

Fine root dynamics in a tropical integrated crop-livestock-forestry system

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1 2

Fine root dynamics in a tropical integrated crop-livestock-forestry system

3 Abstract

4 Integrated crop-livestock-forestry (ICLF) systems explore synergistic interactions between soil, 5 plant, and animals, maximizing land-use efficiency and sustainability. However, belowground dynamics 6 under ICLF have not been investigated deeply, particularly the role of incorporating dead root material, a 7 forefront strategy for releasing nutrients and storing carbon. To better understand belowground interactions, 8 we conducted a 21-month assessment of fine-root growth and decomposition in an ICLF system, starting 9 when Eucalyptus urograndis trees were three years old. Eucalyptus rows were spaced 15 m apart and 10 integrated with annual crops and pasture. Distances of 1.9, 4.3, and 7.5 m from the trees were evaluated 11 under two successional periods: (i) annual crop, when corn was interspaced with palisade grass (Urochloa 12 brizantha); and (ii) pasture, when palisade grass was grazed. We used the minirhizotron technique to track 13 fine-root production and decomposition down to a depth of 70 cm, capturing 2400 images. Root longevity 14 was estimated per root diameter class (0-0.5-, 0.5-1.0-, and 1.0-2.0-mm) and phenotypical groups (e.g., 15 grasses [corn + palisade grass] and Eucalyptus). Our data showed that root decomposition rate and 16 necromass inputs into the soil were reduced at the closest distance from the Eucalyptus rows (i.e., 1.9 m). 17 The incorporation of decomposed roots was higher in the topsoil (0-28 cm) and declined with increasing 18 soil depths. The total decomposed root incorporation was 101 m m⁻² of soil image for 7.5 and 4.3 m inter-19 row positions, almost twice as high as the recorded at 1.9 m (54 m m⁻²) from the trees. Daily root 20 decomposition rates increased during the last rainy season, benefited from numerous dead corn roots, and 21 facilitated by higher soil moisture and temperature. Grasses and Eucalyptus roots at 7.5 m from the tree 22 rows had shorter longevity than those at 1.9 m, remaining 88 and 152 days less, respectively. Root diameter 23 influenced the decomposition rate as thicker roots (diameter between 1.0-2.0 mm) of grasses and 24 *Eucalyptus* stood in the soil for 243 and 261 days longer than the finest roots (diameter < 0.5 mm). Our 25 results highlight that root necromass accretion and decomposition are heterogeneous in ICLF systems. 26 Furthermore, 3-to-5-year-old Eucalyptus trees drive the interactions, creating microclimate conditions that 27 impair corn and palisade grass root production and reduce root turnover close to the trees. These findings 28 provide a scientific base for managing the ICLF system (spatial and temporal arrangements) and developing 29 models of soil carbon addition via roots in such complex and heterogeneous systems. 30

31 Keywords: Alley cropping, minirhizotron, Eucalyptus, palisade grass, root diameter, root turnover, carbon

32 1. Introduction

33 Integrated crop-livestock-forestry (ICLF) systems are promising strategies for restoring and intensifying land production through a more sustainable form of agriculture combining various 34 agroecological principles (Bieluczyk et al., 2020; Bonaudo et al., 2014) and integrations planned to 35 36 potentialize synergistic soil-plant-animal effects (Lemaire et al., 2014; Magalhães et al., 2019). Moreover, 37 by diversifying production (e.g., producing wood, crop, and livestock in the same area), ICLF systems bring 38 multiple sources of income to the farm, reducing market risks and enhancing economic security (Balbino 39 et al., 2011; Oliveira et al., 2018). Countless spatial and/or temporal combinations of pastures with crops 40 and/or trees can be designed in ICLF systems (Bieluczyk et al., 2020), where the incorporation of trees 41 increases intensification, biodiversity, and complexity to this type of agroecosystem (Pezzopane et al., 42 2020b).

43 The arrangement of trees determines whether the ICLF integration results in synergies or 44 competition because they are the dominant component in the system and dictate the resource partitioning, including solar radiation, water, and nutrients (Bieluczyk et al., 2021; Pezzopane et al., 2020a). Due to this 45 46 concern, several studies have investigated the role of aboveground phenology and production after 47 introducing trees in integrated farming systems (e.g., Carvalho et al., 2019; Franchini et al., 2014; Magalhães et al., 2019; Pezzopane et al., 2019). However, the temporal and spatial belowground 48 49 interactions remain poorly understood, leaving many uncertainties and constraining successful advances in 50 these systems (Sarto et al., 2020). For example, roots could be the most outstanding protagonists in 51 enhancing soil aggregation (Batista et al., 2013), nutrient recycling in the system (Garcia et al., 2008), and 52 soil organic matter accumulation (Bieluczyk et al., 2020; Sant-Anna et al., 2017). Furthermore, the 53 supportive management of plant roots has recently been recognized as a crucial factor for achieving more 54 sustainable agriculture in the future (Zhang and Peng, 2021).

55 Fine-root decomposition is a critical, yet poorly understood, source of carbon (C) and nutrients in 56 terrestrial ecosystems (See et al., 2019). Fine roots ($\leq 2 \text{ mm}$ in diameter) are the primary drivers of soil C 57 accrual in agricultural systems. These roots contribute to soil C formation (Rasse et al., 2005) and 58 stabilization (Jackson et al., 2017) through processes such as root production, respiration, exudation, and 59 decomposition (Cheng and Kuzyakov, 2005; Strand et al., 2008). However, the process of root 60 decomposition can be influenced by several factors, such as agricultural systems (Jalota et al., 2006), 61 interrow space in alley crop-based systems (Germon et al., 2016), cultivated agriculture (Sievers and Cook, 62 2018), and forestry (Wang et al., 2010) plant species (Redin et al., 2014), root diameter (Germon et al., 2016), soil depth (Cordeiro et al., 2020; Lambais et al., 2017), seasons of the year (Cordeiro et al., 2020), 63 64 among others. Sarto et al. (2020) demonstrated that incorporating Eucalyptus into a tropical ICLF system 65 decreased the root length density of palisade grass (pasture plants) near the trees, while root growth 66 increased within the soil profile with further distances from the tree line. Although the authors did not examine root decomposition or turnover, investigating these dynamics contributes to understanding C 67 68 dynamics in these systems. Unfortunately, the fine-root residence time in soil, and hence its contribution to C addition, is globally among the least understood aspects of the ecosystem's cycles and functions (Strand 69 70 et al., 2008). Roots typically contain more lignified cells than upper plant parts (Redin et al., 2014), which 71 slows down the decomposition and could be strategic for soil C accrual (Camiré et al., 1991). Therefore,

knowing the root turnover rate *in situ* and the amount of added necromass is crucial for understanding the
role of resource cycling in such systems (Cordeiro et al., 2020; Silver and Miya, 2001).

