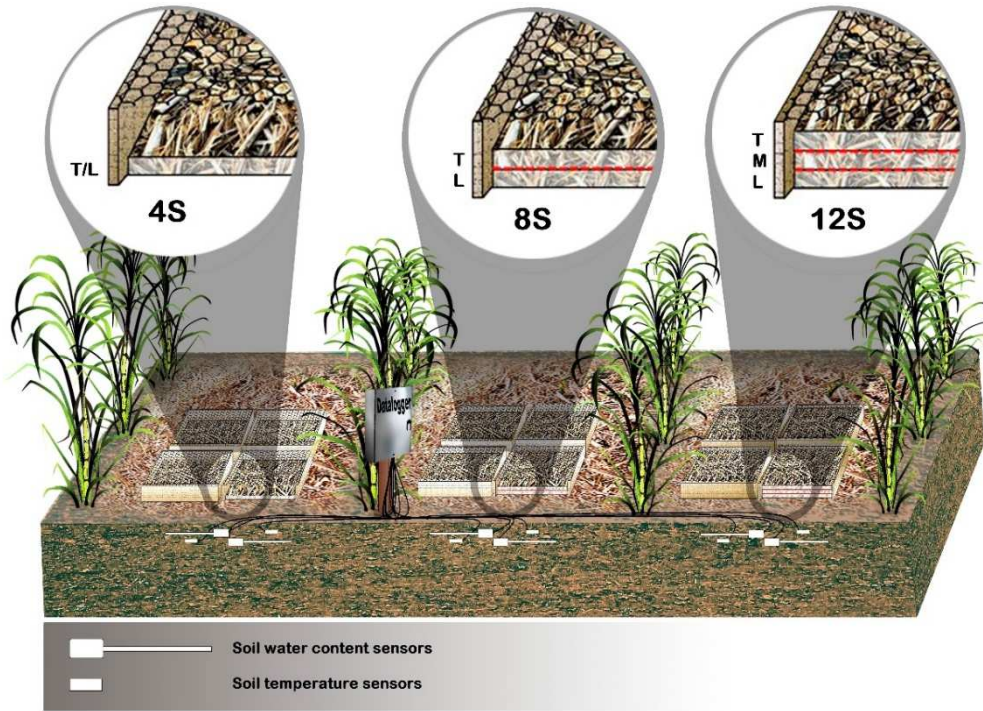
Fig. 3. Evolution of the thickness (a) and water content of the mulch over the 360 days of the
568 experiment (b) and water contents of the mulch layers at two sampling dates and on average for the
year (c). 4S, 8S and 12S correspond to 4, 8 and 12 Mg ha⁻¹, respectively, and L, M and T correspond
570 to the low, middle and top positions, respectively, in the mulch. The vertical bars indicate the
minimum significant difference between treatments (Tukey's test at $P < 0.05$). Values are the mean of
572 36 replicates for thickness or 4 replicates for straw water content.

Fig. 4. Dynamics of total C (a), total N (b), water-soluble C (c) and water-soluble N (d) in the
574 remaining mulch particles for three quantities of straw (4S: Mg ha⁻¹, 8S: Mg ha⁻¹ and 12S: Mg ha⁻¹).
Data are the average of the treatments with 0 (0N) and 100 (100N) kg N ha⁻¹. The vertical bars in the
576 graph indicate the minimum significant difference between treatments (Tukey's test at $P < 0.05$).
Values are the mean of 8 replicates per treatment and per date.

578
Fig. 5. C and N remaining in the mulch straw layers: (a,b) and (c,d) show different positions in the
580 mulch (L: low, M: middle, T: top) for the 12S and 8S treatments, respectively; the straw layer is
located on the top of the mulch in (e,f) and on the bottom of the mulch in (g,h) for the three treatments
582 (4S: Mg ha⁻¹, 8S: Mg ha⁻¹ and 12S: Mg ha⁻¹). The vertical bars in the graph indicate the minimum
significant difference between treatments (Tukey's test at $P < 0.05$). The values are the mean of 8
584 replicates per treatment and per sampling date.

