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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 m² 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, Yield_{SC} , 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 (Sugar_{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 (COV_{CC}) or weeds (COV_{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[®], 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_{SC}, Sugar_{SC}, COV_{CC}, COV_{WEED}, S_{WEED}, 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:

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

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_{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_m²) and
268 conditional R² (both fixed and random effects, R_c²) 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 β 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⁻¹. 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_{SC} 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_{SC} 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_{SC} 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⁻¹ 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 N₂O 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 N₂O 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⁻³
495 ³), 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⁻³). 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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603 K.B., M.S., B.H, and A.M.; Validation, S.A. ; Formal analysis, M.C., K.B., and B.H. ; Investigation,
604 M.C., J.C., A.V., M.S., S.D., and A.M. ; Resources : A.M. ; Data curation : S.A. ; Writing – Original
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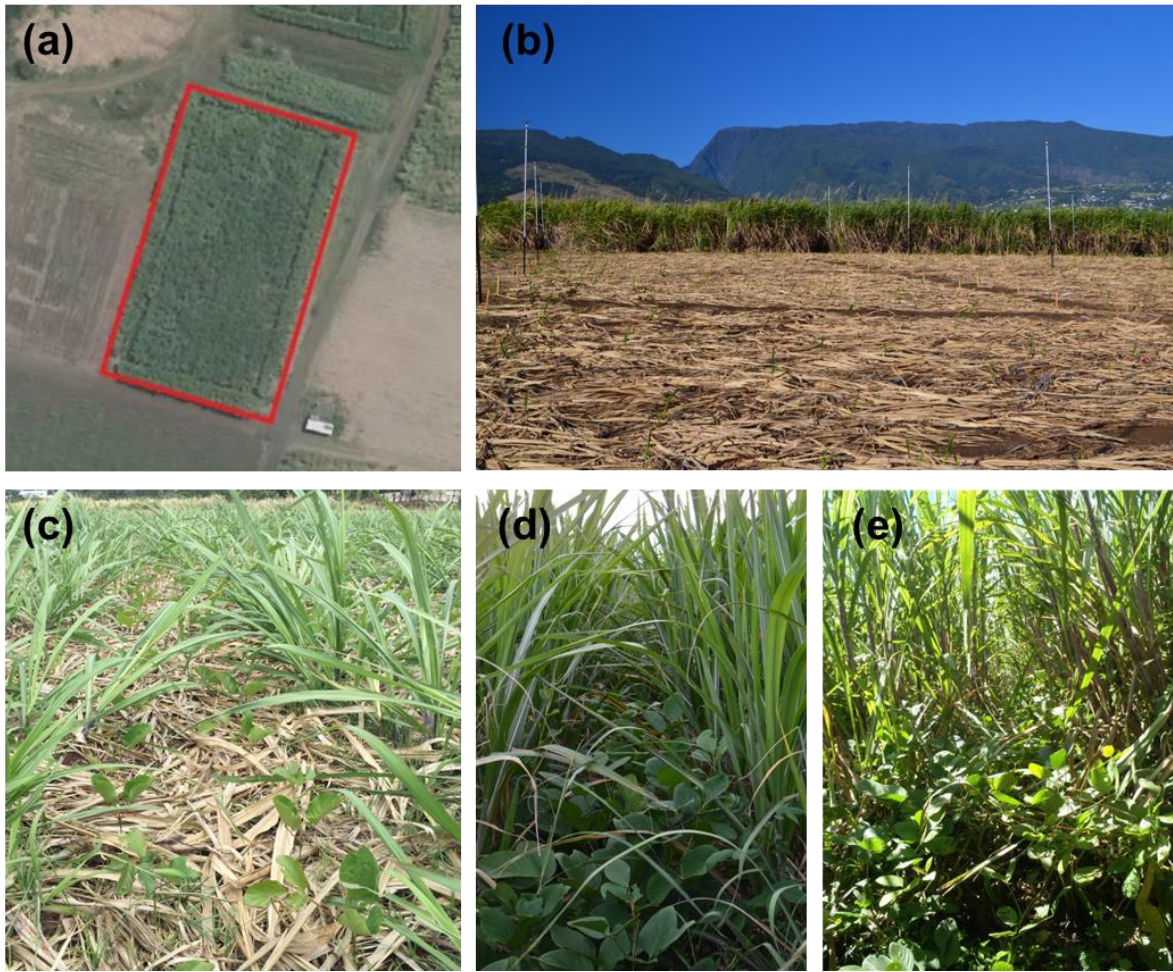
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886 **Table 1.** Variable names, description and units or calculation method.