74 The root decomposition is intimately associated with the surrounding soil conditions, while the 75 root turnover (renewal of the root system) is strongly controlled by soil moisture and temperature (Cordeiro 76 et al., 2020; Germon et al., 2016; Huaraca Huasco et al., 2021). Environmental conditions like higher daily 77 and seasonal soil moisture fluctuations (Anderson et al., 2003), intense soil microbial activity near the 78 surface litter deposition (Buscardo et al., 2018), and higher soil nutrient availability (Aragão et al., 2009; 79 Jourdan et al., 2008) favor turnover and decomposition of fine roots, in particular in shallow soil layers. On 80 the other hand, an increased root diameter class customarily reduces root mortality and slows down root 81 decay (Germon et al., 2016; Lambais et al., 2017; Sun et al., 2018). Constructing thicker roots is very costly 82 for plants in terms of energy and C, hence long-term organs typically constitute these roots and reduce the turnover rates (Eissenstat, 1992). For instance, Eucalyptus roots tend to remain in the soil longer than the 83 84 roots of herbaceous plants (Gill and Jackson, 2000), and competition factors between plant species (Beyer et al., 2013) and tree shading (Rajab et al., 2018) also influence root turnover differently for each integrated 85 86 species. Therefore, many drivers of root decomposition exist, and their status and combination determine 87 root cycling in agroecosystems. Nevertheless, neither the incorporation dynamics of dead root material nor the influence of environmental factors in root cycling in ICLF systems has been previously documented. 88

89 In this context, our study aimed to quantify the effects of an ICLF system on fine-root 90 decomposition along the Eucalyptus trees inter-rows, where corn and pasture were timely intercropped 91 during two years (3-to-5 years after implementation). We expected to find heterogeneous fine-root 92 production and decay rates along the inter-rows, reduced in closer distances to the Eucalyptus rows, since 93 the trees drive interspecific interactions and determine the microclimate in the system. To test our hypothesis under the ICLF system, we addressed the following questions: (i) Does the rate of root 94 95 decomposition change across different distances from Eucalyptus rows? (ii) How is the response of root 96 decay to the complementary changes in agricultural production succession and weather seasons? (iii) Can 97 Eucalyptus trees impair the amount of decomposed root organic matter from agricultural plants by impeding the growth of their roots in deeper soil layers? (iv) How does the environment under the integration of crop, 98 99 pasture, and trees drive the decomposition of roots from different plant species and diameter classes? 100 Answering those questions can be helpful in establishing future protocols for C assessment and modelling 101 parametrization in such complex and heterogeneous systems.

102

103 **2. Material and Methods**

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105 2.1. Study site and experimental design

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107 The experiment was installed in an area previously used for extensive low-grazing intensity 108 pasture at Embrapa Southeast Livestock (21°57′42″S, 47°50′28″W, 856 m asl), São Paulo state, Brazil. The 109 soil was classified as an Oxisol (Soil Survey Staff, 2014) with a sandy clay loam texture. Climate of the 110 region is characterized by dry winters and rainy summers, Cwa according to Köppen classification, with 111 20.6 °C of average annual temperature and 1545 mm of annual rainfall (Alvares et al., 2013).

112	The ICLF system was implemented in 2011 by planting 333 Eucalyptus (Eucalyptus urograndis)
113	trees ha-1 in single rows, spaced in 15 x 2 m at East-West orientation. Piatã palisade grass (Urochloa
114	brizantha) pasture and corn (Zea Mays L.) cultivation were used in successional rotation interspaced within
115	the tree rows. When the crop period of our study assessments started in November 2014, the Eucalyptus
116	trees had 42 months; at the last sampling (August 18th, 2016), they completed 63 months. In October 2014,
117	the Eucalyptus trees showed an average height and diameter at breast height of 19.0 m and 18.5 cm,
118	respectively, which increased to 27.0 m and 21.3 cm in April 2016 (Bieluczyk et al., 2020). The timeline
119	with respective management and minirhizotron positions in the different assessed interrow distances is
120	detailed in Figure 1.

- 121 122
- Figure 1
- 123

In our study, we assessed three different distances (at 1.9, 4.3, and 7.5 m) along the interrow space of *Eucalyptus* trees by using five replicates with repeated measures in time. Each experimental unit (replicate) had an area of 0.5 ha and consisted of a paddock surrounded by an electric fence, which also provided access to supplemental feedings for the cattle (Bieluczyk et al., 2021). Two distinct cycles were studied: (i) a crop period, when corn was interspaced with palisade grass, and (ii) a pasture season, when the palisade grass was formed and grazed by the cattle.

- The soil of the ICLF distances in November 2014 was slightly acidic, with pH ranging from 4.9 to 5.6 (decreased with depth), with a relatively high soil bases saturation in the surface layer (0-20 cm), ranging from 63 to 80%. The available P concentration at 0-20 cm depth was low (< 6 mg kg⁻¹), and we did not find aluminium toxicity. All soil samples showed a sandy clay loam texture. More detailed information about the main physical and chemical soil properties is given in Table S1.
- 135

136 2.2. Management of the areas

137

The palisade grass was desiccated using glyphosate (4.0 L ha⁻¹) in October 2014 for crop cultivation. In November 2014, corn was sown in 0.8 x 0.2 m spacing, simultaneously to palisade grass in 0.4 m rows spacing. The NPK fertilizer 08-28-16 formula (N-P₂O₅-K₂O) was applied at the rate of 500 kg ha⁻¹ in soil corn rows, and 500 kg ha⁻¹ of 20-05-20 formula (N-P₂O₅-K₂O) was applied as topdressing at 30 days after corn seed germination. On March 25th, the corn plants were cut for silage while palisade grass plants remained in the field, forming the pasture for grazing, which started on May 11th, 2015.

The pasture was grazed by 200 kg young bovine males of Canchim breed (3/8 Nellore + 5/8 Charolais). In the rainy season, the cattle stocking was 2 to 3 AU ha⁻¹, and in the dry season, 1.5 AU ha⁻¹. The grazing cattle rotation in the paddocks consisted of grazing for six days, followed by 30 days of pasture rest. During the rainy season, 40.4 kg ha⁻¹ of N were top-dressed on pastures in each resting period. Further information on the management of the areas can be found in Bieluczyk et al. (2020).