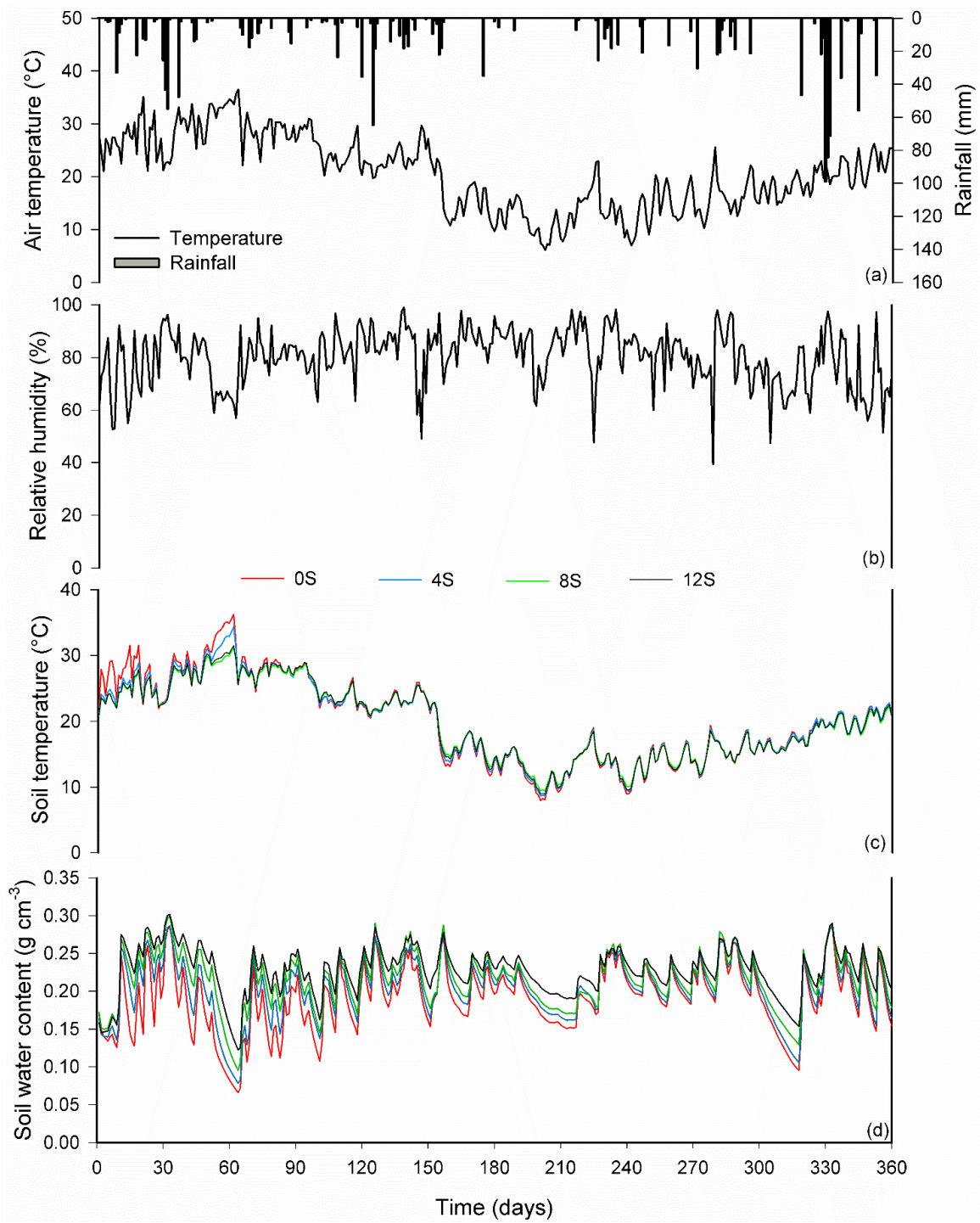
Fig. 6. Evolution of the C:N ratio (a) and of the lignocellulose index (LCI) (b) of the straw for the
586 three layer positions in the mulch (L: low, M: middle, T: top) for the 12S treatment (12 Mg ha⁻¹). The
vertical bars indicate the minimum significant difference between treatments (Tukey's test at $P < 0.05$).
588 Data are the mean of 8 replicates per treatment and per sampling date.

