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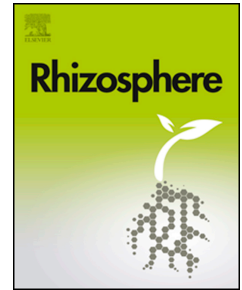
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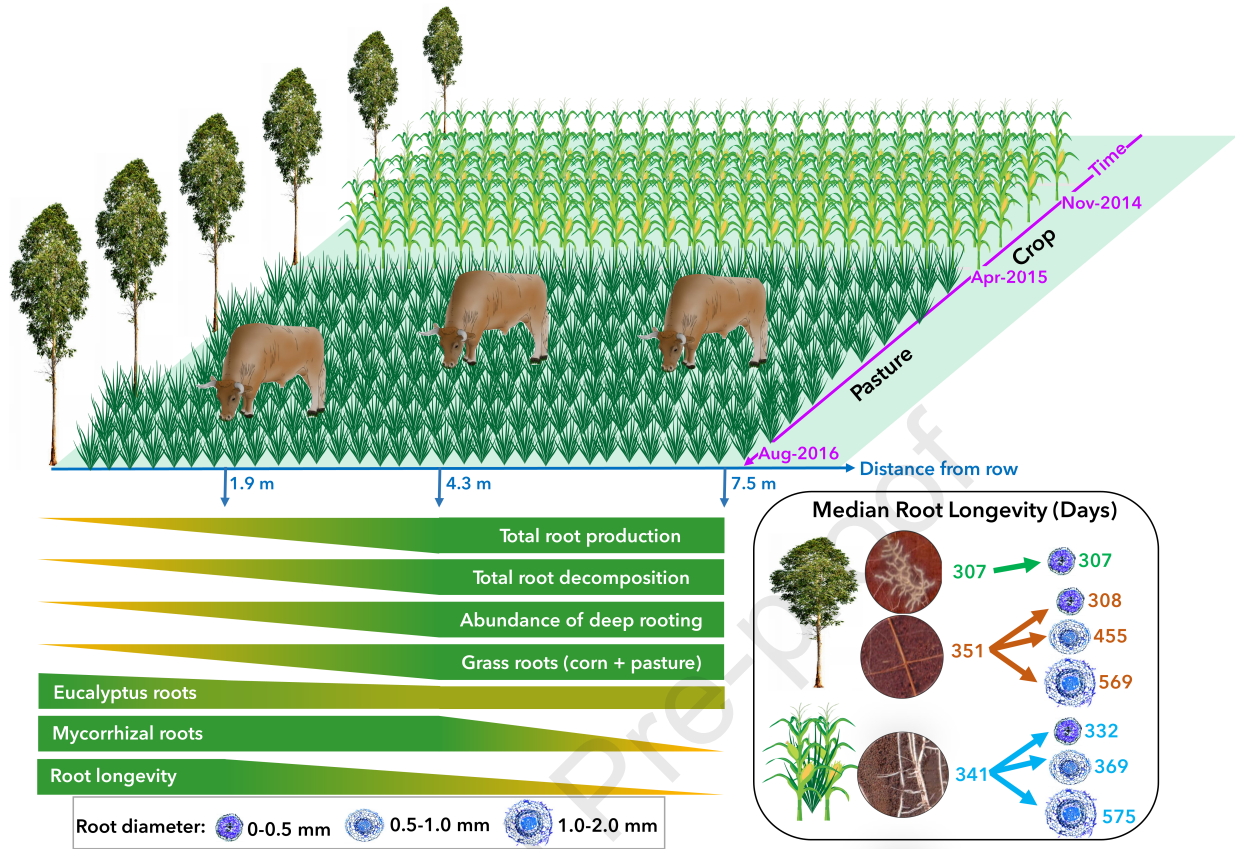
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Abstract

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

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
34 intensifying land production through a more sustainable form of agriculture combining various
35 agroecological principles (Bieluczyk et al., 2020; Bonaudo et al., 2014) and integrations planned to
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,
45 including solar radiation, water, and nutrients (Bieluczyk et al., 2021; Pezzopane et al., 2020a). Due to this
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;
48 Magalhães et al., 2019; Pezzopane et al., 2019). However, the temporal and spatial belowground
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 (≤ 2 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.,
63 2016), soil depth (Cordeiro et al., 2020; Lambais et al., 2017), seasons of the year (Cordeiro et al., 2020),
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
67 examine root decomposition or turnover, investigating these dynamics contributes to understanding C
68 dynamics in these systems. Unfortunately, the fine-root residence time in soil, and hence its contribution to
69 C addition, is globally among the least understood aspects of the ecosystem's cycles and functions (Strand
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,

72 knowing the root turnover rate *in situ* and the amount of added necromass is crucial for understanding the
73 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
83 turnover rates (Eissenstat, 1992). For instance, *Eucalyptus* roots tend to remain in the soil longer than the
84 roots of herbaceous plants (Gill and Jackson, 2000), and competition factors between plant species (Beyer
85 et al., 2013) and tree shading (Rajab et al., 2018) also influence root turnover differently for each integrated
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
88 the influence of environmental factors in root cycling in ICLF systems has been previously documented.

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
94 hypothesis under the ICLF system, we addressed the following questions: (i) Does the rate of root
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
98 the growth of their roots in deeper soil layers? (iv) How does the environment under the integration of crop,
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**

104

105 *2.1. Study site and experimental design*

106

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

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

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

135

136 2.2. Management of the areas

137

138 The palisade grass was desiccated using glyphosate (4.0 L ha⁻¹) in October 2014 for crop
139 cultivation. In November 2014, corn was sown in 0.8 x 0.2 m spacing, simultaneously to palisade grass in
140 0.4 m rows spacing. The NPK fertilizer 08-28-16 formula (N-P₂O₅-K₂O) was applied at the rate of 500 kg
141 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
142 days after corn seed germination. On March 25th, the corn plants were cut for silage while palisade grass
143 plants remained in the field, forming the pasture for grazing, which started on May 11th, 2015.