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

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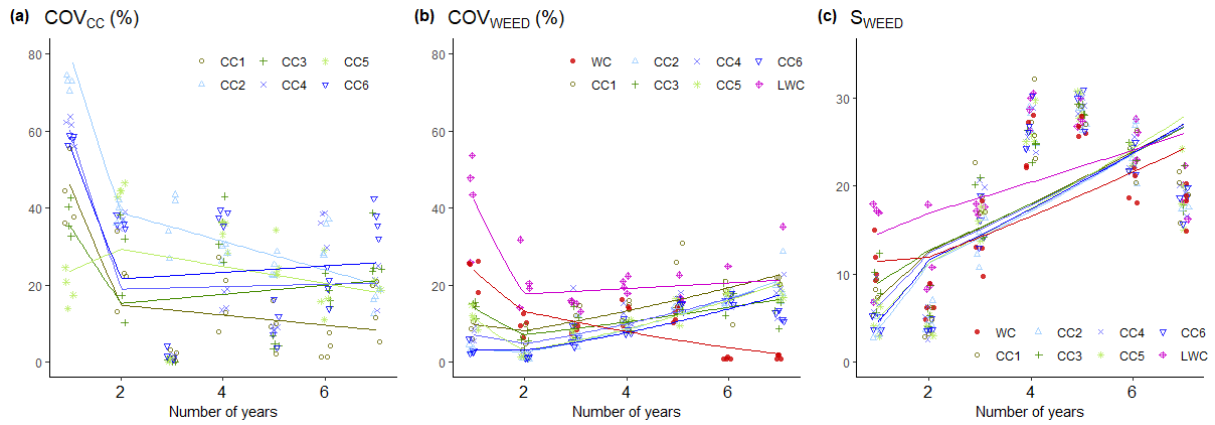
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890 **Fig. 1.** Aerial view of the experiment (a), experiment a few weeks after harvest (b), and growth of the
891 companion crop in the sugarcane inter-row at different growing stages (c-d) illustrated with the example
892 of jack bean (*Canavalia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