Fig. 7. Relationships between straw C or straw N and the average water content of straw layers with
590 different positions in the mulch (L: low, M: middle, T: top) for the three treatments (4S: Mg ha⁻¹, 8S:
Mg ha⁻¹ and 12S: Mg ha⁻¹) over the 360 days of the experiment. Values are the mean of 4 replicates
592 per layer on 9 sampling dates.



1
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Fig. 1.



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Fig. 2.

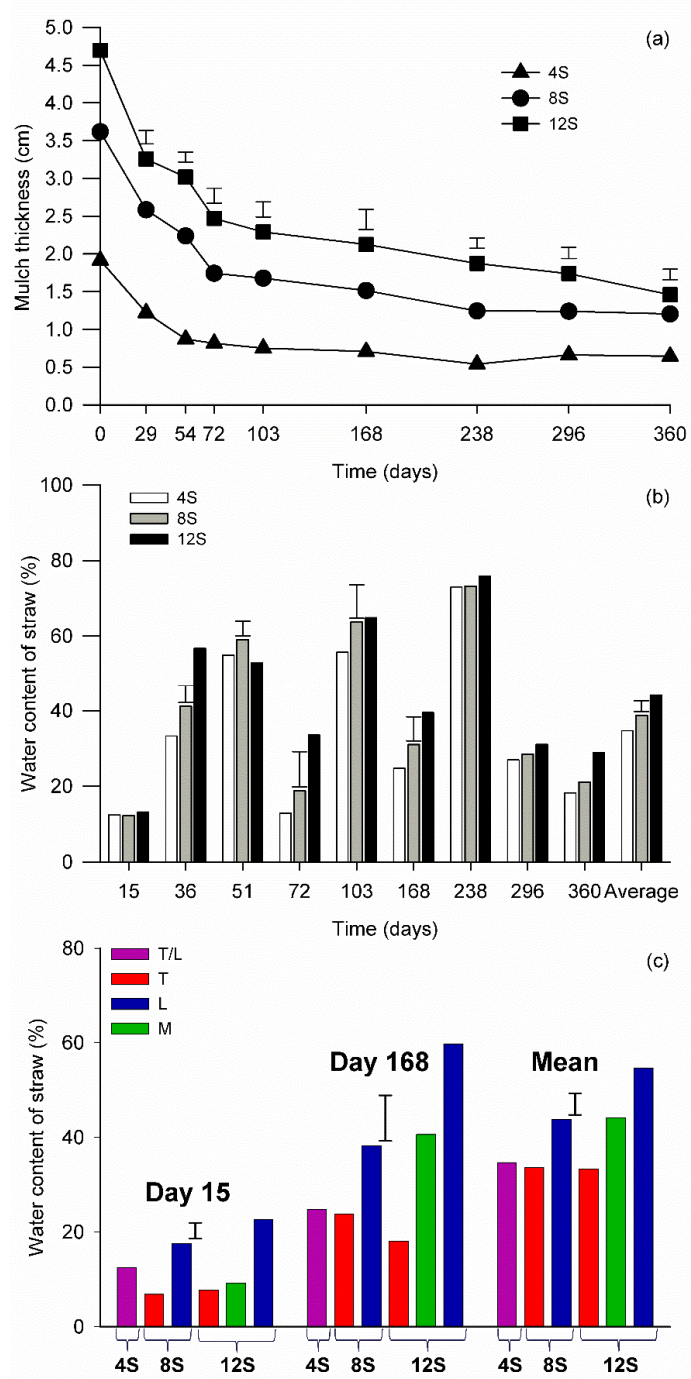
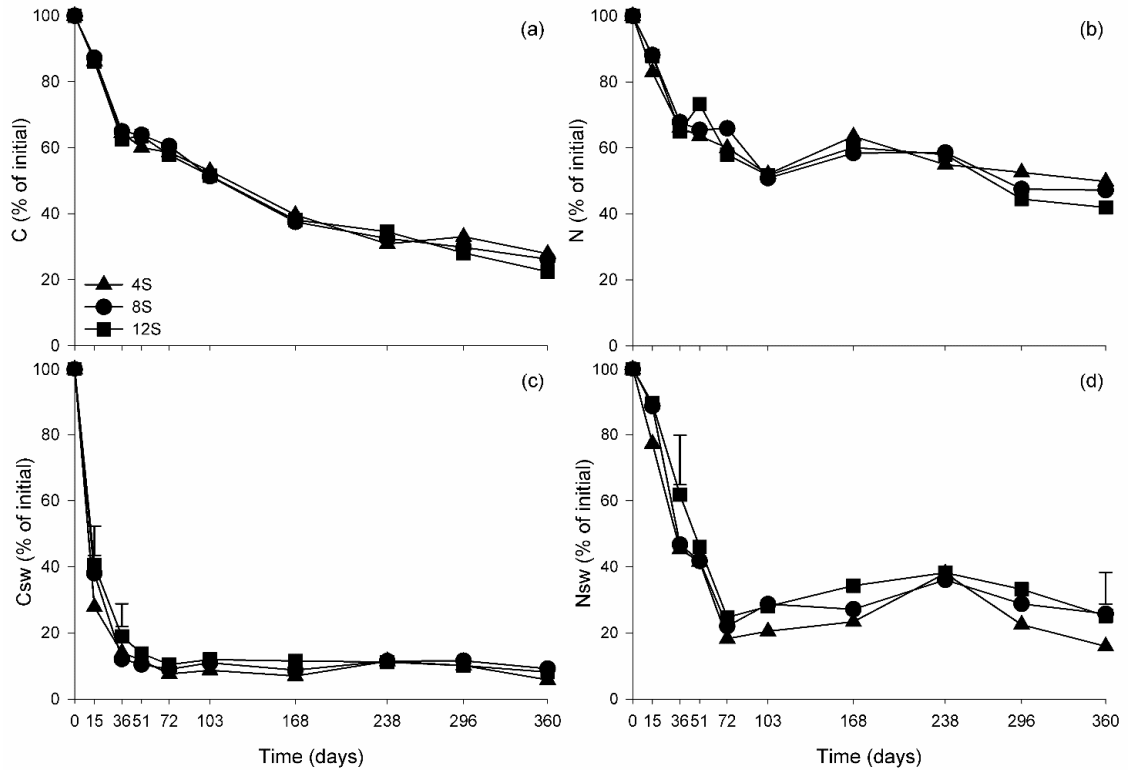


