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1 **A long-term multi-criteria analysis of sugarcane intercropping compared to conventional**  
2 **cropping systems**

3

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24

25 **Abstract**

26 Multi-criteria approaches are needed to integrate the agronomic, environmental, and socio-economic  
27 performances of intercropping agroecosystems and assess their sustainability. Nonetheless, the temporal  
28 dynamics of intercropping agrosystems still need to be better understood, particularly in tropical  
29 systems. This study provides the first long-term multi-criteria analysis of sugarcane intercropping  
30 systems to assess how temporal changes will determine the sustainability of this practice. In an  
31 experimental trial in La Reunion, we compared six sugarcane x companion crop intercropping systems  
32 to a conventional and a low weed control cropping system over seven years. In intercropping systems,  
33 weed cover increased over time, along with species richness and manual weeding. In the conventional  
34 system, herbicide application increased over time, reducing weed pressure. Regarding biodiversity, the  
35 intercropping system only modified the weed community in the first three years, compared with the  
36 conventional or low-weed control system, before the communities homogenized under sugarcane  
37 pressure and climate. Over seven years, the intercropping system reduced herbicide application by 51%  
38 and increased soil cover by 144%, with no significant impact on yield or sucrose content. Nevertheless,  
39 this practice led to an increase of 85% in costs and 162% in working hours, mainly due to companion  
40 crop sowing. Finally, we observed no difference in soil chemical and biological fertility between  
41 cropping systems. However, the physical fertility increased with the development of companion crops  
42 and weeds in the inter-row after seven years. This study illustrates the need to consider the dynamics of  
43 intercropping systems performances over the long term. It highlights the limits of this system for weed  
44 control in sugarcane, notably through an increase in weed pressure over time, but also ways of improving  
45 it regarding costs (particularly sowing). Finally, cropping systems with spontaneous flora in the inter-  
46 row should be studied further to reduce herbicides with a limited impact on production.

47

48 **Keywords:** Interplanting; *Saccharum officinarum*; legume; cover crop; spontaneous flora; herbicides;  
49 soil health; economic analysis; labor time

50

## 51           1. Introduction

52 Intercropping, a practice that has been extensively studied, holds great potential to enhance crop  
53 productivity, resource-use efficiency, and environmental impact in agricultural systems (Brooker et al.  
54 2015). This method involves the simultaneous cultivation of two or more crops on the same field,  
55 fostering a more diversified plant community and enabling complementary and facilitative relationships  
56 (Duchene et al. 2017; Justes et al. 2021; Homulle et al. 2022). The benefits of intercropping are manifold,  
57 including improved yield and quality (Zhang et al. 2007), enhanced economic benefits (Huss et al.  
58 2022), and a range of ecosystem functions such as weed regulation, pest control, soil fertility  
59 improvement, and erosion protection (Gardarin et al. 2022). Intercropping emerges as a promising  
60 approach for sustainable intensification, particularly in regions with impoverished soils and economies  
61 (Mthembu et al. 2019) and areas with intensive agricultural production (de la Fuente et al. 2014).  
62 However, a comprehensive understanding of its multiple ecosystem functions through interdisciplinary  
63 research is still needed (Brooker et al. 2015).

64 Sugarcane (*Saccharum officinarum*) is a major crop source of sugar, ethanol, and raw material for  
65 electric energy production (Bordonal et al. 2018). Sugarcane intercropping with companion crops (sown  
66 as an intercrop) has been increasingly studied to improve short-term soil fertility (Li et al. 2013; Tang et  
67 al. 2021), weed control (Ali et al. 2017; Soulé et al. 2024), soil bacterial community (Solanki et al. 2019;  
68 Liu et al. 2021b, a; Pang et al. 2022), or to produce cash crop, and improve economic efficiency (Nadeem  
69 et al. 2020). However, introducing companion crops with sugarcane can also lead to below-ground  
70 competition (Christina et al. 2023) and highly variable yield responses (Viaud et al. 2023). Depending  
71 on countries and local contexts, studies dealing with sugarcane intercropping often focus on specific  
72 objectives (profitability in India, Singh et al. 2023; soil quality in China, Tang et al. 2021; reduced  
73 herbicide use in France, Mansuy et al. 2019). These specific studies are not enough to assess the  
74 sustainability of intercropping, which requires a multi-criteria analysis. Indeed, the effects of the  
75 transition from conventional crop systems toward intercropping are very diverse, whether in terms of  
76 ecosystem functions, economic impact, or labor arduousness, and these changes will be strongly  
77 influenced by the local context, whether in terms of climate, soil, or social context.

78 While the existing literature provides valuable insights into the short-term benefits of sugarcane  
79 intercropping, its long-term impacts need to be better realized. Long-term studies are needed to assess  
80 the sustained effects of intercropping on soil fertility, crop yield, and overall agricultural sustainability.  
81 As an example, a positive effect of legume intercropping on soil chemical fertility is expected through  
82 an enhancement of the soil organic C and N content (e.g., as demonstrated in other crops in temperate  
83 climates, Cong et al. 2015). Nevertheless, the only study dealing with the long-term effect of legumes  
84 on soil properties in sugarcane-legume intercropping systems did not find an increase in soil organic  
85 carbon content (e.g., in China, Wang et al. 2020). Additionally, recent studies have pointed out that

86 intercropping can have a negative impact on sugarcane yield, which becomes more pronounced over  
87 time (Viaud et al. 2023). This negative impact could be attributed to increased weed pressure (Soulé et  
88 al. 2024), which can have serious implications regarding labor and economic costs. Consequently,  
89 research is needed to consider the economic efficiency of sugarcane cultivation under ecologically  
90 intensified cropping systems over extended periods. Understanding the long-term implications of  
91 sugarcane intercropping over the different dimensions of sustainability is crucial to design sustainable  
92 practices and advise farmers and policymakers on the consequences of agroecological transition.

93 This study aimed to perform a long-term multi-criteria analysis of sugarcane intercropping (Fig. 1)  
94 compared to conventional and low weed control (spontaneous weed community in the inter-row)  
95 cropping systems. In this study, we hypothesized that: i) intercropping will impact productivity (yield),  
96 ecosystem functions (plant biodiversity, reduced herbicide use, and soil fertility), and socioeconomic  
97 efficiency (working hours, change in costs and revenue) compared to conventional chemical or low  
98 weed control systems, and ii) the annual change in these indicators will impact the long-term  
99 sustainability of sugarcane intercropping. To this aim, we performed a seven-year sugarcane  
100 experimental trial in the tropical Island of La Réunion.

101

## 102 2. Material and methods

103

### 104 2.1. Study site

105 This study was carried out on the research station of La Mare, located on the northern coast of Reunion  
106 Island (20°54 S, 55°31 E, 69 m a.s.l., Indian Ocean) over seven sugarcane cropping seasons (i.e., seven  
107 years, one plant crop and six ratoon crops). The climate was tropical, with a rainy season from January  
108 to March and a dry season from May to November. The mean annual rainfall was approximately 1800  
109 mm, and the mean annual temperature was 24 °C (means over ten years). Daily climatic data were  
110 measured in a nearby Campbell meteorological station (100 m from the trial) and described in Table S1.  
111 The soil of the experimental site was a Hypereutric Nitisol according to the WRB classification (USS  
112 Working Group WRB 2015) with a silty loam texture. Soil chemical characteristics were determined  
113 before the sugarcane plantation (Table S2). Total N was analyzed using the Dumas method, and total P  
114 using the Olsen-Dabin method.

115

### 116 2.2. Experimental design and weed control management

117 The experiment consisted of a randomized sugarcane trial with height inter-row conditions (IR, Table  
118 S3) repeated into four blocks with 60 m<sup>2</sup> elementary plots (Fig. S1):

- 119 • A conventional sugarcane cropping system with chemical weed control of both sugarcane row  
120 and inter-row (WC)
- 121 • Six intercropping conditions with companion crops sown each year in the sugarcane inter-row  
122 (CC1 to CC6) with manual weed control on the sugarcane row.
- 123 • A low weed control condition (LWC) with spontaneous flora in the sugarcane inter-row, with  
124 manual or chemical weed control on the sugarcane row.

125 Weed management of all IR conditions included i) the application of a pre-emergent herbicide after  
126 sugarcane planting or harvest in the whole plot, ii) a manual or chemical weeding of the sugarcane row  
127 to limit the impact on sugarcane production (throughout the crop cycle), and iii) a specific manual  
128 weeding of the weeds considered as the most harmful in the whole plot (in particular, tall grasses:  
129 *Panicum maximum* and *Rottboellia cochinchinensis*). In the WC condition, additional post-emergent  
130 herbicides were systematically applied to limit ground cover by weeds below the threshold of 30%  
131 ground cover (sugarcane sector recommendations). Additional manual weedings were occasionally  
132 performed in the CC conditions when ground cover by weeds exceeded 30% in the inter-row. An  
133 Herbicide Treatment Frequency Index (HTFI) was calculated as the sum of the ratio of the herbicide  
134 dose applied divided by the recommended dose across each herbicide application in a specific plot  
135 (<https://agriculture.gouv.fr/indicateur-de-frequence-de-traitements-phytosanitaires-ift>). Details of the

136 chemical compounds used for herbicides are available in the data paper (Ngaba et al. 2023) and are  
137 summarized in Table S4. The number of manual weeding (MW) was recorded.

138

### 139 **2.3. Sugarcane and companion crop management**

140 The R579 sugarcane cultivar was planted with a 1.5 m inter-row in April 2014 and harvested annually  
141 in October (Table S5). Sugarcane stalk fresh mass (hereafter sugarcane yield,  $\text{Yield}_{\text{SC}}$ ,  $\text{Mg ha}^{-1}$ ) was  
142 measured at harvest by sampling all sugarcane stalks on the two rows in the middle of the plot. Sugarcane  
143 was harvested manually in the plant and first ratoon crops and mechanically in the following years.  
144 Sucrose content in the stalks ( $\text{Sugar}_{\text{SC}}$ , %) was measured based on near-infrared spectroscopy of  
145 extractable sucrose. In ratoon crops (2015 to 2021), the sugarcane mulch was left on the soil surface and  
146 homogenized after harvest. Depending on IR conditions and years (Table S3), different companion crops  
147 were sown in the inter-row each year: *Desmodium intortum*, *Canavalia ensiformis*, *Guizotia abyssinica*,  
148 *Avena sativa*, *Vigna unguiculata*, *Crotalaria juncea*, *Crotalaria spectabilis*, *Brassica carinata*,  
149 *Raphanus sativus*, and a mixture of *Vicia sativa* and *Lathyrus sativus*. Sowing densities and sowing dates  
150 after sugarcane harvest are detailed in Table S6. The sowing densities were determined based on  
151 previous studies and literature (Christina et al. 2021b). From the plant crop (2014-2015) to the fourth  
152 ratoon crop (2018-2019), the companion crops were sown manually. The companion crops were sown  
153 with a micro-tractor power harrow in the last two crop cycles. In both cases, the sugarcane mulch was  
154 removed before sowing and then re-spread (except for plant crops with bare soil). A non-limited split  
155 NPK fertilization was applied during the whole experiment in all IR conditions (Table S5). The whole  
156 experiment was irrigated with sprinklers.