144 The pasture was grazed by 200 kg young bovine males of Canchim breed (3/8 Nellore + 5/8
145 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.
146 The grazing cattle rotation in the paddocks consisted of grazing for six days, followed by 30 days of pasture
147 rest. During the rainy season, 40.4 kg ha⁻¹ of N were top-dressed on pastures in each resting period. Further
148 information on the management of the areas can be found in Bieluczyk et al. (2020).

149

150 2.3. Minirhizotron assessments

151

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
160 preferential growth of roots. These tubes were strategically placed in transects at 1.9, 4.3, and 7.5 m from
161 the rows of *Eucalyptus* trees to represent the inter-row space (Figure 1) as to permit seeding in no-till soil
162 management on 17th November 2014 as described in detail by Bieluczyk et al. (2020). The tube centre was
163 located precisely under the corn row, leaving one side of 35 cm to monitor the superficial palisade grass
164 root system and the other 35 cm side to assess deeper soil layers (see Figure 1).

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

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

176

177 2.4. Root image processing

178

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 ($<$
183 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
184 consisting in palisade grass and corn roots, which did not acquire shades of brown with root aging
185 (Bieluczyk et al., 2021); (ii) *Eucalyptus* root length with mycorrhizal colonisation, when dichotomous
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).

189

190 2.5. Root production and decomposition

191 The root length production (RLP) and root length decomposition (RLD) between the two
192 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
193 length, respectively, of each tracked root between t_{-1} and t , divided by the observed soil area of each image.
194 The daily root production ($DRP_{t-1,t}$, $\text{cm m}^{-2} \text{d}^{-1}$) and the daily root decomposition ($DRD_{t-1,t}$, $\text{cm m}^{-2} \text{d}^{-1}$) rates
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.

210

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
214 water content, $\text{m}^3 \text{m}^{-3}$) was measured from 0 to 70 cm depth using a capacitance probe (Sentek, model
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,
218 admitted as the lowest soil moisture during the dry seasons. Then, soil water availability was calculated by
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).

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

226

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
233 was performed by the General Linear Model procedure (PROC GLM) to test the influence of the distances
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
237 System – SAS v. 9.4 (SAS Inc., Cary, USA).

238 To verify the correlation between root decomposition for different diameter classes (0.0-0.5, 0.5-
239 1.0, and 1.0-2.0 mm) with environmental factors (*i.e.*, soil temperature, soil moisture, and
240 photosynthetically active radiation), we performed a principal component analysis (PCA) using the R
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
243 abiotic conditions (*e.g.*, moisture and temperature) for decomposition. Contour plots were elaborated to
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
250 al., 2017; Majdi et al., 2001; Tierney and Fahey, 2001). Kaplan-Meier survival analyses were used to
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
255 these analyses were performed using the R with a significance level of 5%.

256

257 **3. Results**

258

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

260 During the crop period, daily root decomposition rates were much lower (Figure 2) since corn and
261 palisade grass plants had a few months to develop their belowground system. Harvesting corn at the end of
262 the crop period (March 25th, 2015) induced intensive root mortality and an increase in root necromass. From
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
265 2 and 3). During the annual crop cultivation, from November 17th, 2014, to March 25th, 2015, little root
266 decomposition was observed, with a maximum of $8.0 \text{ cm m}^{-2} \text{ d}^{-1}$ (Figure 2A; Table S2). Root decomposition
267 rates were higher in further distances from the tree lines, reaching on average 2.0, 2.7, and $4.8 \text{ cm m}^{-2} \text{ d}^{-1}$
268 at 1.9, 4.3, and 7.5 m from the tree row, respectively (Table 1). The highest peaks of root decomposition

269 occurred during the pasture-rainy season, mainly from January 07th to March 14th, 2016 (Figure 2A; Table
 270 S3), when soil temperatures (Figure 2A) and available water (Figure 2B) also increased. This season's
 271 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,
 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
 280 available nearer to the trees, showing an inter-row gradient (1.9 < 4.3 < 7.5 m), especially in the dry season
 281 of 2015, while in rainy seasons, the values were mainly similar (Figure 2B). During the pasture-dry season
 282 of 2015, the available soil water contents were reduced by 25% and 30% at 4.3 and 1.9 m, respectively,
 283 compared to the 7.5 m distance. During the pasture-rainy season (2015/2016), these differences dropped to
 284 14 and 10%, respectively (Figure 2B).

285 The highest root decomposition rates occurred at 4.3 and 7.5 m *Eucalyptus* inter-row distances,
 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
 289 (*i.e.*, 0.0-0.5 mm) was more intensively impacted by abiotic environmental factors such as soil moisture
 290 and temperature (Figure 3B). For example, daily root decomposition of 0-0.5 mm diameter class (DRLD
 291 0-0.5 mm) was positively correlated with the available soil water ($r = 0.58$), average soil temperature ($r =$
 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
 300 addition, similar root production was observed at 4.3 m and in the middle of the inter-row (*i.e.*, 7.5 m)
 301 (Figure 4A). Furthermore, the relative decomposition $[(\text{decomposed} \div \text{produced}) \times 100]$ was higher at
 302 these distances compared to the 1.9 m position (Figure 4C). By the end of the trial, the proportion of overall
 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
 305 trial was 101 m⁻² for 7.5 and 4.3 m inter-row positions, which was almost twice as high as the total
 306 recorded at 1.9 m (Figure 4B).

307

308 Figure 4

309

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 *Eucalyptus* at a distance of 1.9 m from the rows, and 4.6 times higher at distances of 4.3 and 7.5 m.