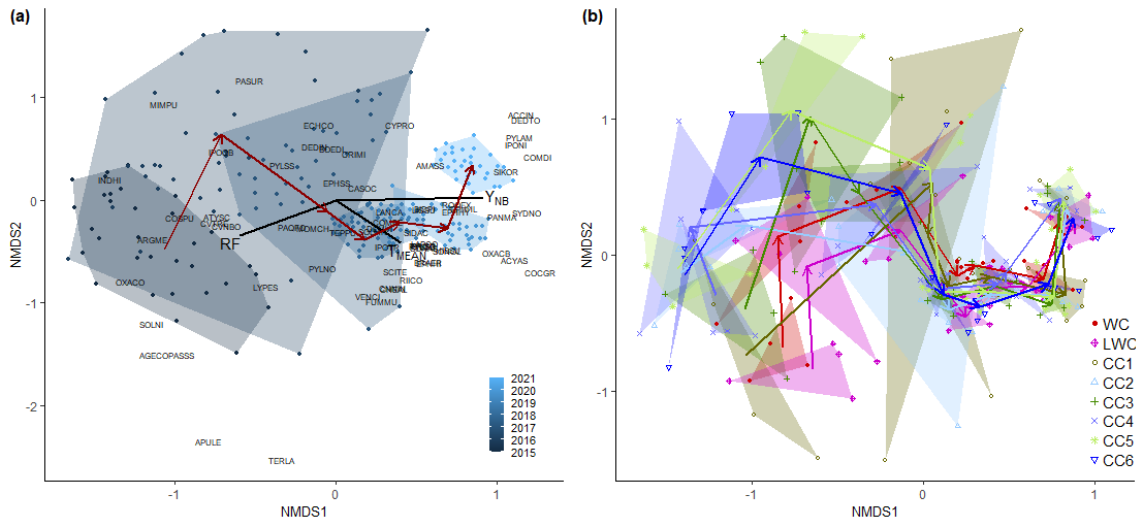
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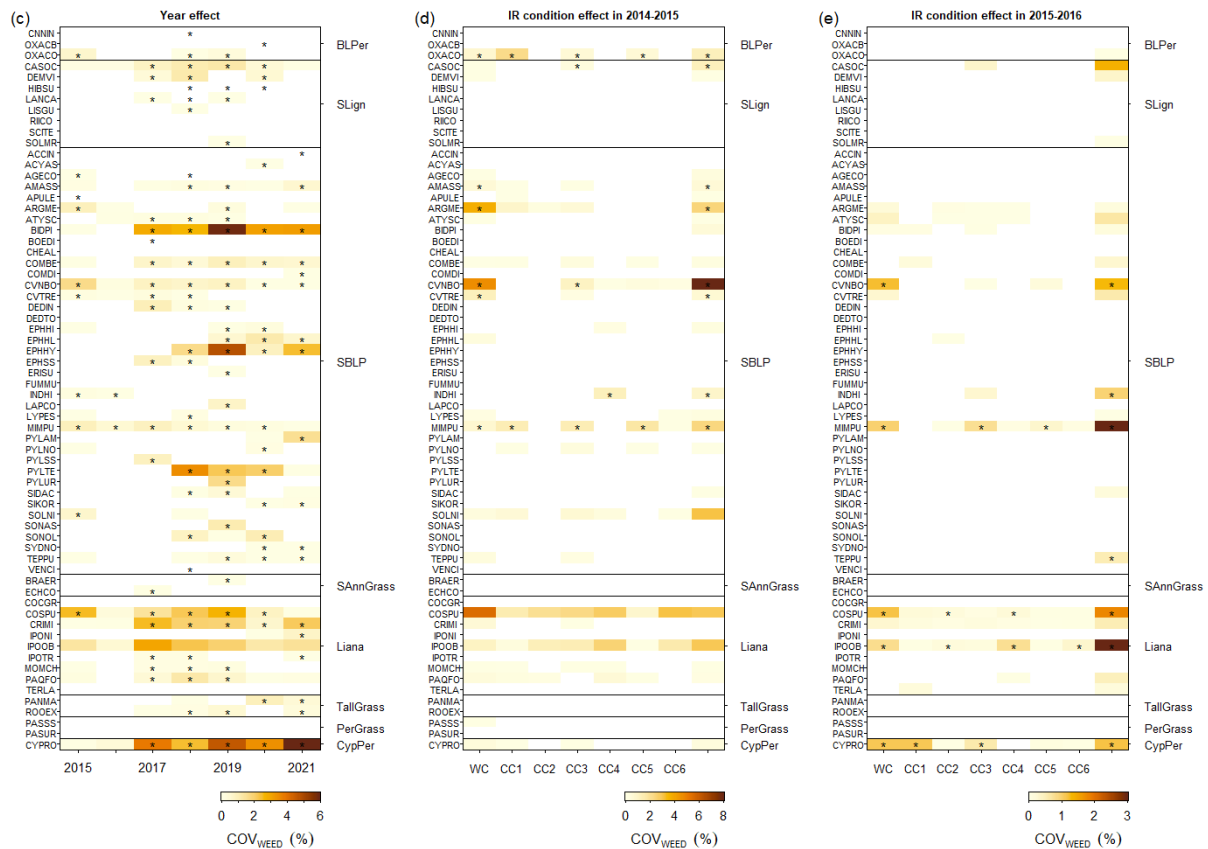
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895 **Fig. 2.** Dynamics of average ground cover by companion crops (COV_{CC} , a),
 896 weeds (COV_{WEED} , b), and
 897 weed species richness (S_{WEED} , c) with the number of years since the beginning of the experiment,