157

### 158 **2.4. Ground cover by companion crop and weeds**

159 The ground cover by companion crops and weeds was estimated in each elementary plot (excluding  
160 borders) using a visual notation method according to a rating scale ranging from 0 to 100% and described  
161 in Table S7. This method makes it possible to assess the ground cover by species in multi-species crops  
162 and was used in previous studies (Marnotte 1984; Christina et al. 2021b; Soulé et al. 2024). In each plot,  
163 ground cover was estimated for i) all plants (companion crops and weeds), ii) companion crops only, iii)  
164 weed community only, and iv) weed species every month during the first six months and then every two  
165 months up to the sugarcane harvest. Ground cover was then linearly interpolated between two dates of  
166 measurement to calculate a mean ground cover by companion crops ( $\text{COV}_{\text{CC}}$ ) or weeds ( $\text{COV}_{\text{WEED}}$ )  
167 between two sugarcane harvest dates (i.e., crop cycle, Table 1). The description of weed species observed  
168 in the experiment is available in Table S8, with mean abundance and frequency of observation in the

169 experiment plots. A total inter-row ground cover by companion crops and weeds was also measured  
170 ( $COV_{TOT}$ ).

171

## 172 **2.5. Soil fertility**

### 173 2.5.1. Indicators of soil chemical fertility

174 Bulk soil was sampled at the end of the experiment (after the 2021 harvest) in three plots of 6 IR  
175 conditions (WC, CC3, CC4, CC5, CC6, and LWC) for soil chemical analysis (0-30 cm depth). Two  
176 companion crops' IR conditions were excluded from this analysis (CC1 and CC2). Standard soil  
177 chemical analyses were carried out in the CIRAD soil laboratory in Saint-Denis de La Réunion (Table  
178 S2). Due to the absence of carbonates, soil organic carbon and total soil nitrogen were quantified using  
179 the Dumas combustion method (ISO 106994:1995) with an elemental analyser (VarioMax Cube CNS,  
180 Elementar, Hanau, Germany). The phosphorus content of the soil had historically been measured using  
181 the Olsen method modified by Dabin (Dabin 1968) in La Réunion, despite the limitations identified as  
182 an indicator of available P (Nobile et al. 2018). Cation exchange capacity (CEC) as well as the content  
183 of exchangeable cations ( $K^+$ ,  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Na^+$ ) were quantified by a solution of cobaltihexamine  
184 trichloride as an extraction reagent, in accordance with standard ISO 23470:2018 (Fallavier 1985).  
185 Finally, pH was quantified using the water and KCl method (ISO 10390:2021).

186 The chemical fertility indicators (Table 1) included nitrogen, phosphorus, and potassium availability  
187 provided by Serdaf, a soil-specific nutrient management expert system developed for sugarcane  
188 fertilization in La Réunion (Versini et al. 2018). Briefly, nitrogen availability corresponding to the soil  
189 N mineralization over a crop growth cycle ( $N_{min}$ ) was calculated in each plot based on total soil nitrogen,  
190 bulk density, stoniness, and infield mineralization rate. Phosphorus deficiency ( $P_{deficiency}$ ) was assessed  
191 using the fertilizer doses of P recommended by Serdaf in each plot. The expert system considers the soil  
192 P content, pH, and the fixing capacity of soil to establish a P recommendation for sugarcane. The more  
193 soil P is available for the crop, the lower the recommendation and  $P_{deficiency}$ . Finally, the exchangeable  
194 potassium content was considered a direct indicator of potassium availability for crops ( $K_{availability}$ ).

### 195 2.5.2. Indicators of soil biological fertility

196 Three indicators adapted from Biofunctool<sup>®</sup>, a set of indicators selected to assess soil health in tropical  
197 contexts (Thoumazeau et al. 2019), were used to describe soil biological fertility (Table 1). The  
198 measurements and soil sampling were performed in January 2022 in the same plots as soil chemical  
199 fertility indicators. Soil mesofauna and little macrofauna activity were assessed by examining substrate  
200 degradation using bait-laminas sticks (van Gestel et al. 2003). Short-term turnover soil carbon pool (0-  
201 10 cm depth) was investigated with the permanganate oxidizable carbon method (POXC) to inform on  
202 the available energy of the system originated from biological activity (Culman et al. 2012). Basal soil



203 respiration was assessed with Situresp® (Thoumazeau et al. 2017), an incubation method that measures  
204 the quantity of carbon emitted by microorganisms over 24 hours.

### 205 2.5.3. Indicators of soil physical fertility

206 Three indicators adapted from Biofunctool® (Thoumazeau et al. 2019) were used to describe the soil  
207 physical fertility (Table 1). The measurements and soil sampling were conducted simultaneously with  
208 those for soil biological and chemical fertility. Aggregate stability at 0-10 cm depth ( $Agg_{SoilSurf}$ ),  
209 informing the capacity of the soil to resist erosion, was assessed on six dried aggregates selected for  
210 sizes ranging between 6 to 8 mm (Le Bissonnais 2016). Water infiltration, providing information on  
211 infiltration rate, run-off, and erosion process, was assessed with the Beerkan method (Lassabatère et al.  
212 2006). Visual Evaluation of Soil Structure (hereafter VESS), informing on soil compaction, was  
213 estimated at 0-20 cm depth following the method proposed by Guimarães et al. (2011).

### 214 2.5.4. Soil fertility index

215 In each plot, four soil fertility indexes were aggregated from the nine indicators following a method  
216 adapted from Obriot et al. (2016): a soil chemical ( $SFI_{Chim}$ ), biological ( $SFI_{Biol}$ ), and physical fertility  
217 index ( $SFI_{Phys}$ ), as well as a global soil fertility index (SFI, Table 1). Briefly, indicator values were  
218 normalized per site based on desirability criteria: "more is better" for POXC, Situresp®, bait-lamina,  
219 Beerkan, Agg,  $N_{min}$ ; "less is better" for  $P_{availability}$ ; and "optimum" for VESS (optimal value = 1). Indexes  
220 were calculated by averaging the indicator values without ponderation (Wagg et al., 2014,  $N_{min}$ ,  $P_{deficiency}$ ,  
221 and  $K_{availability}$  for  $SFI_{Chim}$ ; bait-lamina, Situresp®, and POXC for  $SFI_{Biol}$ ; VESS, Beerkan, and  $Agg_{SoilSurf}$   
222 for  $SFI_{Phys}$ ). The global SFI was calculated by averaging  $SFI_{Chim}$ ,  $SFI_{Biol}$ , and  $SFI_{Phys}$  values.

223

## 224 2.6. Economic and working hour assessment

225 An economic analysis of the three systems (WC, CC, and LWC) was performed to assess the change in  
226 weed control operating costs and revenue from sugarcane sales. The economic analysis was carried out  
227 using the OTECAS software developed by the eRcane Institute as part of the agricultural innovation and  
228 transfer network (2022 version, <https://coatis.rita-dom.fr>) and used in previous studies (Soulé et al.  
229 2024). This software, developed specifically for the sugarcane industry in La Réunion, calculates  
230 revenue and operating costs according to crop management and yields. Only the variable operating costs  
231 across the cropping systems were considered in the expenses: the purchase of herbicides (Table S4) and  
232 seeds (Table S9), as well as labor and mechanization costs (taking account of equipment depreciation,  
233 Table S10). For each plot in the trial network, the costs of herbicide purchase, seed purchase, number of  
234 chemical weeding operations (backpack sprayer), and number of manual and mechanical weeding  
235 operations were calculated. The costs of sowing companion crops were calculated differently  
236 considering manual sowing (from plant to fourth ratoon crops), sowing with a micro-tractor (two last

237 ratoon crops), and the mulch management in the row spacing. The revenue from sugarcane production  
238 in each trial was calculated with OTECAS based on the fresh stalk yield, sugarcane richness, and  
239 additional subsidies in La Réunion. For this calculation, we considered a farm of 5 ha with manual  
240 harvest. The number of working hours for weed control operations was also calculated based on the  
241 OTECAS software (Table S10).

242

## 243 2.7. Data analysis

### 244 2.7.1. Temporal variation analysis and IR condition effect

245 All statistical analyses were performed using R 4.1 (R Development Core Team 2022) with the following  
246 procedure. If necessary, to ensure residue normality, the target variable was transformed using the Box-  
247 Cox function (powerTransform function from car R package, Fox et al. 2023) based on a Gaussian law.  
248 Details on the transformation performed on each variable are given in Table S11. Then, the identification  
249 of the random effects (among plot identification, cultivation year, and nested plot-year effects) was  
250 realized by comparing the linear mixed model (lme function, nlme R package, Pinheiro et al. 2022) and  
251 the only fixed model (gls function, nlme R package) fitted using the restricted maximum likelihood  
252 (REML) estimation and compared using the Akaike information criterion (AIC).

253 For Yield<sub>SC</sub>, Sugar<sub>SC</sub>, COV<sub>CC</sub>, COV<sub>WEED</sub>, S<sub>WEED</sub>, HTFI, and Revenue variables, the influence of the inter-  
254 row condition (IR), the crop cycle (plant or ratoon crop), the number of years since the beginning of the  
255 experiment ( $Y_{NB}$ , 1 to 7), and their interaction were tested as fixed effect considering the cultivation year  
256 (qualitative variable) as random effect using a type III Fisher variance analysis:

$$257 \quad \text{Variable} \sim \text{Cycle} + Y_{NB} + IR + \text{Cycle:IR} + Y_{NB}:IR + 1|Year$$

258 As no data on MW was available for plant crop, only the interaction between  $Y_{NB}$  and the IR condition  
259 was tested for MW, Costs, and  $W_{\text{Hour}}$ . Considering Biofunctool indicators, the influence of the IR  
260 condition was tested without random effect. The assumptions of homogeneity and normality were  
261 checked graphically using histograms of residuals, quantile-quantile plots of Pearson's residuals versus  
262 standardized Gaussian sample, and plots of residuals against fitted values. Pairwise comparisons of slope  
263 response to  $Y_{NB}$  among treatments were performed using the emtrends function with a Tukey p  
264 adjustment method and a 0.05 probability threshold (emmeans R package, Lenth et al. 2023). Pairwise  
265 comparisons of means among treatments were performed using the emmeans function with the same  
266 Tukey p adjustment method. The models' mean predicted and confidence interval values depending on  
267 factors were calculated using the emmeans function. The marginal (only fixed effects,  $R_m^2$ ) and  
268 conditional  $R^2$  (both fixed and random effects,  $R_C^2$ ) were calculated with the rsquared function.