Fig. 3.



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Fig. 4.

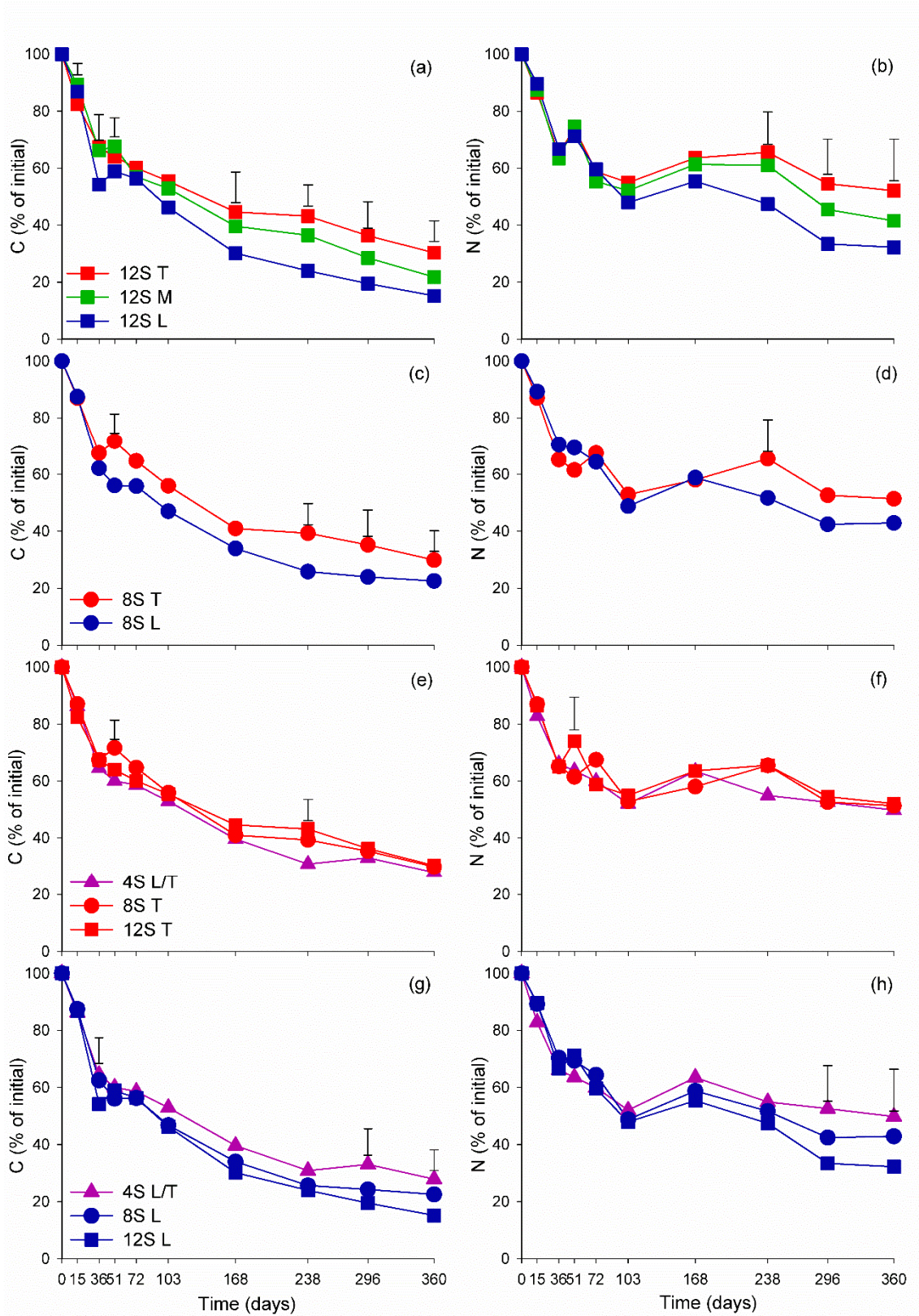


Fig. 5.