 898 depending on the inter-row 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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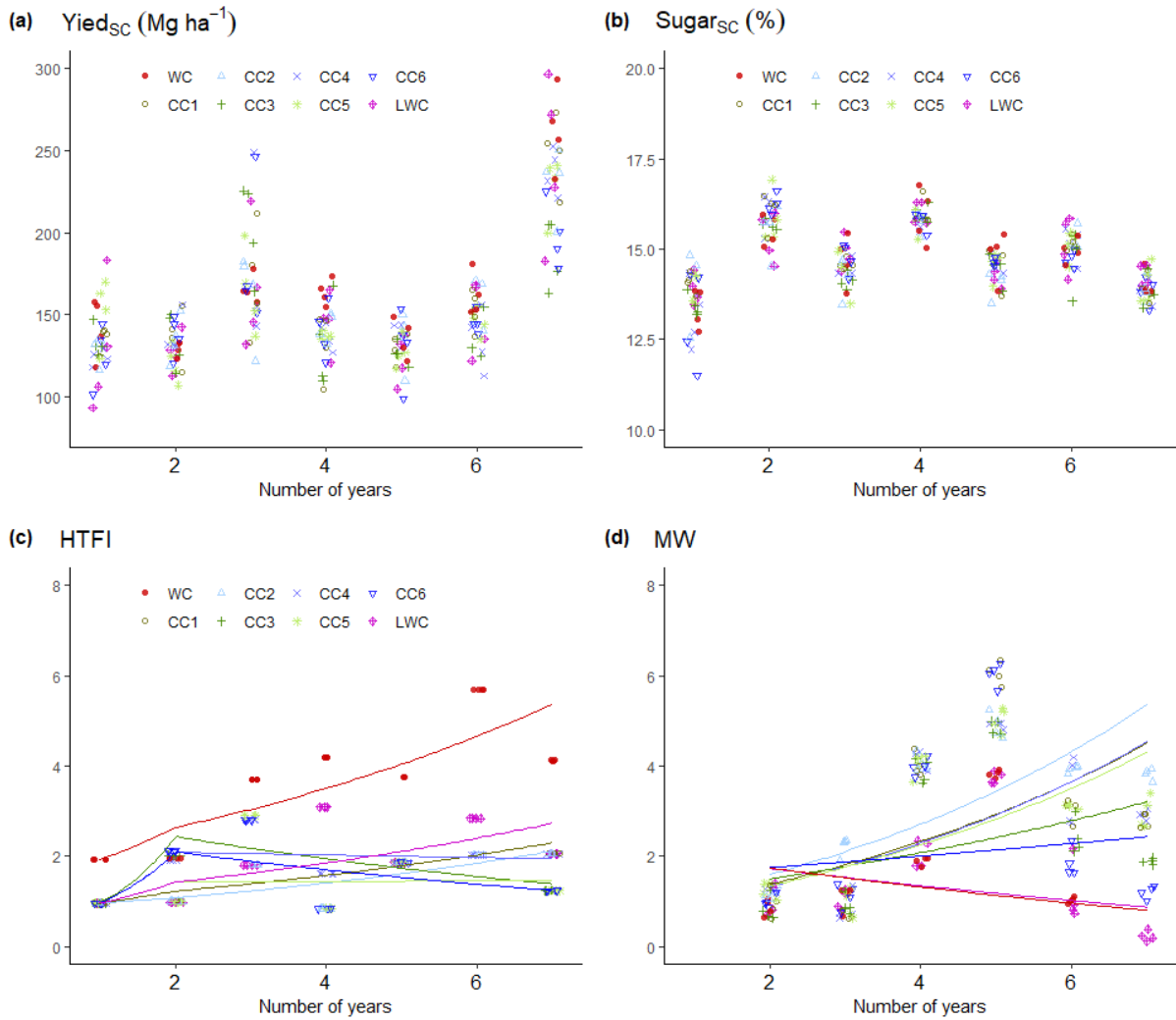
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Fig. 3. Non-metric multidimensional scaling (NMDS, $k=2$, stress = 0.19) ordination of weed communities by (a) cultivation year and the interaction between inter-row conditions (IR) and year (b). In (a) and (b), data points represent communities (plots), 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).