269

### 270 2.7.2. Weed community analysis

271 The species richness ( $S_{WEED}$ ) was calculated as the number of weed species occurring in a plot each year.  
272 The alpha, beta, and gamma diversity indexes were calculated using the vegan package multipart  
273 function (Oksanen et al. 2018). A non-metric multidimensional scaling (NMDS) was performed to  
274 examine the changes in weed species composition in response to cultivation year and IR condition using  
275 the metaDMS function (vegan package). The influence of climate (annual precipitation and mean  
276 temperature) and the number of years since the beginning of intercropping were tested using the envfit  
277 function (vegan package). The influence of the interaction between cultivation year and IR conditions  
278 on community structure was tested with a permutational ANOVA (adonis2 function, vegan package,  
279 with the Bray-Curtis distance calculation method) paired with a posthoc test (pairwise.adonis2 function  
280 from pairwiseAdonis package, Martinez Arbizu 2020) to test for significant differences among  
281 cultivation years and IR conditions. We finally used the multipatt function from the indicpecies package  
282 (De Caceres et al. 2016) to identify weed species significantly associated with each cultivation year  
283 and/or IR condition.

284

### 285 2.7.3. Multi-criteria analysis

286 A multi-criteria analysis was performed on ecosystem function, socio-economic and soil fertility indices  
287 throughout the experiment. To this aim, the following variables were cumulated over the years in each  
288 plot: sucrose yield ( $Yield_{SC} \times Sugar_{SC}$ ), HTFI,  $S_{WEED}$ , the total ground cover by both companion crops  
289 and weeds ( $COV_{TOT}$ ), revenue, costs,  $W_{Hour}$ . Considering the soil fertility indices ( $SFI_{Phys}$ ,  $SFI_{Chim}$ , and  
290  $SFI_{Biol}$ ), the measurements at the end of the experiment were used. The influence of the IR condition on  
291 each variable was tested using a linear analysis of variance after variable Box-cox transformation, and  
292 predicted values with confidence intervals were calculated with the emmeans function. The change in  
293 predicted values from WC to CC or LWC was calculated as a proportion of WC so that an increase was  
294 considered an improvement (Table 1).

295

### 296 3. Results and discussion

#### 297 3.1. Ground cover by companion crops and weeds

298 Although ground cover by companion crops remains constant over time, weed pressure increased from  
299 the first to last ratoon crop in intercropping systems and finally reached cover values similar to the low  
300 control conditions (Fig. 2a,b).  $COV_{CC}$  and  $COV_{WEED}$  were influenced by the  $Y_{NB} \times IR$  interaction and  
301 the Cycle  $\times$  IR (Table S12). The fixed effects explained 74% of  $COV_{WEED}$  variability ( $R_m^2$ , Table S12).  
302 Considering  $COV_{CC}$ , even if the  $Y_{NB} \times IR$  interaction was significant in the variance analysis, it  
303 explained a low part of variability compared to Cycle  $\times$  IR (Table S12). Globally,  $COV_{CC}$  decreased  
304 from 46% in plant crops to 22% in ratoon crops (Fig. 2a). This decrease is due to the faster sugarcane  
305 canopy closure in ratoon crops than in plant crops, which negatively impacts companion plant growth  
306 (Soulé et al., 2024). Afterwards,  $COV_{CC}$  tended to decrease in CC1, CC2, and CC5, but only the CC2  
307 trend was significantly different than CC3 and CC6 trends (Fig. 2a, Table S13).

308 On the contrary,  $COV_{WEED}$  was more influenced by  $Y_{NB} \times IR$ . The decrease in  $COV_{WEED}$  from plant (first  
309 year) to ratoon crop (afterward) was only significant in LWC ( $P = 0.009$ ) and CC5 ( $P = 0.018$ ),  
310 illustrating the influence of sugarcane mulch on weeds (Carvalho et al. 2017). At the beginning of the  
311 growth,  $COV_{WEED}$  was lower in CC and WC conditions than in LWC conditions. These results are  
312 consistent with the broad agreement on the ability of intercropping to limit weed growth both in  
313 sugarcane (Kaur et al. 2016; Geetha et al. 2019; Soulé et al. 2024) or even in other cropping systems  
314 (Verret et al. 2017; Gu et al. 2021). Afterward, while  $COV_{WEED}$  remained constant with  $Y_{NB}$  in LWC, it  
315 decreased in WC and increased in all CC conditions (Fig. 2b, Table S13). The decrease in  $COV_{WEED}$  in  
316 the WC is consistent with what is usually observed in chemical sugarcane systems with well-managed  
317 weed control (Korres et al. 2018) and the increase in the use of herbicides (see section 3.4). On the  
318 contrary, the change in weed pressure over time in intercropping systems is still poorly understood as it  
319 has only been recently highlighted by Soulé et al. (2024) for sugarcane and is still poorly understood  
320 even in other diversified cropping systems (Adeux et al. 2019a). This increase could result from a weed  
321 seed bank enrichment and the selection of highly competitive weeds, as seen in other temperate cover  
322 cropping systems mainly under rotations (Graziani et al. 2012; Mohler et al. 2018; Nichols et al. 2020).  
323 These findings underscore the need for further research in tropical areas, particularly in understanding  
324 the dynamics of weed pressure in intercropping systems.

325 Despite its potential adverse effect through interspecific competition, an increasing ground cover by  
326 companion crops or weeds can protect against erosion (e.g., Labrière et al. 2015; Sharma et al. 2017),  
327 even in sugarcane cropping systems with straw mulching, which is not always enough to limit erosion  
328 (Thomaz et al. 2022). In this study, the ground cover by both weeds and companion crops ( $COV_{TOT}$ )  
329 was higher in CC (47% on average) than in LWC (34%) and WC (21%), remaining constant over time  
330 (Table S12), suggesting that intercropping could provide higher erosion protection than spontaneous

331 flora or chemical conditions. Nonetheless, no clear evidence of a relationship between erosion protection  
332 and sugarcane intercropping can be found in the literature, and such a hypothesis requires further  
333 investigation.

334

### 335 **3.2. Weed species richness and community structure**

336 The inter-row practices influenced the weed species richness and community structure in the short term.  
337 However, weed communities became homogenized after three years under the predominant influence  
338 of climate and sugarcane management (Fig. 3). A total of 66 weed species was observed over the seven  
339 years of the experiment (Table S8). However, the total species richness ranged from 13 to 33 species  
340 depending on year (Table S14). Weed species richness was significantly influenced by the Cycle x IR  
341 ( $P = 0.007$ ) and  $Y_{NB}$  x IR interactions ( $P = 0.010$ , Table S12, Fig. 2c). Nonetheless, the fixed effects only  
342 explained 39% of the variability (Table S12). The random effect illustrates the importance of climate in  
343 the weed species richness variations (Peters et al. 2014). In plant crops,  $S_{WEED}$  was lower in CC2, CC5,  
344 and CC6 than in LWC, while other IR conditions were between both groups. Afterward,  $S_{WEED}$  increased  
345 in all IR conditions (Fig. 2c), with the highest increase in CC2, CC5, and CC6 compared to LWC (Table  
346 S13). At the end of the experiment,  $S_{WEED}$  was similar among LWC and CC conditions. Such results  
347 illustrate the complex effects of intercropping practices on weed richness and why there is no clear  
348 consensus (Poggio 2005; Mohammadkhani et al. 2023; Namatsheve et al. 2024). Weed richness can be  
349 impacted by long-term interspecific competition (Restuccia et al. 2020) and, perhaps predominantly, by  
350 climate or management (Pyšek et al. 2005).

351 The weed community structure was affected by the interaction between the inter-row conditions (IR)  
352 and the cultivation year ( $P < 0.001$ , Table S15). The annual change in community structure resulted in  
353 the homogenization of plots over time in all IR conditions (Fig. 3a), which was confirmed by the  
354 decrease in  $\beta$  diversity index over time (Table S14). This homogenization was strongly related to the  
355 number of years ( $Y_{NB}$ ) since the beginning of the experiment ( $R^2 = 0.84$ ,  $P < 0.001$ ), followed by the  
356 change in total rainfall during the crop cycle ( $R^2 = 0.48$ ,  $P < 0.001$ ), and average temperature ( $R^2 = 0.33$ ,  
357  $P < 0.001$ , Table S16). In our experiment,  $Y_{NB}$  was not significantly correlated with rainfall or mean  
358 temperature, and these two climatic variables were not correlated to each other either. These results  
359 suggest that in our context, sugarcane crop management had a higher effect on weed community  
360 structure than climate and highlighted how crop management led to homogenized weed communities  
361 despite climate variability (Derrouch et al. 2021). Similar observations have been made on other  
362 cropping systems, such as oilseed rape, where tillage intensity was a main factor, closely followed by  
363 rainfall (Hanzlik and Gerowitt 2011). In the case of sugarcane, straw management is known to impact  
364 the weed community (Carvalho et al. 2017). Sugarcane straw can limit the emergence of weeds with a  
365 low amount of resources in the seeds (Ferreira et al. 2010) or, on the contrary, can stimulate other species

366 germination, such as *Ipomoea* spp., *Merremia* spp. (Azania et al. 2002; Correia and Durigan 2004;  
367 Correia and Kronka Jr 2010). The species indicator analysis illustrated that the homogenization was  
368 associated with the disappearance of a few species (*Ageratum conyzoides*, *Indigofera hirsuta*, *Solanum*  
369 *americanum*) after plant crop (i.e., once the straw mulch was applied each year) and the appearance of  
370 many species with all growth habits in ratoon crops (Fig. 3c). In particular, weed abundance of small  
371 ligneous, liana and tall grasses increased over time (Fig. 3c).