319

320

Figure 5

321

322 Mycorrhizal associations increased during the crop period and stabilized during grazing,
 323 accounting for approximately 30% of total *Eucalyptus* roots at distances of 1.9 and 7.5 m (Figure 6A and
 324 6C), but with a higher association of about 50% at the intermediate distance of 4.3 m (Figure 6B).
 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^2), followed by 7.5 m (7.4 m^2) and 1.9 m (5.7 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.

331

332

Figure 6

333

334 3.3. Root decomposition in the soil profile over time

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

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, *Eucalyptus* roots without mycorrhizal colonization were distributed differently
 355 across diameter classes. Roughly 30 to 40% of these *Eucalyptus* 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 *Eucalyptus* 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

389 decomposition. Therefore, our discussion approaches spatiotemporal effects on fine-root decomposition
390 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, either 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
452 et al., 2009; Silver and Miya, 2001), which was the environmental condition observed during the rainy
453 season of 2015/16 in our study.

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

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

469 (Maeght et al., 2013; Cordeiro et al., 2020). These studies may be losing essential information on root
 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
 472 an essential role in C and nutrient cycling (Baptistella et al., 2020), helping the performance of multiple
 473 soil functions (Bieluczyk et al., 2020), even in deeper soil layers (*i.e.*, > 30 cm). Moreover, higher quantity
 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
 480 and 14-28 cm topsoil layers. Soil moisture and temperature typically show more significant fluctuations in
 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*
 493 mycorrhizal). Thinner roots in both grass species and *Eucalyptus* groups decayed faster. For example, 1.0-
 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;
 506 Germon et al., 2016; Lambais et al., 2017; McCormack et al., 2015; See et al., 2019; Sun et al., 2016).

507 Positive mycorrhizal status was present exclusively in very fine diameters of *Eucalyptus* roots, as
 508 96% 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 non-
524 mycorrhizal *Eucalyptus* roots with the same diameter class. Therefore, the results did not reveal a clear
525 pattern of root longevity among the sectioned phenotypic groups. Instead, under the ICLF environment,
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
530 pastures, such as in ICLF systems.

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.

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

553

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563

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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 crop-livestock-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, $^{\circ}\text{C}$] 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 crop-livestock-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 ($\text{cm m}^{-2} \text{d}^{-1}$) 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.

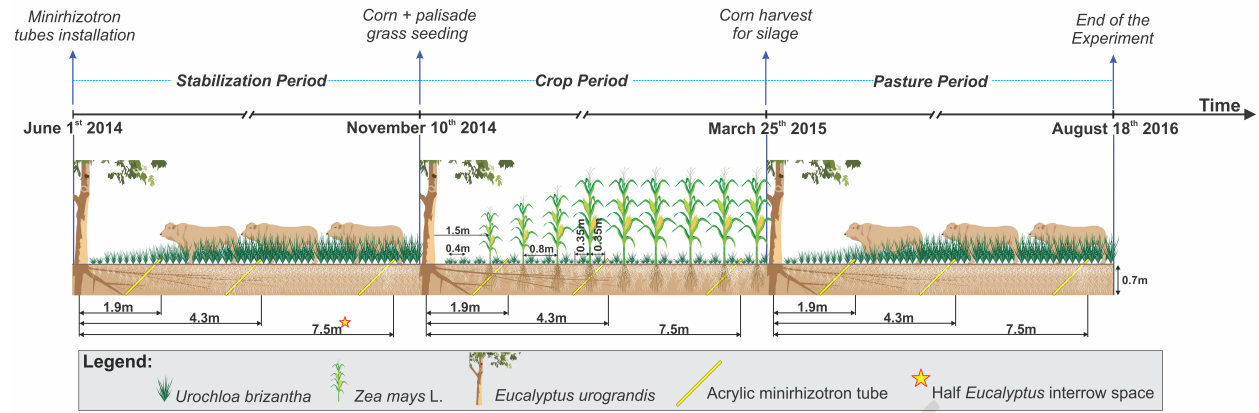
Cultivation	Season	ICLF 1.9m	ICLF 4.3m	ICLF 7.5m
Crop	<i>Rainy</i>	2.0 ± 0.8 Ab	2.7 ± 0.9 Ab	4.8 ± 1.6 Ac
Pasture	<i>Dry</i>	3.2 ± 0.4 Bb	10.1 ± 2.0 ABb	15.4 ± 4.0 Aab
	<i>Rainy</i>	14.4 ± 2.7 Ba	33.0 ± 6.6 Aa	24.4 ± 2.7 ABa
	<i>Dry</i>	12.4 ± 2.0 Aa	13.6 ± 2.9 Ab	15.1 ± 1.5 Aab