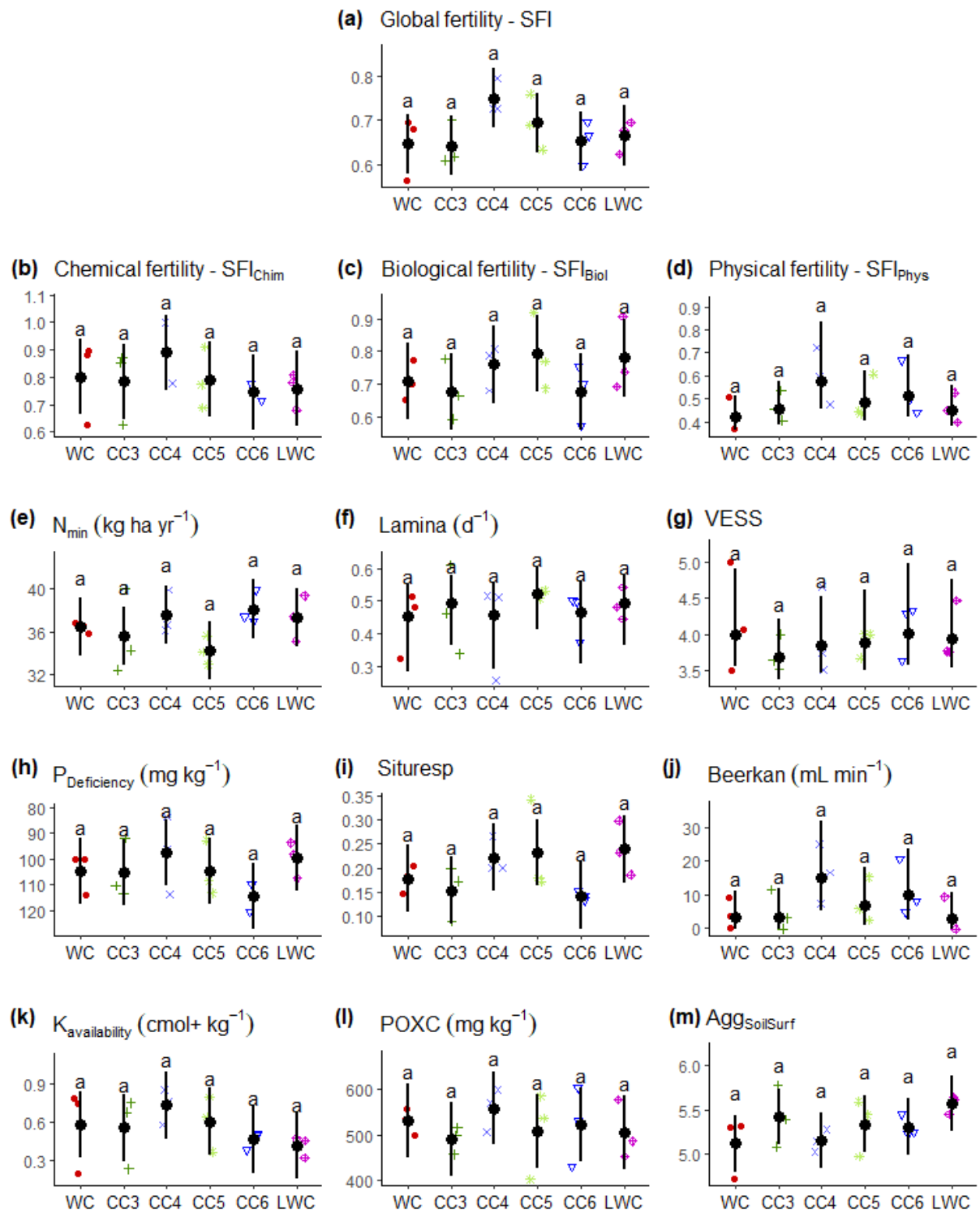


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918 **Fig. 4.** Change in sugarcane yield (Yield_{SC} , a), sucrose content (Sugar_{SC} , b), herbicide treatment
 919 frequency index (HTFI) and number of manual weedings (MW, d) with the number of years since the
 920 beginning of the experiment, 