372 Pairwise comparisons of weed communities revealed how the IR conditions affected the weed  
373 communities in the first two years, with little impact afterward (Fig. 3b, Table S17). In both years, the  
374 WC and LWC had similar weed communities (Table S17), while companion crops significantly  
375 modified weed communities with two distinct effects depending on the sowing of *Canavalia ensiformis*  
376 (CC2, CC4, and CC6 in 2014-2015 and 2015-2016, and CC5 in addition in 2015-2016) or *Desmodium*  
377 *intortum* companion crops (CC1, CC3, and CC5 in 2014-2015, Table S3). *C. ensiformis* had a higher  
378 ground cover compared to *D. intortum* (Fig. 2a), which can explain the different impacts on weed  
379 communities. Indeed, Soulé et al. (2024) showed that the companion crop development, more than their  
380 species identity, determines their regulation effect in sugarcane intercropping systems. Considering  
381 weed species indicators, some species were only associated with LWC and WC but not with the CC  
382 conditions, such as *Amaranthus* sp, *Argemone mexicana*, *Crotalaria retusa* (in plant crop, Fig. 3d), and  
383 *Croton bonplandianus* (in ratoon crop, Fig. 3e). These species, which were well regulated by companion  
384 crops, are known to grow better in the cold season, making them potentially less competitive in summer.  
385 Poggio (2005) also showed that intercropping could influence weeds differently depending on their  
386 emerging season in tropical climates. Additionally, *Oxalis corniculata* and *Mimosa pudica* were not  
387 indicators in CC conditions with *C. ensiformis*, while *Ipomoea obscura* was not an indicator in CC  
388 conditions with *D. intortum* (Fig. 3d,e). Companion crops have the potential to reduce the abundance of  
389 weed species that are competitively inferior (Smith and Gross 2007), such as small species, more  
390 sensitive to light competition. However, thanks to their ability to use other plants as support to grow,  
391 lianas are less sensitive to competition for light and can grow despite shading (Martin et al. 2012). A  
392 hypothesis is that *D. intortum*, itself a liana, was able to limit the growth of weeds with the same growth  
393 type (as *I. obscura*) or due to its potential allelopathic effect (Hooper et al. 2015). From the third ratoon,  
394 IR conditions almost did not affect indicator species (Fig. S2), possibly due to the prominent effect of  
395 sugarcane management and climate.

396

### 397 3.3. Sugarcane yield and sucrose content

398 Despite inter-specific competition between sugarcane, companion crops, and weeds, the intercropping  
399 or low-control systems had a low impact on system productivity (Fig. 4a,b). Sugarcane yield (fresh stalk  
400 yield) was little influenced by the fixed factors tested ( $R_m^2 = 0.21$ , Table S12), with mean yield ranging

401 from 134 to 230 Mg ha<sup>-1</sup>. The yield was not influenced by the number of years since the beginning of  
402 the experiment (Fig. 4a) but only by the interaction between the crop cycle and IR condition (Table S12).  
403 Nonetheless, a unique difference was found between CC5 and CC6 in plant crops ( $P = 0.04$ ), and no  
404 difference among IR conditions in ratoon crops. This absence of the effect of interspecific competition  
405 on sugarcane yield (fresh stalk mass) is inconsistent with previous studies. In a worldwide meta-analysis  
406 on sugarcane legume intercropping, Viaud et al. (2023) showed that legume intercropping statistically  
407 reduced yield by 3% worldwide and 6% in La Réunion compared to monocropping, despite considerable  
408 variability. In our study, even if not significant, the average difference between intercropping and  
409 monocropping was -7%, suggesting that the absence of effect could result from the large variability in  
410 our fresh yield measurements. Another explanation could be the composition of our companion crops  
411 and weed mixtures during the first years of the experiment, which had a higher proportion of companion  
412 crops than weeds (Fig2a,b). Under these conditions, Viaud et al. (2023) showed that the negative impact  
413 on yield should be limited.

414 Similarly, Sugar<sub>SC</sub> was little affected by the inter-row conditions (Fig. 4b, Table S12), and a unique  
415 difference was found in plant crops where LWC weed control had a higher Sugar<sub>SC</sub> than CC6 ( $P = 0.04$ ),  
416 the other IR conditions being intermediate. The absence of the impact of interspecific competition  
417 (intercropping or low weed control) on sucrose content is consistent with previous studies on sugarcane  
418 juice quality (e.g., in China, Yang et al. 2013). Sugar<sub>SC</sub> increased from plant to ratoon crop as classically  
419 observed in sugarcane systems when both are harvested at the same age (Inman-Bamber 2013).

420 In contrast to other sugarcane-producing countries (Park et al. 2005), there is little ratoon yield decline  
421 in La Réunion (eRcane personal communication). This yield stability may be due to the low  
422 mechanization of farming systems and the high quality of the volcanic soils on the island (Dlamini and  
423 Zhou 2022). In our study, no yield decline was observed despite the increasing weed pressure over time,  
424 whether in monocropping or intercropping. As a result, the hypothesis from Soulé et al. (2024), which  
425 suggested that the weed pressure is responsible for the rising impact of intercropping on yield over time,  
426 as supported by Viaud et al. (2023), was not confirmed by our findings. There are two possible  
427 explanations for this observation. The first one suggests that the regions that are more likely to  
428 experience yield decline may be facing an increasingly harmful impact (Wang et al. 2020). The second  
429 one proposes that the impact of weed competition on yield can be limited by weeding the sugarcane row  
430 in our systems. Indeed, recent studies have shown that companion crops or weeds in the inter-row have  
431 little impact on the above-ground part of the harvested sugarcane despite their possible impact on the  
432 sugarcane roots (Christina et al. 2023). Nevertheless, this system leads to an increase in weeding in the  
433 sugarcane row.

434

435

### 436 3.4. Chemical and manual weedings

437 Sugarcane intercropping systems make it possible to reduce herbicide use compared to monocropping  
438 at the cost of increased manual weeding (Fig. 4c,d). Both HTFI ( $P < 0.001$ ) and MW ( $P < 0.001$ ) were  
439 influenced by the interaction between YNB and IR conditions (Table S12). On average across years,  
440 HTFI was lower by 59% in CC and 49% in LWC conditions compared to WC (Fig. 4c). This decrease  
441 is higher than previous observations in an experimental network in Reunion Island (-37%, Soulé et al.  
442 2024) but similar to other countries (Kaur et al. 2016) suggesting that the herbicide reduction will be  
443 highly influenced by local conditions such as natural flora, soil, and climate. The ability of intercropping  
444 to reduce pesticide use has also been highlighted in many cropping systems (Yan et al. 2024).  
445 Additionally, HTFI increased annually in the WC condition, which could be explained by the selection  
446 of more competitive weeds requiring higher herbicide treatments and leading to the observed decrease  
447 in  $COV_{WEED}$  in this condition (Fig. 2b). Contrary to WC and LWC, MW increased annually in all CC  
448 conditions, with the highest increase observed in CC2 and the lowest in CC6 (Table S12). This increase  
449 in manual weeding over time is linked to the increase in weed pressure (Fig. 2b). Moreover, MW was  
450 higher by 103% on average in CC conditions compared to WC or LWC (Fig. 4d), and among them, CC6  
451 had the lowest MW, and CC1 and CC2 were the highest. Such observation that intercropping requires a  
452 higher manual work was also done by Mansuy et al. (2019) and Soulé et al. (2024) in Reunion Island  
453 but has been poorly highlighted in the international literature, which mainly focuses on using  
454 complementary herbicides (Yan et al. 2024).

455 Despite being poorly investigated in the literature, low weed control in the inter-row could be a  
456 promising system to reduce herbicide use. In our experiment, LWC had a similar MW to WC.  
457 Additionally, it required a slightly higher use of herbicide than some CC conditions due to the  
458 complementary use of herbicide on the sugarcane row. However, the choice of areas to be left colonized  
459 by weeds must be carefully considered, as the presence of weeds throughout the plot can lead to yield  
460 loss of 0.1-0.2 Mg ha<sup>-1</sup> per day of weed control delay, and the absence of weed control can lead to 80%  
461 of yield loss (Marnotte et al. 2008). Nonetheless, this practice is worth pursuing as it starts to be adopted  
462 in other perennial cropping systems, such as vine (Fernández-Mena et al. 2021) and is increasingly  
463 studied in banana cropping systems (Achard et al. 2018) as a substitute companion crops.

464

### 465 3.5. Soil fertility

466 Despite seven years of intercropping, including legumes, little effect could be observed on soil fertility,  
467 particularly regarding chemical and biological fertility indicators (Fig. 5). However, physical fertility  
468 increased with the plant development in the inter-row (Fig. S3). At the end of the experiment, no  
469 statistical differences were found among IR conditions for all soil health indicators (Fig. 5, Table S18).  
470 Similarly, the soil chemical characteristics measured at the end of the experiment (pH, N, C, P, K...)



471 were similar among IR conditions (Table S2). The absence of impact on chemical and biological fertility  
472 is not inconsistent with previous studies on sugarcane intercropping systems. Although short-term  
473 experiments have shown that there is a higher soil NPK availability after legume dies in intercropping  
474 systems (Lian et al. 2019; Solanki et al. 2019), the only studies that examined the long-term effect of  
475 sugarcane legume intercropping did not report any positive effect on soil properties, e.g., soil organic  
476 carbon content, even after seven years (Wang et al. 2020), like our results. Similarly, short-term  
477 experiments highlighted how intercropping could improve biological fertility through the enhancement  
478 of soil bacterial abundance and diversity (Pang et al. 2022), in particular, diazotrophs (Solanki et al.  
479 2019), but no long-term effect has been highlighted to our knowledge. Such absence of response could  
480 be linked to i) relatively low biomass produced by companion crops in intercropping systems compared  
481 to rotation (de Resende et al. 2003; Shoko et al. 2007), ii) soil organic matter content that is already high  
482 due to the high biomass production of sugarcane, or iii) significant losses of legume-N after their death  
483 through volatilization and N<sub>2</sub>O emissions as recently suggested by Viaud (2023). Indeed, a growing  
484 number of studies pointed out legume N losses through ammonia volatilization (Glasener and Palm  
485 1995; Nett et al. 2016) and N<sub>2</sub>O emissions (Peyrard et al. 2016), which are favored by sugarcane mulch  
486 (Pinheiro et al. 2018). In our system with straw mulch, a low amount of C combined with low soil C  
487 stabilization ability (Feller and Beare 1997) and higher mineralization rate in tropical conditions (Ogle  
488 et al. 2005) may explain why the effect of legume on soil chemical fertility was less noticeable than in  
489 temperate conditions.