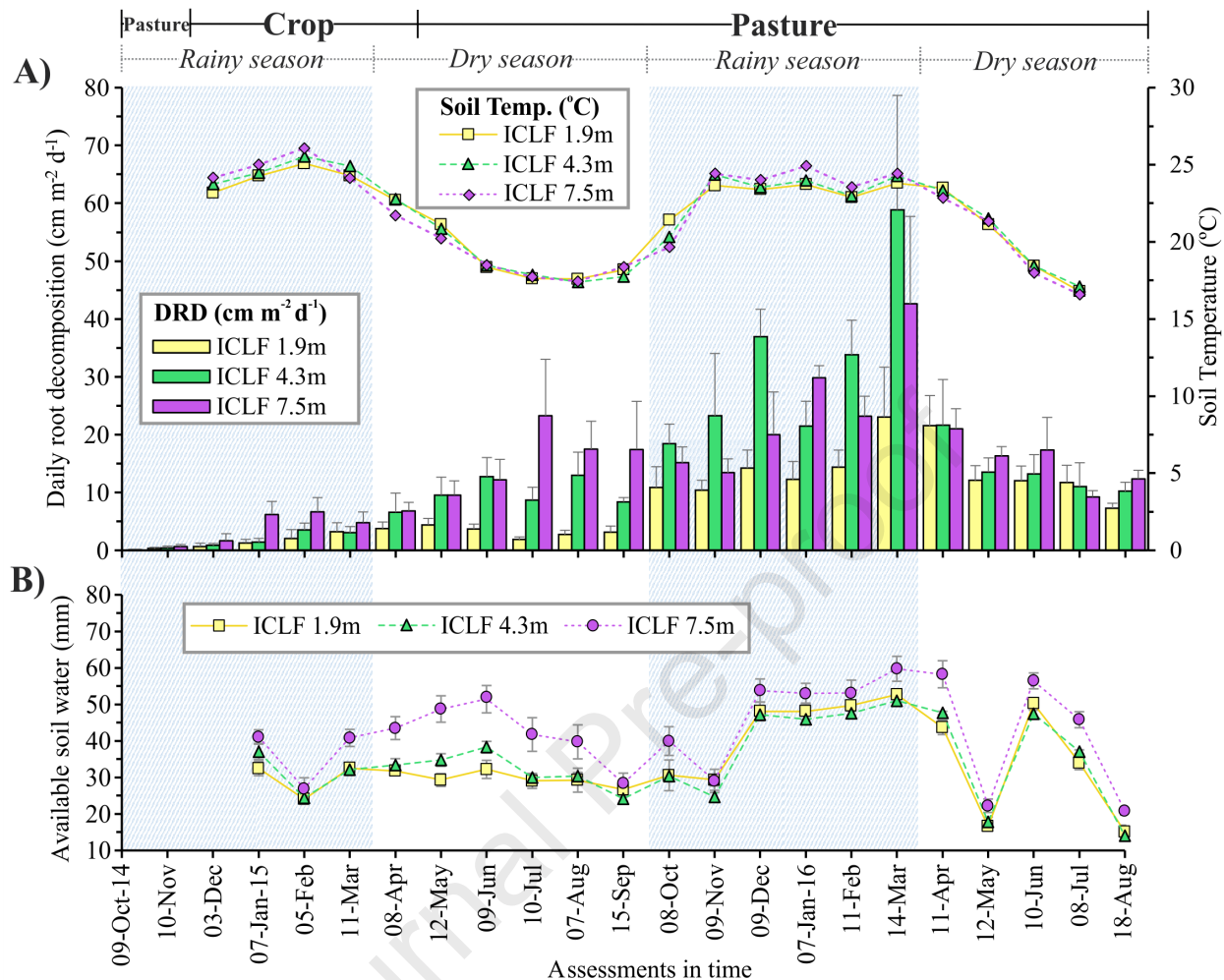
Uppercase letters compare the three ICLF distances, and lower-case letters compare evaluation periods by Tukey's t-test $p \leq 0.05$.

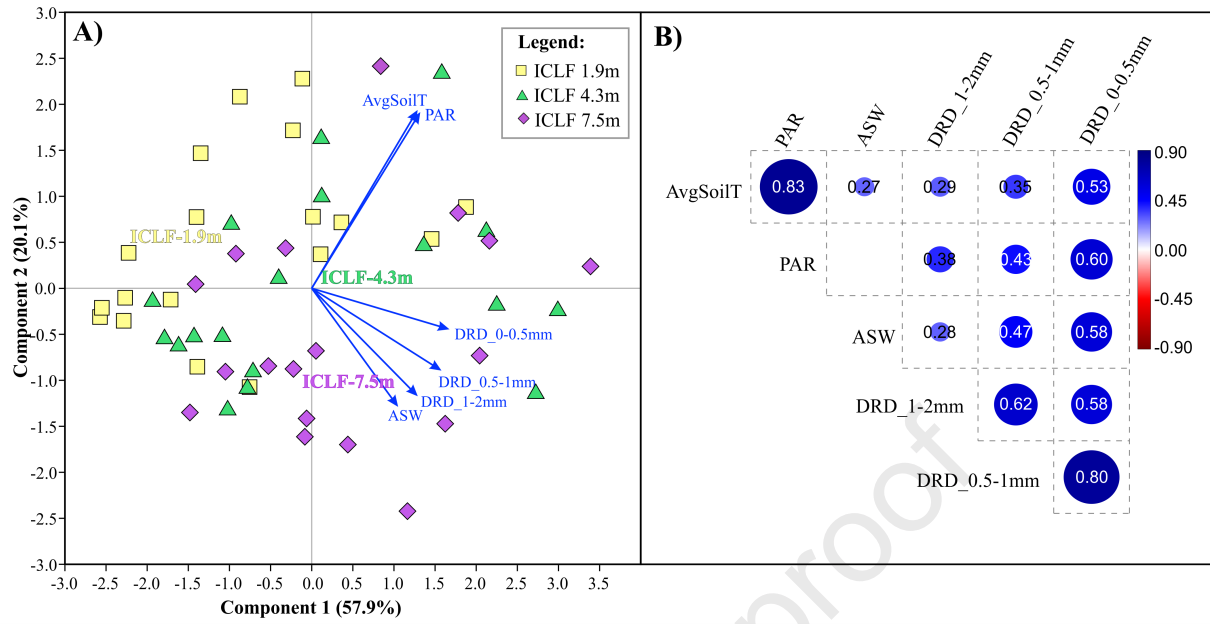
Table 2 – Median longevity (days), turnover rate (year^{-1}), loss (%), and the number of roots observed from grasses in the 0-70 soil layer over two years in an integrated crop-livestock-forestry (ICLF) system.