1

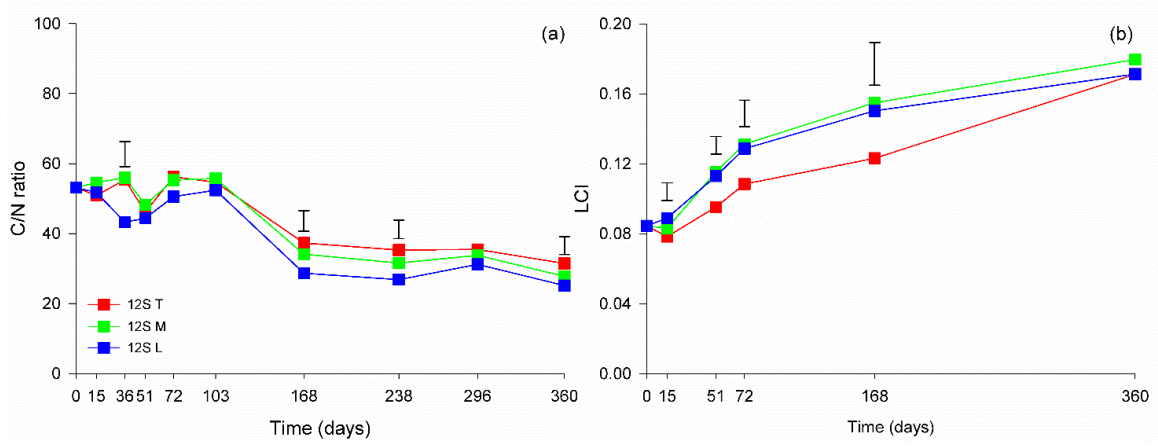


Fig. 6.

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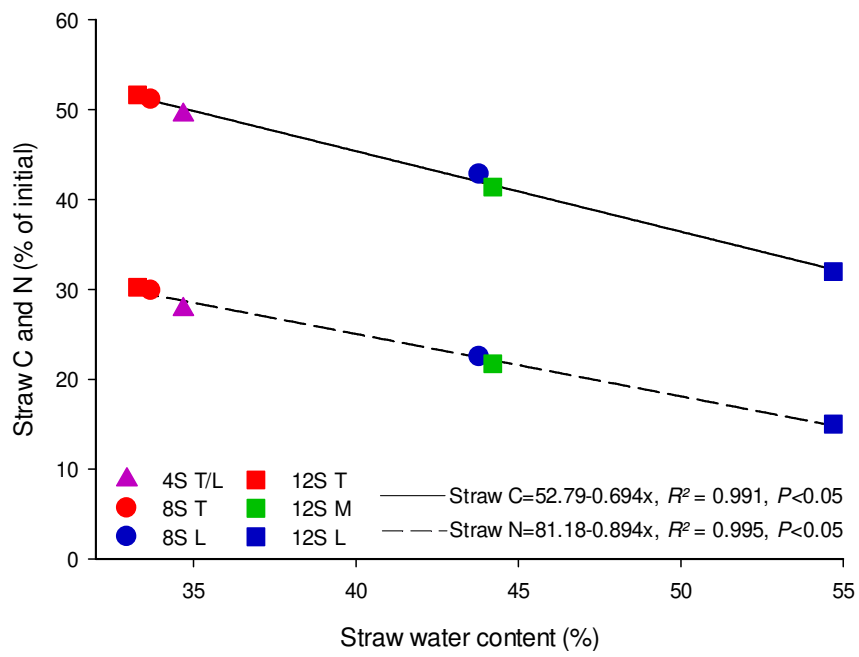


Fig. 7.

1
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1 **Table 1**

2 Decomposition rate (k) and mean residence time ($t_{1/2}$) for the mulch with three straw quantity (4, 8 and 12 Mg ha⁻¹) and two N rate (0 and 100 kg ha⁻¹) and
 3 mulch straw layers (L: low, M: middle, T: top).

Parameters	Initial straw quantity (Mg ha ⁻¹)			N rate (kg ha ⁻¹)		Straw layers					
	4	8	12	0	100	4S L/T	8S T	8S	12S T	12S M	12S L
C_0 (Mg ha ⁻¹) ^a	1.47c	2.99b	4.45b	2.97a	2.97a	1.47ab	1.51a	1.51a	1.43b	1.52a	1.52a
k (day ⁻¹) ^b	0.0042a	0.0040a	0.0046a	0.0045a	0.0044a	0.0042b	0.0037bc	0.0055a	0.0033c	0.0046b	0.0064a
$t_{1/2}$ (day ⁻¹) ^c	166a	155a	153a	158a	159a	166bc	188ab	126de	209 ^a	155cd	110e

4 Values followed by the same letters are not significantly different (Tukey at $P < 0.05$).

5 ^a C_0 is straw C pool.

6 ^b k is the degradation rate constant.

7 ^c $t_{1/2}$ is the half-life of the mulch.

8