490 Studies in other cropping systems have shown that intercropping can improve soil structure in tropical  
491 conditions by increasing soil porosity and infiltration rate and reducing run-off (e.g., in cotton, Blaise et  
492 al. 2021). Compared to chemical fertility, the impact of sugarcane intercropping on soil physical fertility  
493 has been poorly investigated. Nonetheless, a few studies suggest the ability of intercropping to reduce  
494 bulk density and improve infiltration (e.g., in India, Singh et al. 2008, with a bulk density of 1.26 g cm<sup>-3</sup>  
495 <sup>3</sup>), but such response is not always observed even in soils with similar compaction (e.g., Singh et al.  
496 2021, with bulk density of 1.3 g cm<sup>-3</sup>). In our experiment, the soil physical fertility index was positively  
497 correlated with plant development (CC and weeds) in the inter-row (Fig. S3). Despite still being unclear,  
498 the effect of intercropping on soil decompaction is worth pursuing, particularly in mechanized sugarcane  
499 cropping systems with highly compacted soils (Cherubin et al. 2016).

500

### 501 3.6. Cost, working hours, and revenue

502 Globally, total weed control costs and working hours were doubled in intercropping systems compared  
503 to chemical monocropping or low weed control systems (Fig. 6). This difference was mainly due to costs  
504 and working hours needed for sowing (manual up to 2019 and with micro-tractors afterward). The costs  
505 and working hours for herbicide application were lower in CC than in WC, but an increase in manual  
506 weeding price and working hours compensated for it. Nonetheless, costs ( $P < 0.001$ ) and working hours  
507 ( $P < 0.001$ ) were influenced by  $Y_{NB} \times IR$  interactions (Table S12). While costs and working hours  
508 remained stable over the years in WC, LWC, CC1, CC2, and CC5, they slightly decreased in CC3, CC4,  
509 and CC6 (remaining higher than WC and LWC, Fig. 6a,e, Table S13). By comparison, only 25% of  
510 revenue variability was explained by the fixed effects in the analysis (Table S12), highlighting the  
511 prominent effect of cultivation year variability (as for  $Yield_{SC}$  and  $Sugar_{SC}$ ). Revenue was also  
512 significantly influenced by  $Y_{NB} \times IR$  interaction ( $P = 0.02$ , Table S12), but no difference in trends could  
513 be highlighted in the pairwise comparison (Table S13). Similarly to yield, no apparent effect of IR  
514 conditions was observed on revenue. In our experiment, where a large part of chemical weeding was  
515 performed with a backpack sprayer, changes in manual and chemical weeding offset each other in CC  
516 conditions. This compensation was also highlighted by Soulé et al. (2024) for different levels of  
517 mechanization in the farms on Reunion Island. Additionally, Soulé et al. (2024) illustrated how using  
518 tractors (instead of manual sowing or micro-tractors in this experiment) could significantly reduce  
519 sowing costs in La Réunion. Nonetheless, our economic results are very different from those observed  
520 in other countries, such as India (Kaur et al. 2016), Pakistan (Nadeem et al. 2020), or China (Tang et al.  
521 2021), where higher net profits in intercropping have been reported compared to monocropping. In these  
522 countries, the companion plant is harvested and provides additional revenue. In Reunion Island,  
523 harvesting companion plants was also a traditional practice for the personal consumption of small-scale  
524 growers. Nonetheless, in this experiment, the companion crops were chosen to reduce weed infestation  
525 to limit herbicide use and not for valorization as part of the ECOPHYTO national program. In addition,  
526 the economic balance in these systems will be strongly influenced by labor costs, which are higher on  
527 Réunion Island than in other countries, as well as the sale price of sugarcane, which in Réunion is based  
528 on the conventional price.

529

530

### 531 3.7. Multi-criteria analysis and long-term sustainability

532 To compare the long-term sustainability of intercropping or low weed control practices and chemical  
533 weed control, we evaluated the systems based on cumulated productivity, ecosystem functions (plant  
534 biodiversity, reduced herbicide use, and soil fertility), and socio-economic efficiency (working hours,  
535 change in costs and revenue, Fig. 7). Among the seven-years cumulated indices, the ecosystem function  
536 index for herbicide application ( $EFI_{Herb}$ ,  $P < 0.001$ ), biodiversity ( $EFI_{Biodiv}$ ,  $P < 0.001$ ), total inter-row  
537 ground cover ( $EFI_{Gcover}$ ,  $P < 0.001$ ), as well as the socio-economic index for weed control costs ( $SEI_{Cost}$ ,  
538  $P < 0.001$ ) and working time ( $SEI_{Hour}$ ,  $P < 0.001$ ) were influenced by the IR condition (Fig. 7, Table  
539 S19). On the contrary, the IR conditions had no significant impact on  $EFI_{Prod}$  ( $P = 0.18$ ),  $SEI_{Revenue}$  ( $P =$   
540  $0.25$ ),  $SFI_{Biol}$  ( $P = 0.62$ ),  $SFI_{Chim}$  ( $P = 0.81$ ), and  $SFI_{Phys}$  ( $P = 0.18$ ). The cumulated herbicide application  
541 in CC was slightly lower than LWC ( $P = 0.02$ ), itself lower than WC ( $P < 0.001$ ), resulting in an increase  
542 in  $EFI_{Herb}$  by 51% for CC and 45% for LWC, compared to WC.  $EFI_{Biodiv}$  was not different between CC  
543 and WC ( $P = 0.70$ ) but was higher in LWC compared to WC or CC ( $p < 0.001$ ). As a result,  $EFI_{Biodiv}$   
544 increased by 20% in LWC compared to WC. Cumulated ground covers differed among all three IR  
545 conditions, and  $EFI_{Gcover}$  increased by 144% in CC and 65% in LWC compared to WC. Finally,  
546 cumulated costs ( $P = 0.95$ ) and working hours ( $P = 0.98$ ) were not different between WC and LWC.  
547 Nonetheless,  $SEI_{Cost}$  and  $SEI_{Hour}$  decreased by 87 and 161%, respectively, in the CC condition compared  
548 to the WC condition.

549 Our analysis confirmed that intercropping is an appropriate practice to reduce herbicide use and is  
550 relevant in reducing pesticide use by 50% by 2025 in the agricultural sector (national ECOPHYTO II  
551 program in France). Additionally, this practice could provide increased protection against erosion in  
552 tropical islands subject to regular extreme storms that affect sugarcane production (Christina et al.  
553 2021a). Nonetheless, because of increased costs and working hours, farmers would likely adopt such  
554 intercropping practices only with financial incentives, which could take various forms, including labels  
555 for sale, payment for ecosystem services, or the harvest of the companion plant for additional return.  
556 Despite being largely ignored in the international literature, our analysis also suggests that a fine-tuned  
557 regulation of the spontaneous weeds in the inter-row could be another promising practice to limit the  
558 impacts of herbicide on the environment without additional costs or working hours. Additionally, this  
559 practice led to more diversified weed communities that can benefit the environment, promoting  
560 ecosystem functions such as pollinators, auxiliaries, or additional sources of organic matter (Mézière et  
561 al. 2015). Recent studies suggest that diversified weed communities could limit the negative effect of  
562 competitive and dominant species on crop productivity while potentially promoting ecosystem functions  
563 provided by subordinate species (Storkey and Neve 2018; Adeux et al. 2019a, b). Nonetheless, this  
564 practice will face the common perceptions of weeds as “crop enemies” by several stakeholders  
565 (sugarcane growers, agricultural advisors, researchers, Merfield 2022). To effectively regulate weed

566 species in diversified sugarcane systems, a more detailed evaluation of their harmfulness is now required  
567 (MacLaren et al. 2020).

568

#### 569 **4. Conclusion**

570 Our study presents the first long-term multi-criteria evaluation of intercropping in sugarcane. In  
571 particular, the evolution of weed communities over the long term and the impact on soil fertility have  
572 been little studied in sugarcane under tropical conditions. Our findings show that intercropping can be  
573 a long-term sustainable practice to reduce herbicide use and increase erosion protection. However,  
574 intercropping involves increased costs and working hours on the French Island of La Réunion, especially  
575 for companion crop sowing. Therefore, farmers must receive systemic support to transition towards  
576 agroecological practices in these intensive tropical cropping systems. In addition, we found that  
577 regulating spontaneous weeds in the inter-row appears to be a promising crop management technique  
578 that provides ecosystem functions similar to intercropping. However, sugarcane researchers have still  
579 largely unstudied this practice.

580

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600 <https://dataverse.cirad.fr/dataverse/APEEDAIS>).

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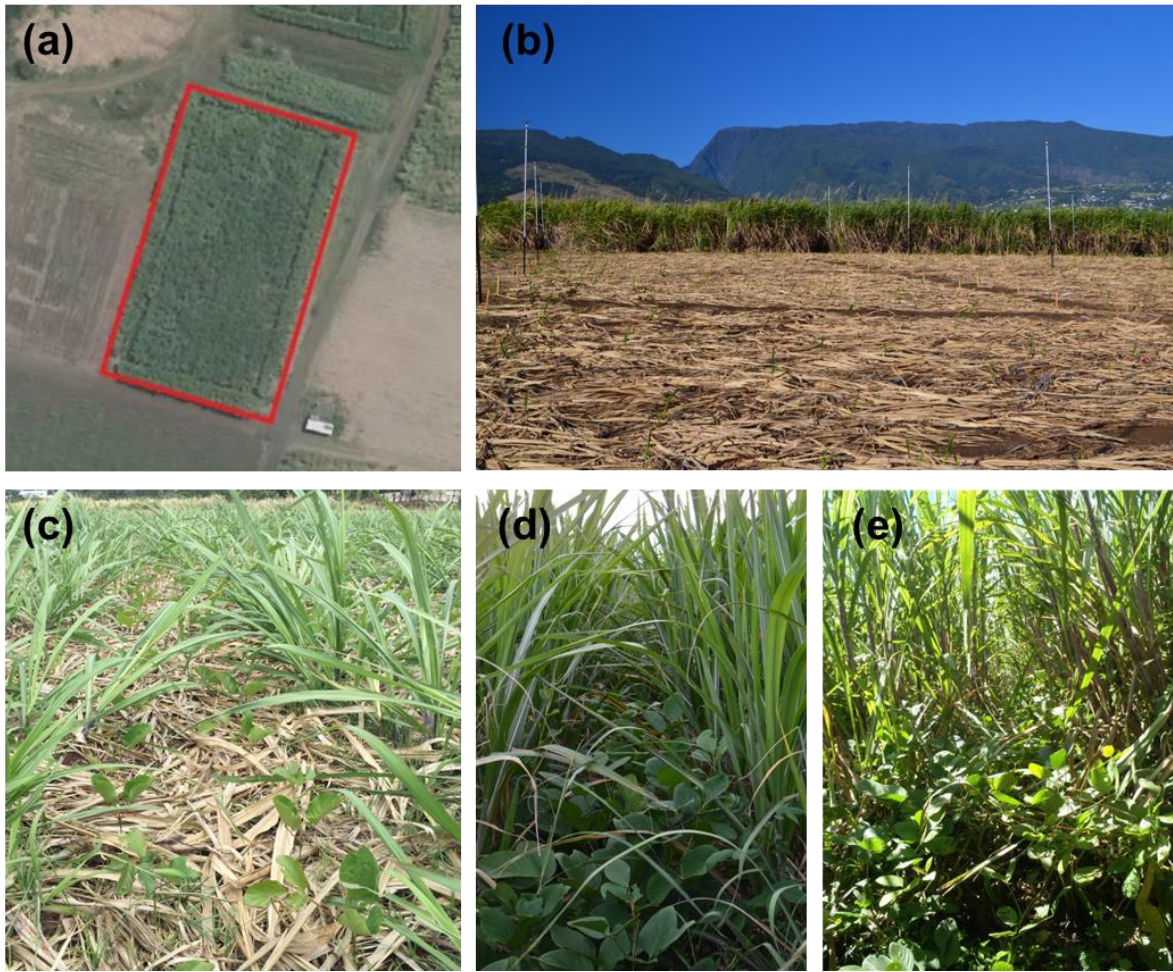
885

886 **Table 1.** Variable names, description and units or calculation method.