149

150 2.3. Minirhizotron assessments

152 The minirhizotron technique captures repetitive in situ belowground images over time (Johnson et 153 al., 2001; Rahman et al., 2020), and the method is considered a reliable approach to characterizing 154 individual roots morphology, growth, and lifespan (Bieluczyk et al., 2021; Lambais et al., 2017). To 155 accurately use the technique, we installed fifteen acrylic tubes in June 2014, five months before the 156 evaluations, to promote soil stabilization on their surface (Johnson et al., 2001). We did not install tubes in 157 the first external inter-row of the paddock and maintained a minimum distance of 30 m from transversal 158 fences and supplemental feedings to avoid edge effects (Bieluczyk et al., 2021). The acrylic tubes of 1.2 m 159 in length and 6.35 cm internal diameter were introduced into the soil at 45° to the vertical to avoid preferential growth of roots. These tubes were strategically placed in transects at 1.9, 4.3, and 7.5 m from 160 the rows of Eucalyptus trees to represent the inter-row space (Figure 1) as to permit seeding in no-till soil 161 management on 17th November 2014 as described in detail by Bieluczyk et al. (2020). The tube centre was 162 located precisely under the corn row, leaving one side of 35 cm to monitor the superficial palisade grass 163 164 root system and the other 35 cm side to assess deeper soil layers (see Figure 1).

The bottom end of the acrylic tubes was sealed to avoid the ingress of soil water. We protected the exposed part of the transparent tubes above the soil surface with a white PVC tube and a removable cap to avoid light and water infiltration and prevent heating. The surface exposed tube area was protected with a metal grid, avoiding damage by animal trampling and allowing grazing and insertion of the scanner. Photos of the tube installation procedure are available in Figure S1 in the supplementary material.

Images of 300 dpi obtained with a minirhizotron scanner system (CI-600 Root Scanner, CID Inc., Camas, WA, USA) and covered a 345° segment of the tube-soil interface, consisting of an effective soil area of 422 cm². We sampled the sites fortnightly in the crop period, and once a month after May 2015, under pasture grazing, totalling 2400 minirhizotron images. The scanner was hand-pushed into each tube to scan the 0-20, 20-40, 40-60, 60-80, and 80-100 cm lengths along diagonally (45° vertical angle) inserted tubes. The vertical depths corresponded to 0-14, 14-28, 28-42, 42-56, and 56-70 cm soil layers.

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177 2.4. Root image processing

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179 We captured the minirhizotron images in 2D JPEG format, which sequentially were processed 180 using the WinRHIZO TRON MF 2013c (Regent Instruments Inc., Quebec, Canada) software. Individual 181 root length and diameter were hand-traced, and images were superimposed to identify the root phenotype 182 changes over time. We considered only fine roots (≤ 2 mm), grouped them into three diameter classes (< 0.5, 0.5 to 1.0, and 1.0 to 2.0 mm), and separated them into three species groups: (i) group of grasses 183 184 consisting in palisade grass and corn roots, which did not acquire shades of brown with root aging (Bieluczyk et al., 2021); (ii) Eucalyptus root length with mycorrhizal colonisation, when dichotomous 185 186 structures and/or a fungal mantle was present (Guo et al., 2008; Lambais et al., 2017) and, (iii) non-187 mycorrhizal Eucalyptus root length, which acquired shades of brown with root aging (Bieluczyk et al., 188 2021).

190 2.5. Root production and decomposition

191 The root length production (RLP) and root length decomposition (RLD) between the two successive scanning times at t_{-1} and t (*RLP*_{t-1,t} or *RLD*_{t-1,t}, cm m⁻²) were calculated by adding and losing 192 193 length, respectively, of each tracked root between t_1 and t, divided by the observed soil area of each image. The daily root production (DRP_{t-1,t}, cm m⁻² d⁻¹) and the daily root decomposition (DRD_{t-1,t}, cm m⁻² d⁻¹) rates 194 195 were obtained by dividing RLP and RLD, respectively, by the number of days between successive scans. 196 After each field sampling, cumulative root production (CRP, m m⁻²) was calculated by summing up RLP 197 (converted to m m⁻²). Similarly, to calculate the cumulative root decomposition (CRD, m m⁻²), we summed 198 up RLD after each field sampling. Therefore, in our study, we discuss length measurements rather than root 199 mass when we refer to root production or decomposition.

200

201 2.6. Root longevity

202 Root individual longevity was calculated as the days between the root's first appearance and the 203 complete decomposition (disappearance). Roots were only considered decomposed when they disappeared 204 to avoid distinguishing subjectivity (Satomura et al., 2007). We considered all roots individually; roots 205 declared decomposed as uncensored and standing roots (live + dead) as censored. With this analytical 206 approach, root longevity was estimated and predicted with the Cox's proportional hazards regression, 207 investigating the influence of (i) the ICLF inter-rows distances, analyzing roots of grasses and *Eucalyptus*; 208 (ii) the classes of diameter, sectioning into 0.0-0.5, 0.5-1.0 and 1.0-2.0 mm; and (iii) groups of roots, 209 comparing those of the grasses to the non-mycorrhizal and mycorrhizal *Eucalyptus* roots.

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211

2.7. Photosynthetically active radiation, soil water availability, and soil temperature

212 Soil water availability, soil temperature, and photosynthetically active radiation (PAR) were used 213 as environmental factors influencing root decomposition dynamics. First, soil moisture (volumetric soil water content, m³ m⁻³) was measured from 0 to 70 cm depth using a capacitance probe (Sentek, model 214 215 Diviner 2000[®]) at one position near each minirhizotron tube (15 tubes). Next, the soil water holding 216 capacity was calculated by the difference between field capacity, considered the highest measured soil 217 moisture (excluding excessively high values obtained after intense rainfalls), and permanent wilting point, admitted as the lowest soil moisture during the dry seasons. Then, soil water availability was calculated by 218 219 the difference between actual soil moisture and permanent wilting point. Several studies recently used this 220 methodology (Pezzopane et al., 2015; Bosi et al., 2020a, b, 2022).

Photosynthetically active radiation (PAR) was measured continuously with linear quantum sensors
 CQ311 (Apogee, Logan, Utah, USA) at each assessed position. In addition, soil temperature was measured
 by thermometers inserted five centimetres into the soil. The PAR and soil temperature sensors were
 connected to data loggers CR1000 (Campbell Scientific, Logan, Utah, USA), recording averages every 60
 minutes.