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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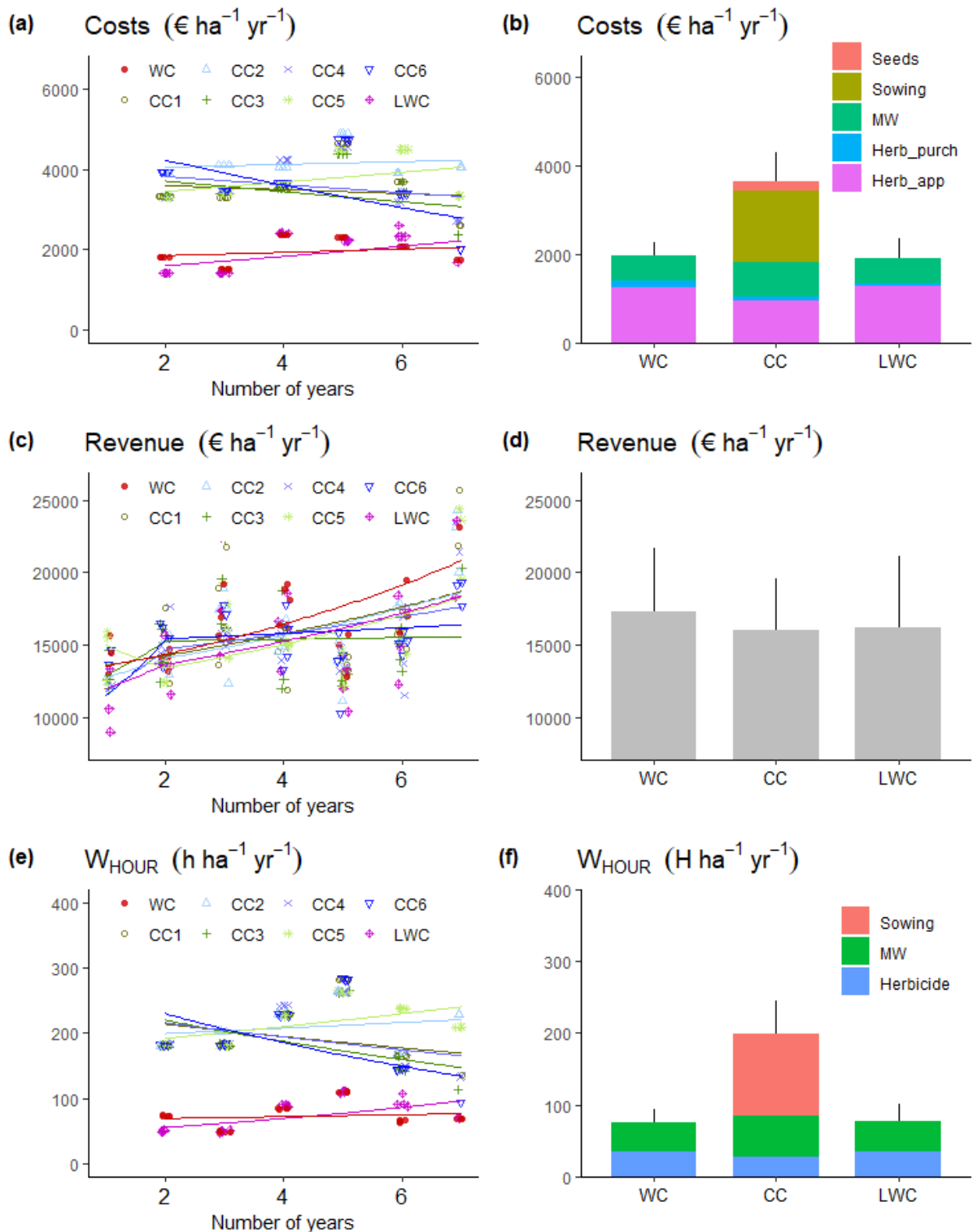
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927 **Fig. 5.** Comparison in soil fertility index (SFI) after seven years of experiment in terms of global (SFI,
 928 a), chemical (SFI_{Chim}, b), biological (SFI_{Biol}, c), and physical fertility (SFI_{Phys}, d), and soil indicators from