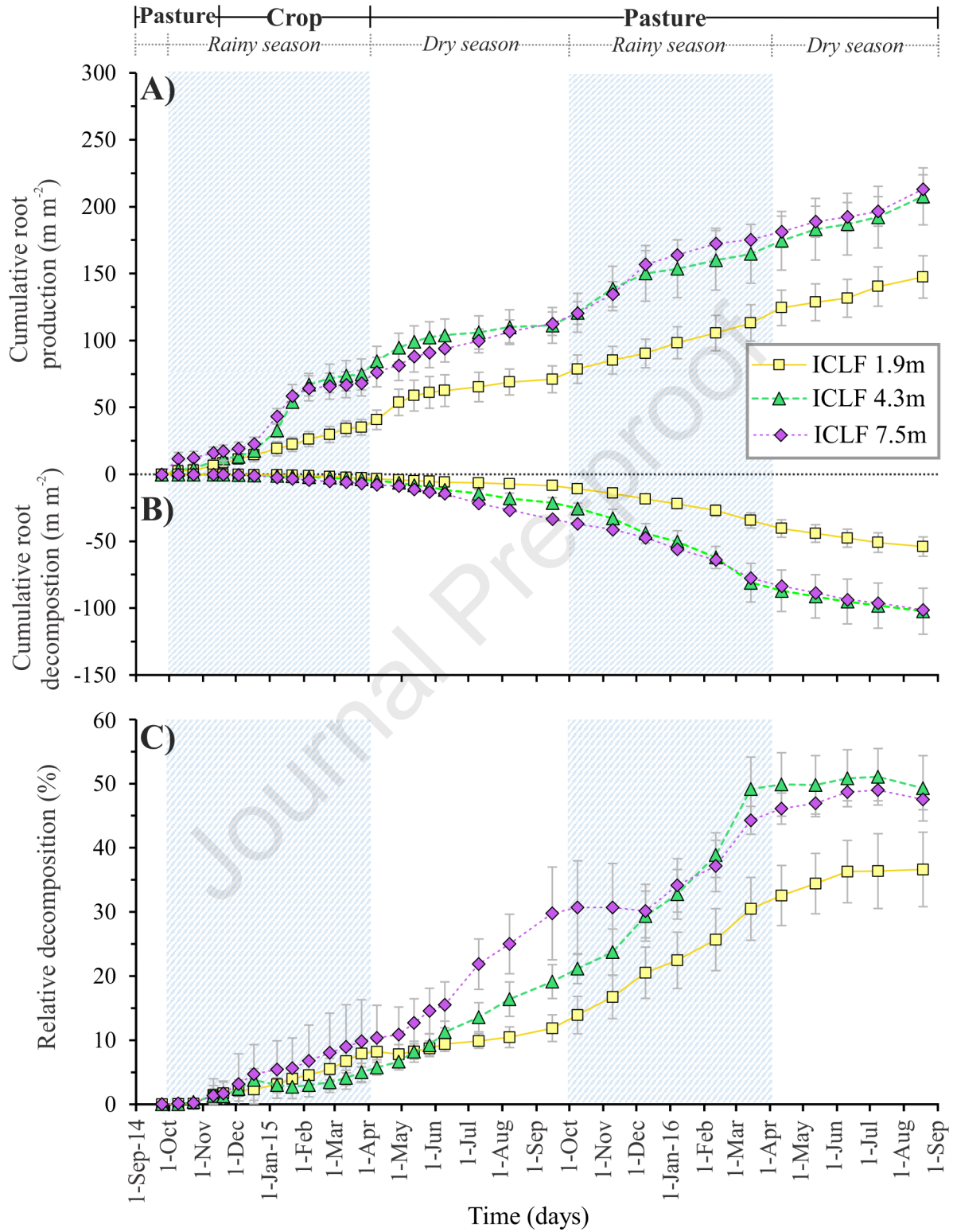
Plant category	Class	Longevity (days)	Turnover (year^{-1})	Root loss (%)	Roots observed (#)
Grasses	ICLF 1.9m [§]	395 A	0.92	34	14679
	ICLF 4.3m	349 B	1.04	42	24349
	ICLF 7.5m	307 C	1.19	47	19828
Eucalyptus	ICLF 1.9m	421 A	0.87	54	944
	ICLF 4.3m	364 B	0.99	68	874
	ICLF 7.5m	269 C	1.36	72	1165
Grasses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

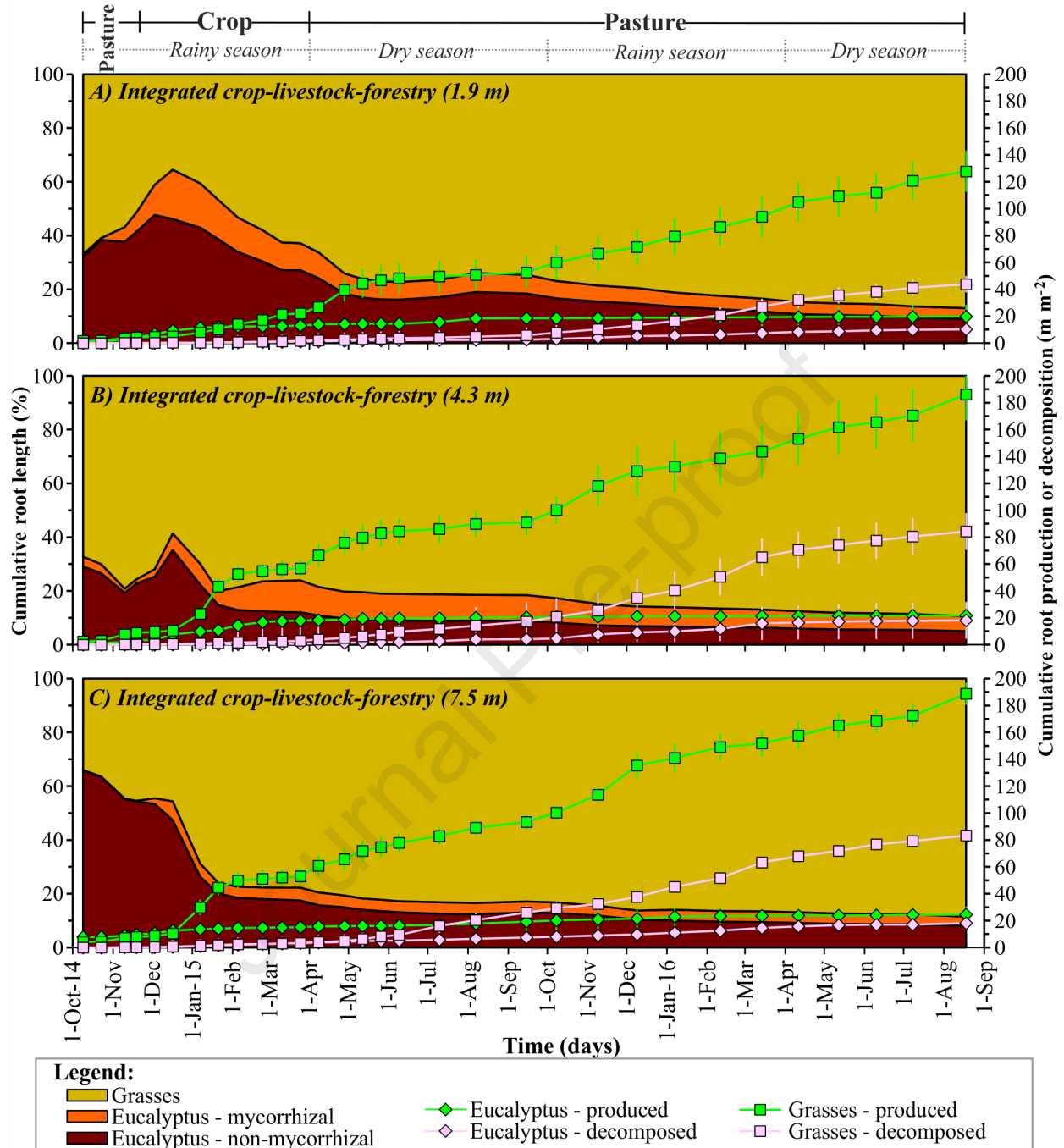
[§]1.9, 4.3 e 7.5m correspond to the assessed positions in ICLF inter-row space. Uppercase letters the classes by Kaplan Meier test ($p < 0.05$).