227 *2.8. Statistics*

228

229 We analysed the ICLF effects at 1.9, 4.3, and 7.5 m Eucalyptus inter-row positions on root 230 decomposition dynamics by investigating the distribution of the decomposed roots along the soil profile 231 down to a depth of 70 cm. Data of the assessed parameters were statistically analysed considering a 232 completely randomized experiment design, with five replications and repeated measures in time. ANOVA was performed by the General Linear Model procedure (PROC GLM) to test the influence of the distances 233 234 on daily root decomposition for the rainy crop season as for pasture dry-2015, rainy 2015/2016, and dry-235 2016 successional seasons over time. When the treatment effect was significant, the Tukey test compared 236 the means (p < 0.05). All the above statistical analyses were performed using the Statistical Analysis System – SAS v. 9.4 (SAS Inc., Cary, USA). 237

To verify the correlation between root decomposition for different diameter classes (0.0-0.5, 0.5-238 239 1.0, and 1.0-2.0 mm) with environmental factors (i.e., soil temperature, soil moisture, and photosynthetically active radiation), we performed a principal component analysis (PCA) using the R 240 241 software version 3.5.2 (RStudio Team, 2018). For PCA, we only considered data after the corn harvest 242 (April 8th, 2015, to August 18th, 2016), after high-intensity root mortality, subsequently dependent on soil abiotic conditions (e.g., moisture and temperature) for decomposition. Contour plots were elaborated to 243 244 represent the cumulative root decomposition along the soil profile and through time in the areas. The data 245 were interpolated by the kriging method (Oliver and Webster, 1990) using the statistical program Surfer 246 v.10 (10.0® (Golden Software Inc.).

247 The non-parametric Kaplan-Meier method was used to estimate the median root longevity. This 248 methodology was widely used in literature to estimate human time survival probability (Goel et al., 2010), 249 and recent studies estimate median root lifespan and survival probability (Germon et al., 2016; Lambais et al., 2017; Majdi et al., 2001; Tierney and Fahey, 2001). Kaplan-Meier survival analyses were used to 250 251 estimate the fine-root longevity statistics as a function of ICLF distances, diameter classes, and specific 252 root groups. The semi-parametric Cox Proportional Hazard Model (Cox, 1972) was used to identify 253 whether ICLF distances, diameter classes, and particular groups of roots significantly affected the fine root 254 longevity period in the soil. We used a "Survival" package in R (Therneau, 2014), and all calculations and these analyses were performed using the R with a significance level of 5%. 255

256

3. Results

258

259 *3.1. Daily root decomposition, available soil water, and soil temperature*

During the crop period, daily root decomposition rates were much lower (Figure 2) since corn and 260 261 palisade grass plants had a few months to develop their belowground system. Harvesting corn at the end of the crop period (March 25th, 2015) induced intensive root mortality and an increase in root necromass. From 262 263 that moment, numerous dead roots were available to be decomposed by soil microorganisms, 264 complementarily influenced by seasonality (variations in available soil water and soil temperature) (Figures 2 and 3). During the annual crop cultivation, from November 17th, 2014, to March 25th, 2015, little root 265 decomposition was observed, with a maximum of 8.0 cm m⁻² d⁻¹ (Figure 2A; Table S2). Root decomposition 266 267 rates were higher in further distances from the tree lines, reaching on average 2.0, 2.7, and 4.8 cm m⁻² d⁻¹ 268 at 1.9, 4.3, and 7.5 m from the tree row, respectively (Table 1). The highest peaks of root decomposition

occurred during the pasture-rainy season, mainly from January 07th to March 14th, 2016 (Figure 2A; Table 269 270 S3), when soil temperatures (Figure 2A) and available water (Figure 2B) also increased. This season's average root decomposition rate was 14.4, 33.0, and 24.4 cm m⁻² d⁻¹ for ICLF 1.9, 4.3, and 7.5 m distances, 271 272 respectively (Table 1). 273 274 Figure 2 275 276 Table 1 277 278 During the pasture period and in dry and rainy seasons, overall root decomposition close to the 279 tree rows (*i.e.*, 1.9 m) was lower than the further distances (Table 1). Soil available water was also less available nearer to the trees, showing an inter-row gradient (1.9 < 4.3 < 7.5 m), especially in the dry season 280 281 of 2015, while in rainy seasons, the values were mainly similar (Figure 2B). During the pasture-dry season of 2015, the available soil water contents were reduced by 25% and 30% at 4.3 and 1.9 m, respectively, 282 compared to the 7.5 m distance. During the pasture-rainy season (2015/2016), these differences dropped to 283 284 14 and 10%, respectively (Figure 2B). The highest root decomposition rates occurred at 4.3 and 7.5 m Eucalyptus inter-row distances, 285 286 and the lowest was recorded at 1.9 m distance (Figure 2A; Table 1). This pattern was also evident in the 287 principal component analysis (PCA), where 1.9 m results were more distant (negatively correlated) from 288 the decomposed roots of different root diameter classes (Figure 3A). The decomposition of thinner roots (i.e., 0.0-0.5 mm) was more intensively impacted by abiotic environmental factors such as soil moisture 289 and temperature (Figure 3B). For example, daily root decomposition of 0-0.5 mm diameter class (DRLD 290 0-0.5 mm) was positively correlated with the available soil water (r = 0.58), average soil temperature (r = 0.58) 291 292 0.53), and photosynthetically active radiation (PAR) (r = 0.58). The decomposition rates for different 293 diameter classes of roots were positively intercorrelated (r > 0.6), meaning that they tended to show similar 294 dynamics over time, although probably on different scales. 295 296 Figure 3 297 298 3.2. Cumulative root production, decomposition, and decomposed proportion 299 Cumulative root production was lower at 1.9 m from the trees compared to 4.3 and 7.5 m. In addition, similar root production was observed at 4.3 m and in the middle of the inter-row (i.e., 7.5 m) 300 301 (Figure 4A). Furthermore, the relative decomposition [(decomposed \div produced) \times 100)] was higher at these distances compared to the 1.9 m position (Figure 4C). By the end of the trial, the proportion of overall 302 303 decomposed roots had decreased from approximately 48% at 4.3 and 7.5 m to 36% at a distance of 1.9 m 304 from the tree row (Figure 4C). The total amount of decomposed roots added to the soil at the end of the trial was 101 m m⁻² for 7.5 and 4.3 m inter-row positions, which was almost twice as high as the total 305 recorded at 1.9 m (Figure 4B). 306

307 308

Figure 4

310	At the beginning of the trials, Eucalyptus roots (mycorrhizal plus non-mycorrhizal) accounted for
311	a substantial proportion of total root mass (Figure 5). Initially, after sowing the annual crops, Eucalyptus
312	roots proportion ranged between 41 and 65% of total root mass depending on the distance from rows
313	(Figures 5A, 5B, and 5C). However, this percentage abruptly decreased after January 2015, when grasses
314	began growing higher quantities of roots. Eucalyptus roots proportion continued to decrease gradually until
315	the end of the trials, reaching 13.0%, 10.6%, and 11.5% at distances of 1.9, 4.3, and 7.5 m, respectively.
316	By the end of our assessment cycles, grasses produced 6.5, 8.6 and 7.7-fold more roots than Eucalyptus at
317	these respective distances. At the same time, the decomposed grass roots were 4.3 times higher than those
318	of <i>Eucalyptus</i> at a distance of 1.9 m from the rows, and 4.6 times higher at distances of 4.3 and 7.5 m.