 929 Table 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.

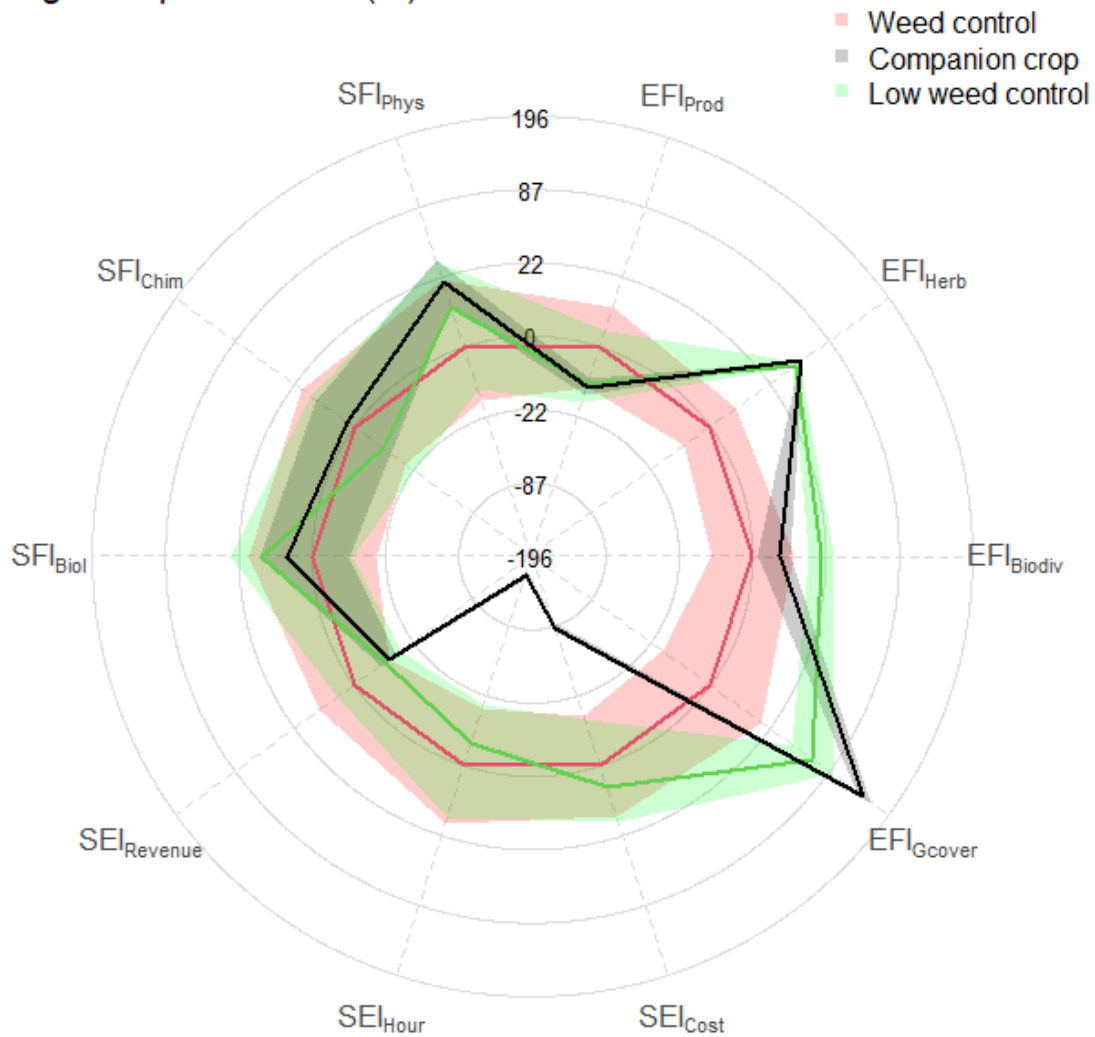
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935 **Fig. 6.** Change in weed control costs (a), revenue (c), and weed control working hours ($W_{\text{HO$ UR}, e) with
 936 the number of years since the beginning of the experiment, depending on the inter-row condition:
 937 chemical weed control (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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