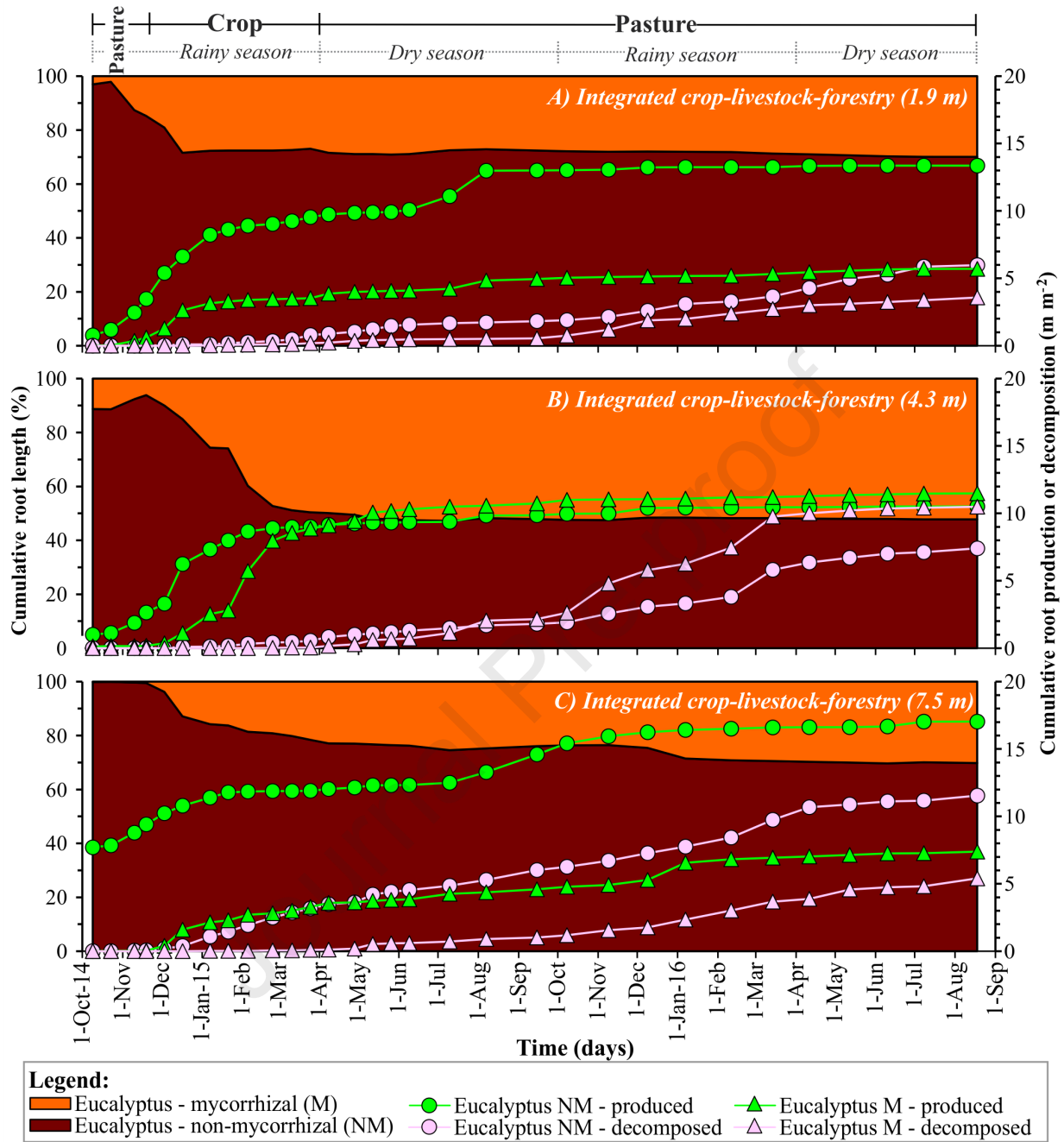


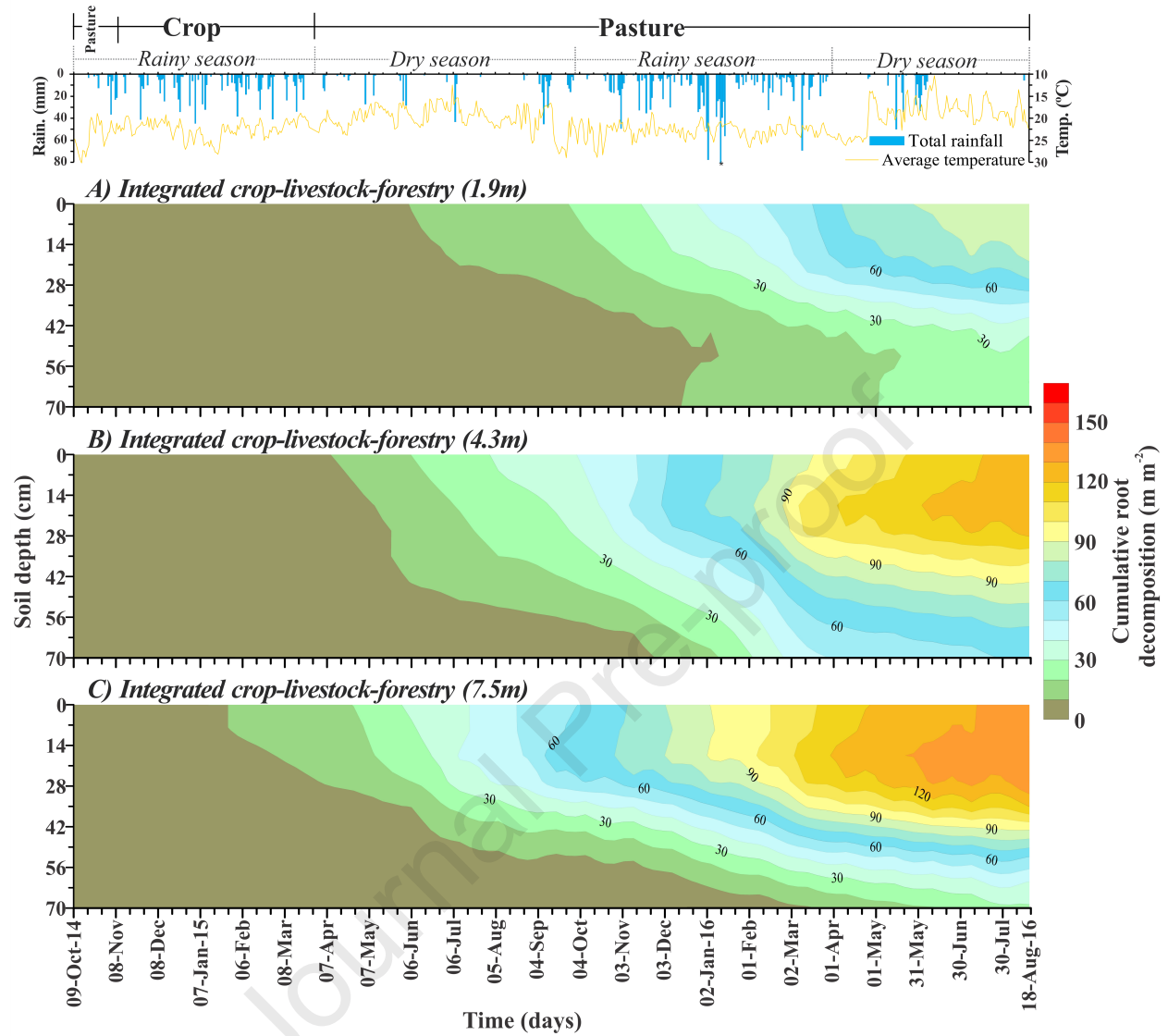


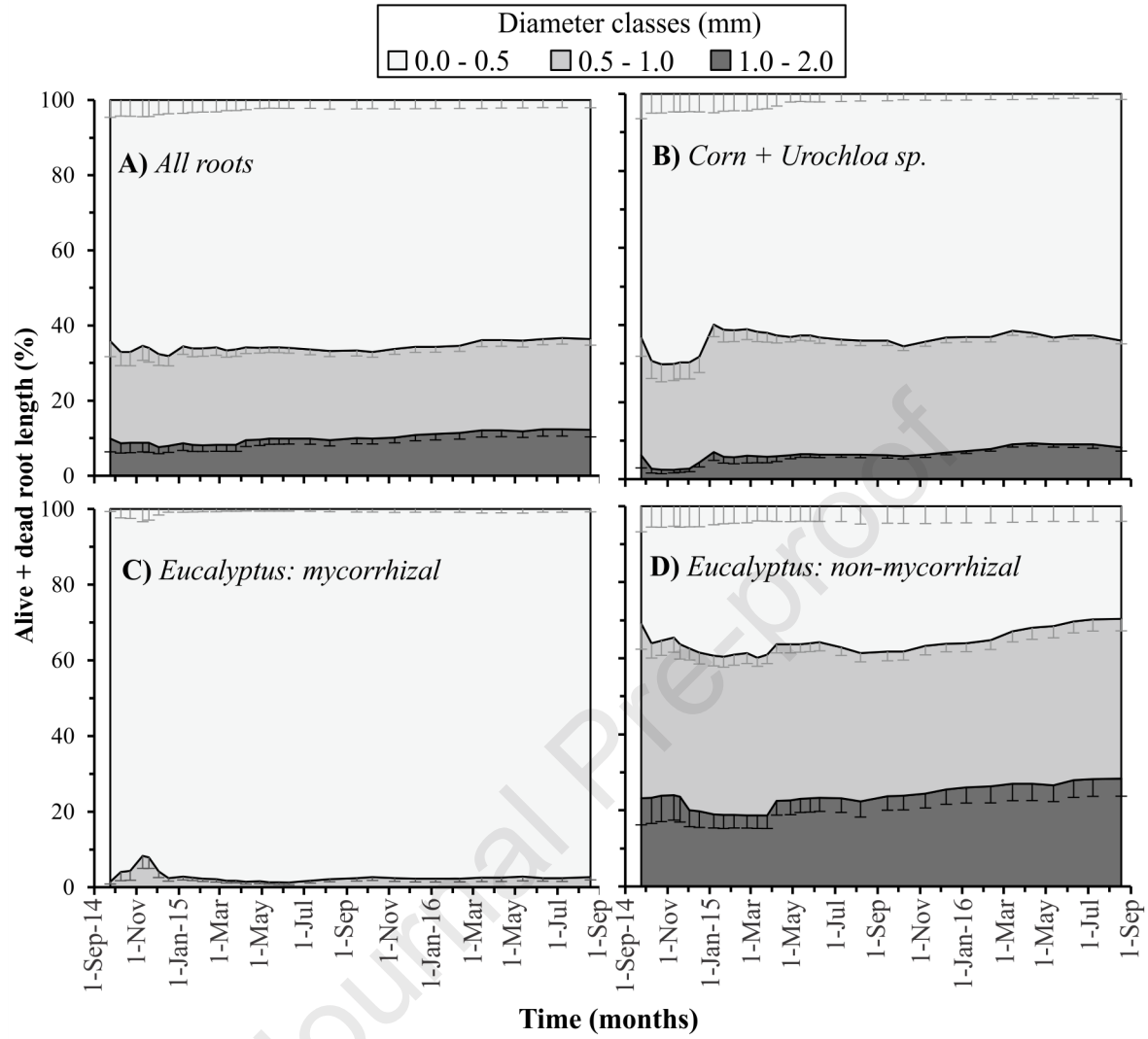