319320

309

- Figure 5
- 321

Mycorrhizal associations increased during the crop period and stabilized during grazing, 322 323 accounting for approximately 30% of total Eucalyptus roots at distances of 1.9 and 7.5 m (Figure 6A and 6C), but with a higher association of about 50% at the intermediate distance of 4.3 m (Figure 6B). 324 325 Furthermore, by the end of the trial, the cumulative production of Eucalyptus-mycorrhizal roots was higher 326 at 4.3 m (11.5 m m⁻²), followed by 7.5 m (7.4 m m⁻²) and 1.9 m (5.7 m m⁻²) distances. However, very low 327 rates of mycorrhizal associations appeared after January 2016. Since mycorrhizas had a small diameter (see 328 section 3.4) and low longevity (see section 3.5) most of these roots had decomposed by the end of the 329 experiment, representing 63, 91, and 73% of the root produced at 4.3, 1.9 and 7.5 m being already 330 decomposed.

331332

Figure 6

333

334 *3.3. Root decomposition in the soil profile over time*

Figure 7 shows the variation in cumulative root decomposition over the experiment. Values higher 335 than 10 m m⁻² firstly appeared in the topsoil layers (0-14 and 14-28 cm) and earlier at 7.5 m ICLF inter-336 row position, followed by 4.3 m and 1.9 m. Cumulative root decomposition decreased with soil depth in all 337 338 locations. During the rainy season, the accumulation of decomposed root material was faster, as evidenced 339 by the proximity of the changing colors on the graph. However, some differences between distances to the tree rows can be noted: (i) in the 0-28 cm soil layer, fine root decomposition reached 80 m m^{-2} at a distance 340 of 1.9 m (Figure 7A), while the accumulated amount was much higher at the other distances, reaching 120 341 342 (Figure 7B) and 130 m m^{-2} (Figure 7C) at 4.3 and 7.5 m, respectively; (ii) in soil layers deeper than 42 cm, the accumulated values at the end of the trials were lower than 30 m m⁻² at 1.9 m Eucalyptus inter-row 343 distance and ranged from 60 to 90, and 30 to 90 m m⁻² at 4.3 and 7.5 m, respectively; and, (iii) increasing 344 345 distance from Eucalyptus trees resulted in greater soil profile heterogeneity in cumulative root decomposition, with higher root decomposition in the topsoil. 346

347 348

Figure 7

349							
350	3.4. Root diameter proportion						
351	Grass roots (palisade grass + corn) were mainly extremely fine roots (i.e., diameter < 0.5 mm).						
352	More than 60% of grasses fine root length (0.0-2.0 mm) were finest roots with a root diameter between 0.0						
353	and 0.5 mm (Figure 8A). No more than 10% of grasses' fine roots length (< 2 mm) was thicker than 1.0						
354	mm. On the other hand, <i>Eucalyptus</i> roots without mycorrhizal colonization were distributed differently						
355	across diameter classes. Roughly 30 to 40% of these <i>Eucalyptus</i> roots were thinner than 0.5 mm, 40 to 50%						
356	had a diameter between 0.5 and 1.0 mm, and 20 to 30% were thicker than 1.0 mm (Figure 8D). Only very						
357	few <i>Eucalyptus</i> fine roots developed associations with visible ectomycorrhizas in minirhizotron images.						
358	More than 96% of the roots with mycorrhizal colonization were thinner than 0.5 mm, while the remaining						
359	length was in the 0.5-1.0 diameter class.						
360							
361	Figure 8						
362							
363	3.5. Parameters influencing root turnover						
364	There was an evident gradient in the inter-row space of ICLF for both Eucalyptus roots (Figure						
365	9A) and grass roots (Figure 9C), with roots being decomposed faster at further distances from the trees and						
366	remaining in the soil for a shorter period of time (Table 2). The number of decomposed fine roots of grasses						
367	and Eucalyptus increased by 13 and 18%, respectively, from the 1.9 to 7.5 m ICLF position (Table 2).						
368	Furthermore, increasing the distance from the tree row from 1.9 to 7.5 m reduced the longevity of grass and						
369	Eucalyptus roots by 88 and 152 days, respectively. The longevity of the fine roots of Eucalyptus (Figure						
370	9B) and grass (Figure 9D) was prolonged, and the turnover rate was reduced with increasing root diameter						
371	(Table 2). As an example of this pattern, Eucalyptus roots with a diameter between 1.0-2.0 mm resided on						
372	average for 569 days in soil, while roots thinner than 0.5 mm remained only for 308 days. When groups of						
373	roots were compared (Figure 9E), non-mycorrhizal Eucalyptus roots stood on average ten days longer than						
374	grass roots and 44 days longer than mycorrhizal Eucalyptus roots (Table 2). However, we must consider						
375	that most of the mycorrhizal roots had a diameter range of 0-0.5 mm, which favored their faster						
376	decomposition.						
377							
378	Figure 9						
379							
380	Table 2						
381							
382							
383	4. Discussion						
384							
385	Our minirhizotron assessments made it possible to understand the complexed impact of many field						
386	management events, integration of different plants, cattle grazing, and weather on the root decomposition						
387	dynamics in situ. The primary strength of the technique is that it is non-destructive, maintaining the same						
388	field position during time assessments and simultaneously permitting separate root production and						

decomposition. Therefore, our discussion approaches spatiotemporal effects on fine-root decomposition
 dynamics under a complex integrated crop-livestock-forestry (ICLF) system.

391

392 4.1. Eucalyptus inter-row space

393 Overall, root growth in this ICLF system decreased with decreasing distances from the Eucalyptus 394 rows, for example, it was decreased by 30% at 1.9 m distance compared to the middle of the inter-row 395 space (i.e., 7.5 m). Meanwhile, the difference between these distances for cumulative root decomposition 396 was approximately 50%. Bieluczyk et al. (2021) previously demonstrated that Eucalyptus trees mostly 397 dominated the system's interactions and limited the overall root growth, mainly during the crop period, 398 when corn was intercropped with palisade grass. Furthermore, because the root production was lower near 399 the trees, a lower amount of decomposed roots allocated to the soil was expected in our study. However, 400 this study shows that root turnover was higher and roots decayed faster at 7.5 m from the row compared to 401 1.9 m, thus increasing inter-row heterogeneity in incorporating root necromass and root-originated C into 402 the soil.