Variable	Description	Unit or calculation
<i>Sugarcane, companion crop and weeds</i>		
Yield <sub>SC</sub>	Sugarcane yield in fresh stalk mass	Mg ha <sup>-1</sup>
Sugar <sub>SC</sub>	Sucrose content	%
COV <sub>CC</sub>	Mean ground cover by companion crop during the cycle	%
COV <sub>WEED</sub>	Mean ground cover by weeds during the crop cycle	%
S <sub>WEED</sub>	Weed specific richness	Number
<i>Weed control management</i>		
HTFI	Herbicide treatment frequenct index	dimensionless
MW	Number of manual weedings	Number
<i>Socio-economic records</i>		
Costs	Total costs of weed control	€ ha <sup>-1</sup>
Revenue	Revenue from the sale of sugarcane	€ ha <sup>-1</sup>
W <sub>Hour</sub>	Total of working hour for weed control in the field	h ha <sup>-1</sup>
<i>Soil fertility indicators</i>		
N <sub>min</sub>	Soil N mineralization over the crop cycle	kg ha <sup>-1</sup> yr <sup>-1</sup>
P <sub>deficiency</sub>	P deficiency based on soil P content and recommended doses	mg kg <sup>-1</sup>
K <sub>availability</sub>	K availability based on exchangeable potassium content	cmol+ kg <sup>-1</sup>
Lamina	Soil degradation rate (mesofauna and little macrofauna activity indicator)	d <sup>-1</sup>
Situresp	Basal soil respiration indicator	dimensionless
POXC	Short-term turnover soil carbon pool indicator	mg kg <sup>-1</sup>
VESS	Visual evaluation of soil structure	dimensionless
Beerkan	Water infiltration speed indicator	mL min <sup>-1</sup>
Agg <sub>SoilSurf</sub>	Aggregate stability in the 0-10cm soil layer.	dimensionless
<i>Ecosystem function index compared to chemical weed control condition</i>		
EFI <sub>Prod</sub>	Increase in productivity in terms of sugar	$[\text{Yield}_{SC} * \text{Sugar}_{SC}]_{CC} / [\text{Yield}_{SC} * \text{Sugar}_{SC}]_{WC} - 1$
EFI <sub>Herb</sub>	Reduction in herbicide application	$1 - [\text{HTFI}]_{CC} / [\text{HTFI}]_{WC}$
EFI <sub>Biodiv</sub>	Increase in weed specific richness	$[\text{S}_{WEED}]_{CC} / [\text{S}_{WEED}]_{WC} - 1$
EFI <sub>Gcover</sub>	Increase in ground cover in the inter-row by both weeds and companion crops	$[\text{COV}_{TOT}]_{CC} / [\text{COV}_{TOT}]_{WC} - 1$
<i>Socio-economic index compared to chemical weed control condition</i>		
SEI <sub>Revenue</sub>	Increase in revenue from sugar yield	$[\text{Revenue}]_{CC} / [\text{Revenue}]_{WC} - 1$
SEI <sub>Cost</sub>	Reduction in cost of weed control	$1 - [\text{Cost}]_{CC} / [\text{Cost}]_{WC}$
SEI <sub>Hour</sub>	Reduction in working hours	$1 - [\text{W}_{Hour}]_{CC} / [\text{W}_{Hour}]_{WC}$
<i>Soil fertility index compared to chemical weed control condition</i>		
SFI <sub>Biol</sub>	Increase in soil biological fertility index	$[\text{SFI}_{Biol}]_{CC} / [\text{SFI}_{Biol}]_{WC} - 1$
SFI <sub>Chim</sub>	Increase in soil chemical fertility index	$[\text{SFI}_{Chim}]_{CC} / [\text{SFI}_{Chim}]_{WC} - 1$
SFI <sub>Phys</sub>	Increase in soil physical fertility index	$[\text{SFI}_{Phys}]_{CC} / [\text{SFI}_{Phys}]_{WC} - 1$

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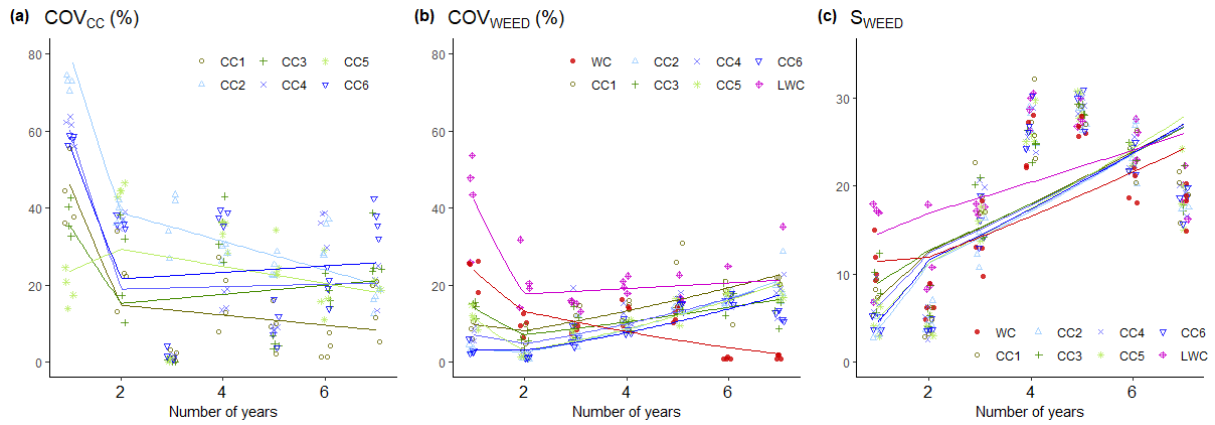
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890 **Fig. 1.** Aerial view of the experiment (a), experiment a few weeks after harvest (b), and growth of the  
891 companion crop in the sugarcane inter-row at different growing stages (c-d) illustrated with the example  
892 of jack bean (*Canavalia ensiformis*). Source: eRcane©.

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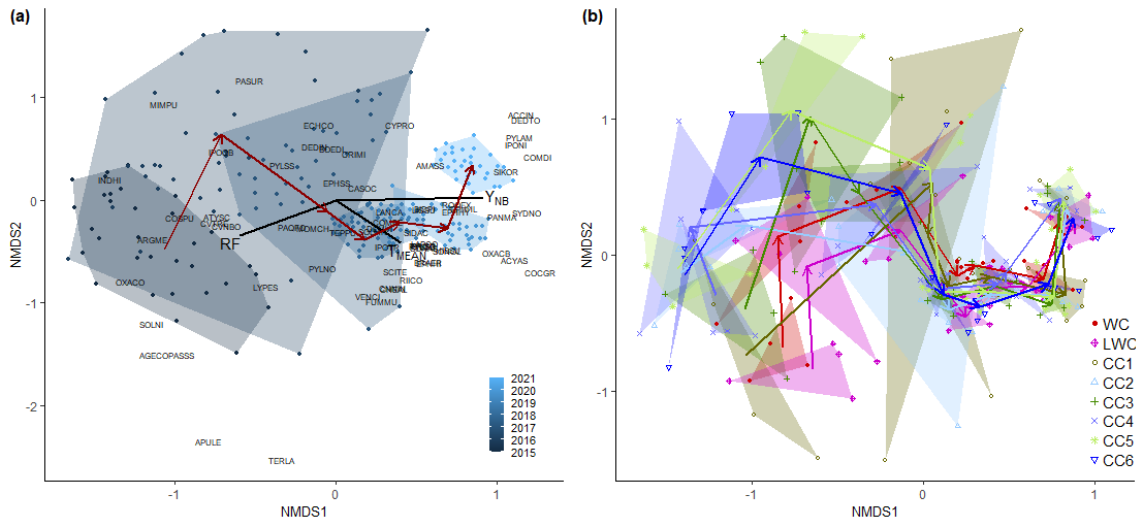