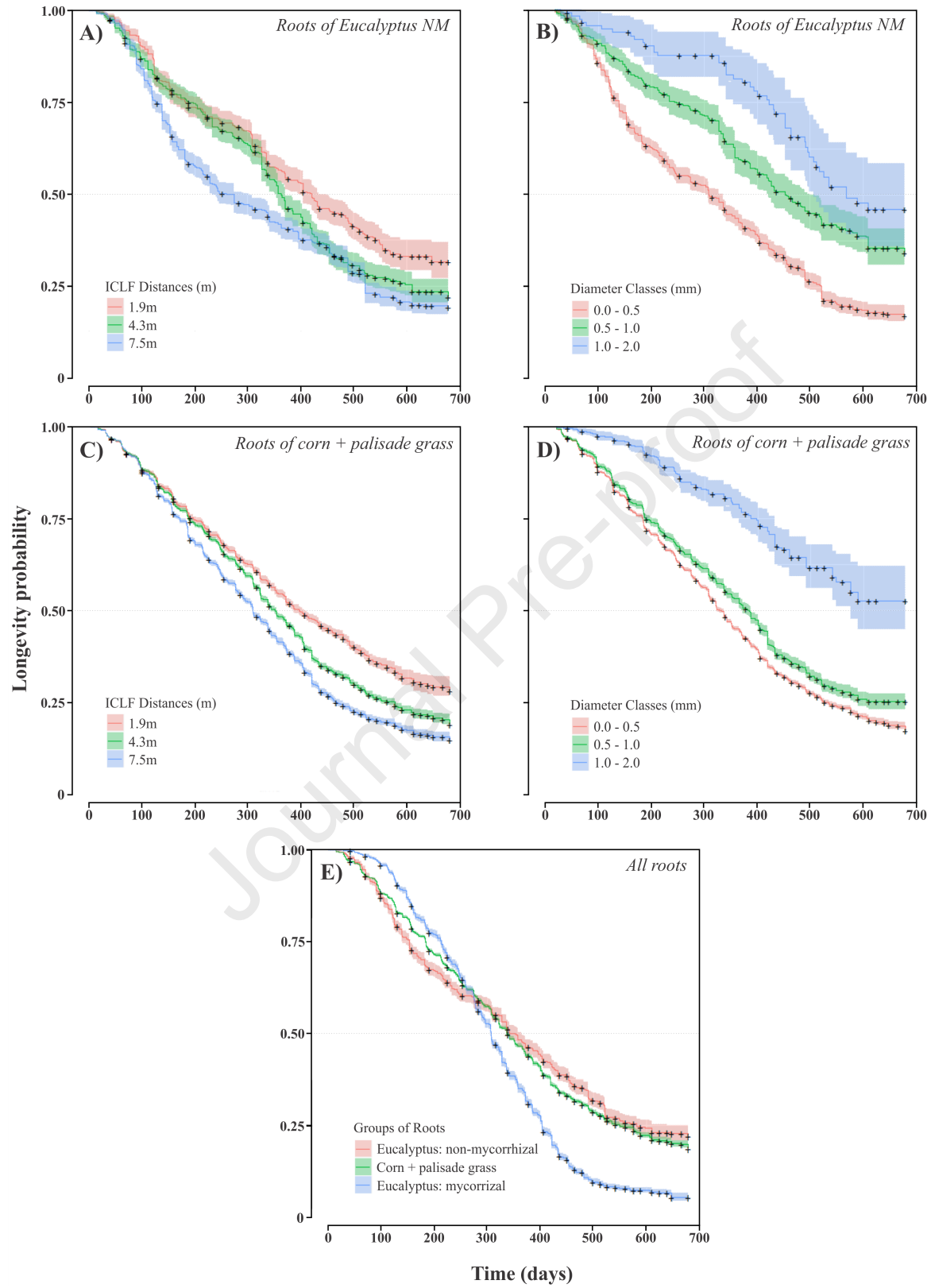












Highlights

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

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:

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