403 Our results showed that root decomposition was positively influenced by PAR (r = 0.60), which 404 likely increased the soil temperature (r = 0.83), probably leading to a shorter root longevity (Eissenstat and 405 Yanai, 1997) and promoting root respiration and decomposition (Chen et al., 2000). However, Figure 2A 406 shows a unimodal curve in soil temperature for the three ICLF locations (*i.e.*, 1.9, 4.3 and 7.5 m), with 407 similar values and variations throughout the year, indicating no differences between distances. This 408 suggests that the permanent soil organic cover, one of the three principles of conservation agriculture (FAO, 409 2022), is effectively functioning in the entire ICLF understory space, and soil temperature was not a crucial 410 factor influencing root turnover rates between Eucalyptus tree rows.

411 The longevity of grass and *Eucalyptus* roots decreased by 88 and 152 days, respectively, when grown 412 at a distance of 1.9 m compared to 7.5 m from the tree row. Previous literature suggests that tree root 413 longevity is shorter as the lateral roots become more distal (e.g., Sun et al., 2016, 2018). This explains why 414 Eucalyptus roots decomposed faster at further distances from the trunks, where their lateral roots are more 415 distal. Moreover, the intermediate positions between tree rows (i.e., 4.3 and 7.5 m) showed higher soil water 416 availability and more intense soil moisture fluctuations over time. The lower water availability in closer 417 positions to Eucalypts was probably due to rainwater interception by the tree canopies, as previously 418 reported by Bosi et al. (2020b), thus directing a substantial part of the rainwater to tree trunks and reducing 419 rainfall at 1.9 m from the trees. We found positive correlations between root decomposition and available 420 soil water (r = 0.58), as previously reported by studies such as Germon et al. (2016) and Cordeiro et al. 421 (2020). Therefore, eighter higher soil moisture or more intense drying and wetting cycles (known as the 422 "Birch effect" - Jarvis et al., 2007) could have accelerated root mortality, decomposition, and turnover at 423 4.3 and 7.5 m ICLF distances for all plant species (i.e., corn, palisade grass, and Eucalyptus).

424 Our data demonstrates that 1.9 m from the trees was a competitive interface zone compared to the other 425 two distances, with lower PAR and water availability. Additionally, near the tree, the root longevity 426 increased, and the decomposition slowed down. Root renewal may not be a good strategy for pasture plants 427 in a competitive environment due to the energy cost of growing new roots (See et al., 2019). As a result, 428 palisade grass may have developed physiological mechanisms to keep its roots alive during pasture

429 cultivation, directing its energy to photosynthesis and adaption to competitive restrictions under the trees. 430 Unlike the effects of competition, grazing has been shown to increase both root productivity, biomass, 431 mortality, and turnover compared to excluded areas (Pucheta et al., 2004; López-Mársico et al., 2015; 432 Fedrigo et al., 2022), therefore, plants frequently renew their root systems in response to grazing (Silva et 433 al., 2014). In our ICLF system, grazing effects on root renewal were more intensive at 4.3 and 7.5 m of the 434 inter-row space due to the higher shoot biomass production, as demonstrated by Pezzopane et al. (2019), 435 who assessed the same area and period as our study. The study also showed that pasture dry mass at these 436 distances did not differ from the full sun integrated system (ICL), indicating that trees did not impede shoot 437 growth of pasture plants. Additionally, an assessment by Bieluczyk et al. (2021) reported synergistic effects 438 between pasture and *Eucalyptus* trees at 4.3 and 7.5 m, resulting in increased root growth compared to ICL.

439

440 *4.2. Seasonality and vegetation change*

441 Root growth and decomposition occurred simultaneously over time, but at different rates and 442 patterns. Cutting corn plants for silage on March 25th, 2015, was a crucial factor inducing root mortality. 443 Since palisade grass shoot growth was sharply restrained when intercropped with corn in the whole ICLF 444 system space (Bieluczyk et al., 2021), the majority of roots produced at the end the crop cycle were from 445 corn plants. This led to a substantial quantity of dead corn roots to be decomposed in the coming seasons. 446 However, after the sequent dry season, less than 30% of roots produced had been decomposed. During the 447 following rainy season, decomposition rates increased significantly, reaching over 40% at 4.3 and 7.5 m 448 from the rows. On the contrary, in the last dry season, decomposition rates decreased and relative 449 decomposition stabilized. Therefore, root decomposition depended not only on the standing roots stock 450 (living plus dead roots) but also responded to the variation of soil environmental conditions across different 451 seasons. Root decay typically increases when both temperature and available soil water increase (Cusack et al., 2009; Silver and Miya, 2001), which was the environmental condition oberved during the rainy 452 season of 2015/16 in our study. 453

454 Our findings showed that soil available water and temperature positively correlated with root 455 decomposition, especially of the finest root diameter class (0-0.5mm). Combined higher temperatures and 456 more available soil water can potentially increase the abundance of soil microbial decomposers, increasing 457 the respiration and decay of fine root biomass in tropical soils (Buscardo et al., 2018; Chen et al., 2000; 458 Cordeiro et al., 2020). These microorganisms break and depolymerize larger soil organic molecules, 459 transforming them into low molecular weight components to later assimilate their carbon and nutrients 460 (Conant et al., 2011). On the other hand, when soil temperature and moisture decline over long periods 461 (e.g., months), the fine-root residence time is prolonged since respiration, decomposition, mineralization, 462 and nitrification rates are decreased (Huaraca Huasco et al., 2021).

463

464 *4.3. Soil profile*

In our two-year trial, cumulative root production and decomposition followed a top-to-bottom soil
profile intensity, declining root incorporation with soil depth. Similar effects have been previously shown
for different natural and agroecosystems (Cordeiro et al., 2020; Germon et al., 2016; Lambais et al., 2017).
Unfortunately, soil layers deeper than 30 cm were not considered in most root assessments in the literature

(Maeght et al., 2013; Cordeiro et al., 2020). These studies may be losing essential information on root 469 470 dynamics. For example, we found out that more than 50% of the decomposed allocated roots in soil layers 471 deeper than 30 cm. In our case, corn and palisade grass developed deep roots. As a result, they are playing an essential role in C and nutrient cycling (Baptistella et al., 2020), helping the performance of multiple 472 soil functions (Bieluczyk et al., 2020), even in deeper soil layers (i.e., > 30 cm). Moreover, higher quantity 473 474 of decomposed root material was added throughout the soil profile in intermediary Eucalyptus inter-row 475 positions (i.e., at 4.3 and 7.5 m). We comprehend that more addition of root-derived organic matter, 476 combined with its faster cycling in these inter-row positions, provided more organic substrate to the soil's 477 organisms' food web in the entire soil profile, which has been previously proven to benefit the soil C accrual 478 (Müller-Stöver et al., 2012; See et al., 2019)

479 Even though roots grew deep into the soil, the most intense decomposition dynamic was in 0-14 and 14-28 cm topsoil layers. Soil moisture and temperature typically show more significant fluctuations in 480 481 the topsoil. These changes are buffered with depth, decreasing the influence on fine root turnover rates and 482 decomposition (Germon et al., 2016). Furthermore, superficial soil layers (e.g., 0-20 cm) contain more soil 483 organic matter and nutrients, thus more abundantly supplying microorganisms' proliferation and leading to 484 higher decomposition ability rates (Cordeiro et al., 2020). We also believe that after each grazing event, 485 palisade grass renewed part of its roots combined with their shoot regrowth (Baptistella et al., 2020; 486 Bieluczyk et al., 2020, 2021), prioritizing the replacement of more proximal/shallow low-diameter roots. 487 This is because the deep distal root mortality would not be energy-favorable, representing a greater cost in 488 carbon for the plants (Sun et al., 2018).