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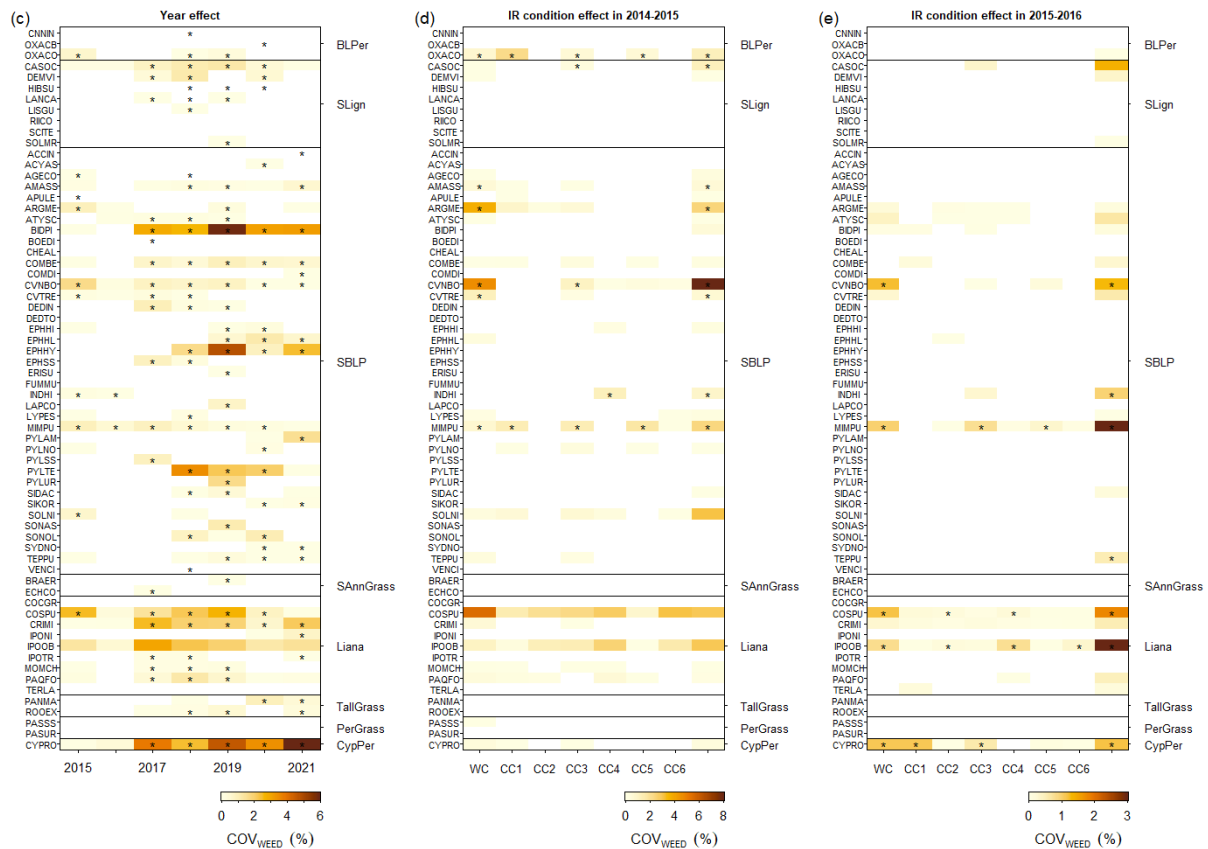
895 **Fig. 2.** Dynamics of average ground cover by companion crops ( $COV_{CC}$ , a),  
 896 weeds ( $COV_{WEED}$ , b), and  
 897 weed species richness ( $S_{WEED}$ , c) with the number of years since the beginning of the experiment,  
 898 depending on the inter-row condition: chemical weed control (WC), companion crops sown in the inter-  
 899 row (CC1 to CC6, Table S3), and low weed control (LWC). The lines represented the marginal  
 900 predictions by the statistical models from Table S12 (not taking into account the random effect), and the  
 901 points represented the observed values.

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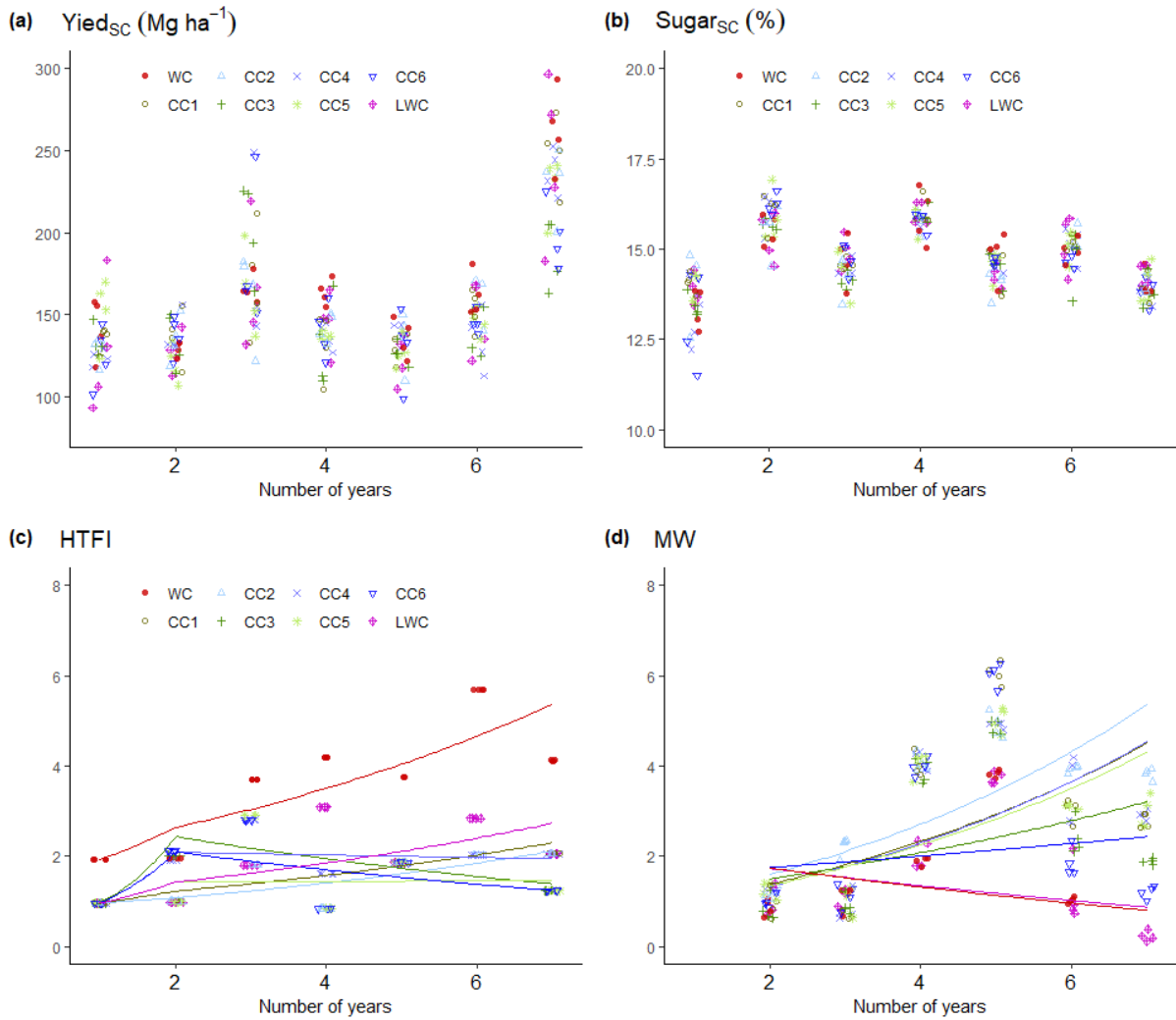
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**Fig. 3.** Non-metric multidimensional scaling (NMDS,  $k=2$ , stress = 0.19) ordination of weed communities by (a) cultivation year and the interaction between inter-row conditions (IR) and year (b). In (a) and (b), data points represent communities (plots), and colored polygons delimitate the space of each cultivation year (a) or IR x Year levels (b). Red arrows represent the annual change between community centroids. Black vectors in (a) represent the direction and magnitude of correlations between annual rainfall (RF), mean daily temperature ( $T_{MEAN}$ ), the number of years since the beginning of the experiment ( $Y_{NB}$ ), and the ordination axis scores representing the change in weed community (Table S16). Species are projected and indicated with EPPO codes (Table S8). The change in weed species abundance (mean ground cover,  $COV_{WEED}$ ) over years (c) or between IR conditions in plant crop (2014-2015, d) and the first ratoon (2015-2016, e) are presented. Indicator species (statistically associated with a particular year or condition,  $p < 0.005$ ) are indicated by '\*'. Weed species growth habits are indicated: broad-leaf perennials (BLPer), small ligneous (SLign), small broad-leaf plants (SBLP), small annual grasses (SAnnGrass), liana, tall grasses (TallGrass), and perennial sedges (CypPer).



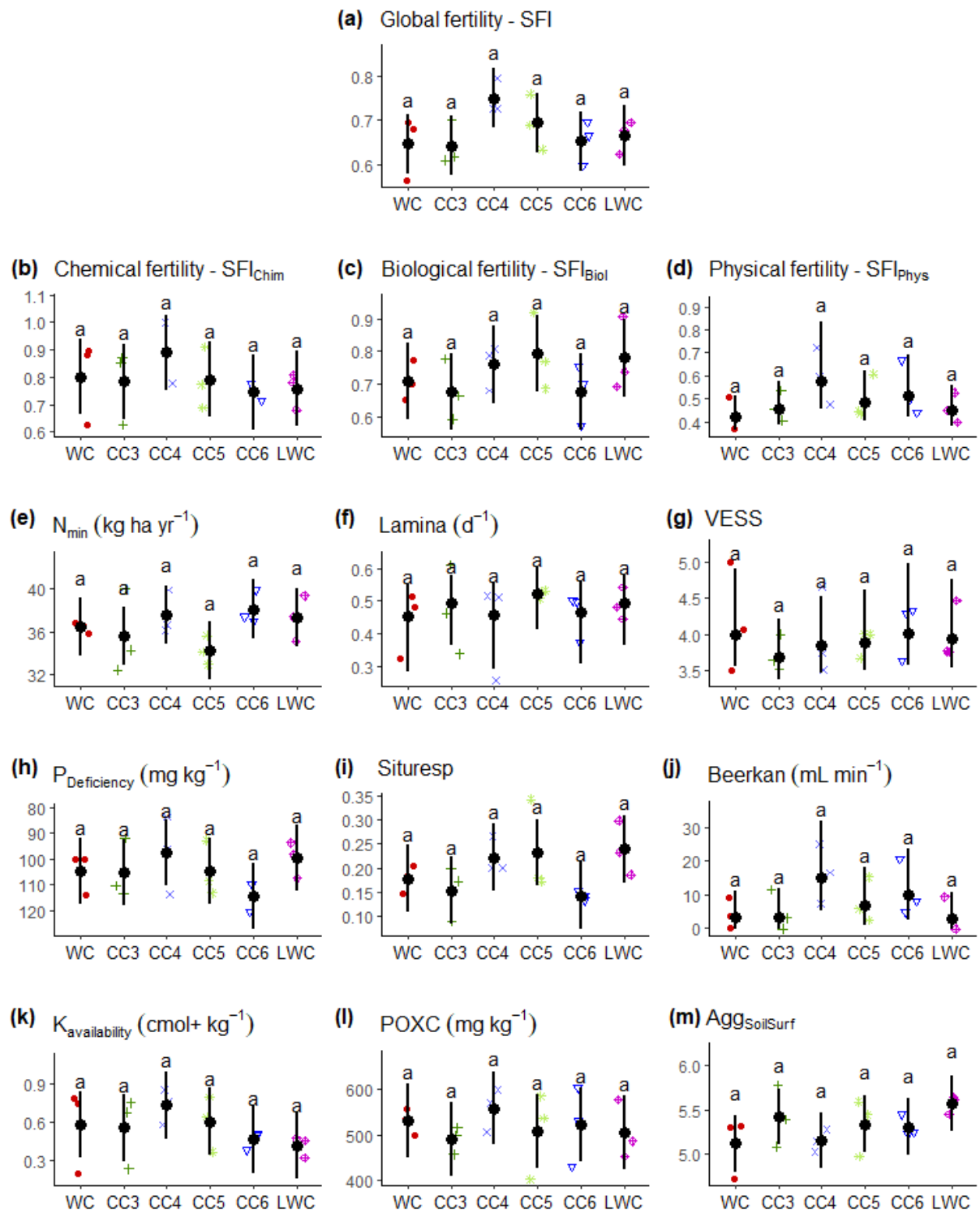


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918 **Fig. 4.** Change in sugarcane yield (Yield<sub>SC</sub>, a), sucrose content (Sugar<sub>SC</sub>, b), herbicide treatment  
 919 frequency index (HTFI) and number of manual weedings (MW, d) with the number of years since the  
 920 beginning of the experiment, depending on inter-row condition: chemical weed control (WC),  
 921 companion crops sown in the inter-row (CC1 to CC6, Table S3), and low weed control (LWC). The lines  
 922 represented the marginal predictions by the statistical models from Table S12 (not taking into account  
 923 random effect), and the points represented the observed values.