489

490 *4.4. Plant species and root traits*

491 The root decay was dependent on their diameter class (0-0.5, 0.5-1.0, and 1.0-2.0 mm) and 492 phenotypical group (grasses [corn + palisade grass], Eucalyptus non-mycorrhizal and Eucalyptus mycorrhizal). Thinner roots in both grass species and Eucalyptus groups decayed faster. For example, 1.0-493 494 2.0 mm grass and Eucalyptus roots resided for 243 and 261 more days, respectively, compared to finest 495 roots (diameter < 0.5 mm) (Table 2). Furthermore, 71% of the thinnest diameter class of *Eucalyptus* roots 496 and 72% of more lateral-distal Eucalyptus roots (7.5m position) disappeared entirely after two years. 497 Therefore, besides root diameter influence, it seems that *Eucalyptus* trees have changed root growth strategy 498 with aging to avoid competition (see Figures 5 and 6). Trees could have replaced perturbed roots under a 499 very intensive agriculture management by growing deep vertical rooting (e.g., meters deep) where water 500 typically can be more available during droughts (Germon et al., 2020; Laclau et al., 2013; Lambais et al., 501 2017). Moreover, root diameter is a conservative, often-studied root trait. The literature has widely shown 502 that the finer the root of a given plant species, the greater the nutrient uptake capacity, respiration rate, and 503 nitrogen concentration, and the lower the nutrient transport capacity, longevity, and tissue densities (Iversen 504 et al., 2017; McCormack et al., 2015). Furthermore, like our results, smaller average root diameter classes 505 have been globally proven to show fast root turnover and higher decomposition rates (Freschet et al., 2017; Germon et al., 2016; Lambais et al., 2017; McCormack et al., 2015; See et al., 2019; Sun et al., 2016). 506

507Positive mycorrhizal status was present exclusively in very fine diameters of *Eucalyptus* roots, as50896% of their length was thinner than 0.5 mm. If we compare the three group categories considering all

509 roots, the mycorrhizal roots decomposed at least 34 days faster than the other groups. However, when we 510 consider that almost all mycorrhizal roots had a diameter smaller than 0.5 mm, 307 days root standing time 511 was similar to the 308 days for 0-0.5 mm Eucalyptus non-mycorrhizal roots, thus showing no influence of 512 the fungal colonization on root turnover. Previous studies have shown that mycorrhizal colonization 513 prolonged the longevity of roots from forest tree plantations, thus reducing fine root turnover (Guo et al., 514 2008; King et al., 2002; Lambais et al., 2017). This is probably due to the symbiosis which increases plant 515 water and nutrient absorption capacity and consequently, enhances plant tolerance to drought and poor soil 516 nutrient availability (Lambais et al., 2017; Wu and Xia, 2006). However, we believe that this was not the 517 case for our ICLF system. Intensified crop and livestock frequent field management and soil fertilization 518 reflected lower fungal colonization occurrence than pure forest Eucalyptus plantation (Lambais et al., 2017; 519 Bieluczyk et al., 2021), and the ectomycorrhizal abundance probably was insufficient and unstable to 520 prolong the longevity of *Eucalyptus* fungal associated roots.

521 We expected to find a much-prolonged longevity for *Eucalyptus* roots compared to agricultural 522 plant roots due to their higher lignin and C:N levels. Instead, we only found a slight difference of ten days 523 longer longevity. Unexpectedly, grass roots with the thinnest diameter showed longer longevity than nonmycorrhizal Eucalyptus roots with the same diameter class. Therefore, the results did not reveal a clear 524 525 pattern of root longevity among the sectioned phenotypic groups. Instead, under the ICLF envinronment, 526 root diameter classes had a greater influence on root longevity than the plant species. However, as our 527 investigation mainly had an agronomic perspective, we assessed only the 0-70 cm soil layer, where 528 agricultural plants typically develop most root growth and decomposition. Therefore, we encourage future 529 studies to evaluate the role of Eucalyptus in developing very deep roots when integrated into crops and pastures, such as in ICLF systems. 530

531

532 **5. Conclusions**

533 Our study found that integrating 3–5-year-old Eucalyptus trees into crops and pasture reduced root 534 production by 30% near their rows (*i.e.*, at 1.9 m) compared to the middle of inter-row (*i.e.*, at 7.5 m), but 535 also increased root longevity by 3-5 months depending on plant species, leading to heterogeneous root 536 decomposition rates between tree inter-row space.

537 Crop rotation caused root mortality, and decomposition was related to increased soil moisture and 538 temperature during the subsequent rainy season. Root diameter was the most significant root trait 539 influencing decay rate, with thicker roots lasting in the soil for 243-261 days longer than finest roots. 540 Mycorrhizal associations peaked when *Eucalyptus* were three years old and disappeared gradually 541 afterward, but the symbiosis did not have any significant effect on root longevity.

542 *Eucalyptus* trees hindered crop and pasture root growth in deeper soil layers by reducing water 543 and light under their canopies, as well as overall root production and decomposition near their rows. But at 544 4.3 m or greater distance, crops and palisade grass roots grew deeper and were continuously renewed under 545 grazing. Moreover, our findings revealed that at 4.3 m from tree rows, root production, decomposition, and 546 abundance of deep rooting from crops and pasture increased compared to 1.9 m distance but remained 547 stable at further distances.

In short, our results demonstrated that root decomposition rate was heterogeneous within the integrated crop-livestock-forestry system space and time, and *Eucalyptus* rows had a negative impact on belowground plant development near their rows. We comprehend these variations in root dynamics and turnover affect soil carbon accrual and food webs. Therefore, further research is needed to investigate these issues spatially and temporally under the integrated crop-livestock-forestry system.

553

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Figure 1. Land use with the respective time of assessments and installation positions of acrylic minirhizotron tubes in the integrated crop-livestock-forestry system.

Figure 2. Daily root decomposition [DRD] and soil temperature (A) and available soil water (B) in the integrated croplivestock-forestry [ICLF] interrow positions. *1.9, 4.3, and 7.5 correspond to the distances from *Eucalyptus* rows. The shaded (blue) areas correspond to the rainy seasons.

Figure 3. Principal component analysis (A) and Spearman correlations (B) for daily root decomposition [DRD, cm m⁻²] in different fine-root diameter classes [0-0.5, 0.5-1.0, and 1.0-2.0 mm], available soil water [ASW, mm], average soil temperature [AvgSoilT, °C] and photosynthetically active radiation [PAR, MJ m⁻²] throughout time in 1.9, 4.3 and 7.5m distances from *Eucalyptus* rows in the integrated crop-livestock-forestry [ICLF] system in post corn harvesting assessments (April 8th, 2015, to August 18th, 2016).

Figure 4. Cumulative root production (A) and decomposition (B), and relative decomposition (C) in the integrated croplivestock-forestry [ICLF] interrow distances. *1.9, 4.3, and 7.5 correspond to the distances from *Eucalyptus* rows. The shaded (blue) areas correspond to the rainy seasons.

Figure 5. Relative cumulative root production [%] for the three different plant groups (left axis) and cumulative root production and decomposition $[m m^{-2}]$ of grasses and Eucalyptus roots (right axis) in an integrated crop-livestock-forestry system. *1.9, 4.3, and 7.5 correspond to the distances from *Eucalyptus* rows.

Figure 6. Relative cumulative root production [%] for the mycorrhizal and non-mycorrhizal *Eucalyptus* roots (left axis) and their cumulative root production and decomposition $[m m^{-2}]$ (right axis) in an integrated crop-livestock-forestry system. *1.9, 4.3, and 7.5 correspond to the distances from *Eucalyptus* rows.

Figure 7. Cumulative root decomposition along the soil profile in crop and pasture periods in 1.9 (A), 4.3 (B), and 7.5m (C) interrow positions in the integrated crop-livestock-forestry system.

Figure 8. Percentual distribution in 0.0-0.5, 0.5-1.0, and 1.0-2.0 mm diameter classes of cumulative roots [dead + alive] of all groups of roots (A), of grasses [corn + palisade grass], (B), of *Eucalyptus* with positive mycorrhizal status (C) and *Eucalyptus* with non-mycorrhizal status (D) in an integrated crop-livestock-forestry system.

Figure 9. Root longevity probability for non-mycorrhizal *Eucalyptus* roots in each interrow distance [1.9, 4.3, and 7.5m] (A) and diameter class [0-0.5, 0.5-1.0 and 1.0-2.0 mm] (B), for roots of grasses in interrow distances (C) and diameter class (D), and entirely for groups of roots [grasses, *Eucalyptus* non-mycorrhizal, and *Eucalyptus* mycorrhizal] (E) in an integrated crop-livestock-forestry [ICLF] system. Longevity probabilities were estimated using a proportional hazards regression. See Table 3 for detailed statistical results.

Table 1. Daily root length decomposition (cm $m^{-2} d^{-1}$) averages in sectioned periods of crop and pasture cultivations through different seasons in 1.9, 4.3, and 7.5m inter-row distances in an integrated crop-livestock-forestry (ICLF) system.

Cultivation	Season	ICLF 1.9m	ICLF 4.3m	ICLF 7.5m
Crop	Rainy	$2.0 \pm 0.8 \text{ Ab}$	2.7 ± 0.9 Ab	4.8 ± 1.6 Ac
Pasture	Dry	$3.2 \pm 0.4 \text{ Bb}$	10.1 ± 2.0 ABb	15.4 ± 4.0 Aab
	Rainy	$14.4\pm2.7~\mathrm{Ba}$	33.0 ± 6.6 Aa	$24.4\pm2.7~\mathrm{ABa}$
	Dry	12.4 ± 2.0 Aa	$13.6\pm2.9~Ab$	$15.1\pm1.5\;Aab$

Uppercase letters compare the three ICLF distances, and lower-case letters compare evaluation periods by Tukey's t-test $p \le 0.05$.



Table 2 – Median longevity (days), turnover rate (year⁻¹), loss (%), and the number of roots observed from grasses in the 0-70 soil layer over two years in an integrated crop-livestock-forestry (ICLF) system.

Diant astagomy	Class	Longevity	Turnover	Root loss	Roots observed
I faint Category	Class	(days)	$(year^{-1})$	(%)	(#)
	ICLF 1.9m [§]	395 A	0.92	34	14679
Grasses	ICLF 4.3m	349 B	1.04	42	24349
	ICLF 7.5m	307 C	1.19	47	19828
	ICLF 1.9m	421 A	0.87	54	944
Eucalyptus	ICLF 4.3m	364 B	0.99	68	874
	ICLF 7.5m	269 C	1.36	72	1165
	0.0-0.5 (mm)	332 C	1.10	42	50498
Grasses	0.5-1.0 (mm)	369 B	0.99	43	7598
	1.0-2.0 (mm)	575 A	0.63	20	760
	0.0-0.5 (mm)	308 C	1.18	71	2269
Eucalyptus	0.5-1.0 (mm)	455 B	0.80	53	582
	1.0-2.0 (mm)	569 A	0.64	40	132
	Grasses	341 B	1.07	42	58856
Groups	Eucalyptus NM	351 A	1.04	66	2983
_	Eucalyptus M	307 C	1.19	81	6592

[§]1.9, 4.3 e 7.5m correspond to the assessed positions in ICLF inter-row space. Uppercase letters the classes by Kaplan Meier test (p<0.05).

Minirhizotron tubes installation		Corn + palisade grass seeding		Corn harvest for silage		End o Experi	End of the Experiment	
Î	Stabiliza	tion Period	Crop Peri	od	Pasture P	eriod		
June 1	st 2014	Novembe	r 10 th 2014	March	25 th 2015	August	18 th 2016	Time
			1.5m				;	
	1.9m		1.9m		1.9m		0.7m	
	4.3m	→ 7.5m [×] ,	4.3m	7.5m ,	4.3m	7.5m		
	Legend:						space	





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Highlights

Fine-root dynamics were studied in the interspace of 15 m apart *Eucalyptus* rows. *Eucalyptus* reduced root growth of crops and pasture by 30% in 1.9 m from tree trunks. Roots of 1-2 mm in diameter remained 243 to 261 days longer than those with 0-0.5 mm. Further distances from tree rows doubled the incorporation of decomposed roots. Soil C accrual in ICLF should be investigated within such heterogeneous root dynamics.

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Declaration of interests

 \boxtimes The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

□The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