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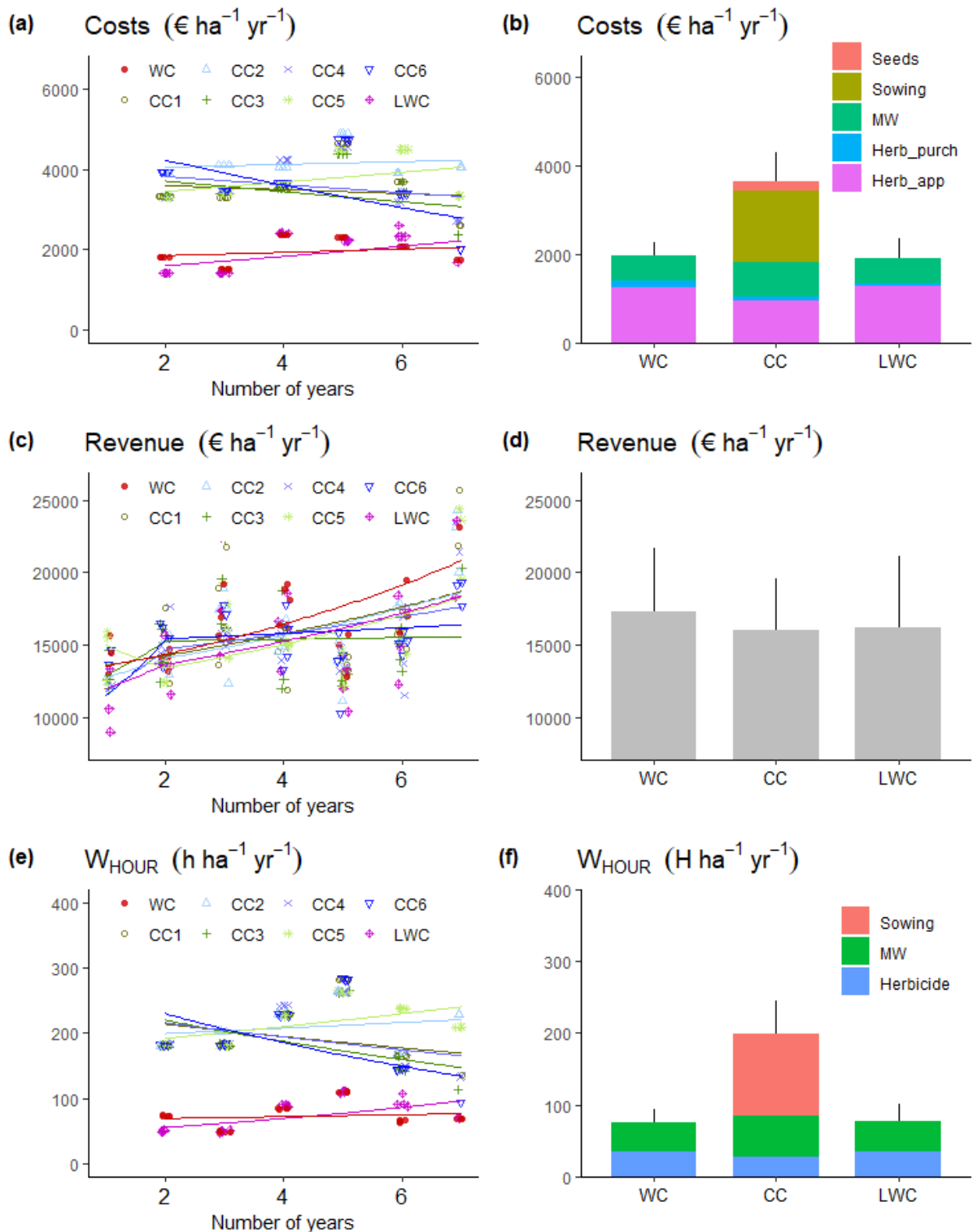
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927 **Fig. 5.** Comparison in soil fertility index (SFI) after seven years of experiment in terms of global (SFI,  
 928 a), chemical (SFI<sub>Chim</sub>, b), biological (SFI<sub>Biol</sub>, c), and physical fertility (SFI<sub>Phys</sub>, d), and soil indicators from  
 929 Table 1 (e-m), depending on the inter-row condition: chemical weed control (WC), companion crop  
 930 sequences (CC3 to CC6, Table S3), and low weed control (LWC). Mean values (black points) and  
 931 confidence intervals (bars) predicted by the linear models from Table S18 are presented. The letter ‘a’  
 932 indicated non-significant differences in the pairwise comparisons.

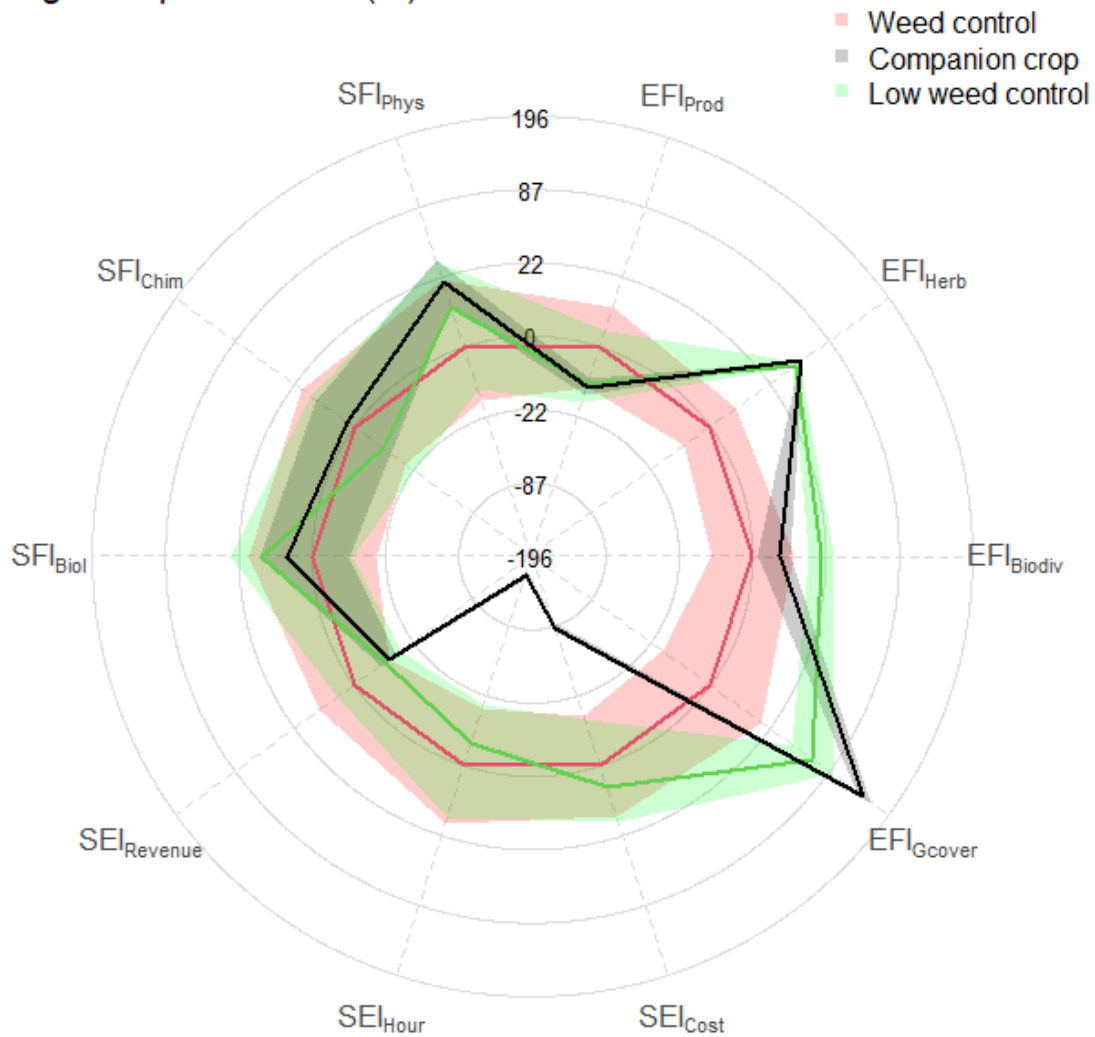
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935 **Fig. 6.** Change in weed control costs (a), revenue (c), and weed control working hours ( $W_{\text{HO$ UR}, e) with  
 936 the number of years since the beginning of the experiment, depending on the inter-row condition:  
 937 chemical weed control (WC), companion crops sown in the inter-row (CC1 to CC6, Table S3), and low  
 938 weed control (LWC). The lines represented the marginal predictions by the statistical models from Table  
 939 S12 (not taking into account random effect), and the points represented the observed values. The mean  
 940 observed values and standard deviations are represented in b, d, and f, with the distinction between  
 941 categories: seed purchase (Seeds), sowing price or working time (Sowing), manual weeding (MW),  
 942 herbicide purchase (Herb\_purch), and herbicide application price (Herb\_app).

Change compared to WC (%)



944 **Fig. 7.** Comparison in seven-year ecosystem function indices (SEI), socio-economic indices (SEI), and  
 945 soil function indices (SFI) defined in Table 1 depending on the inter-row conditions: chemical weed  
 946 control (WC), companion crops sown in the inter-row (CC), and low weed control (LWC). Values are  
 947 expressed in % in change compared to WC, and the axis was square transformed for visual purposes. A  
 948 positive value indicates an improvement compared to the chemical weed control. Lines and shadows  
 949 represent the mean and confidence intervals predicted by the statistical model from Table S19.  
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