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RESEARCH ARTICLE

A 7-year multi-criteria analysis of sugarcane intercropping compared to conventional cropping systems

Mathias Christina[1,2] · Julien Chetty[3] · Aude Ripoche[2,4,5,6] · Antoine Versini[7,8] · Karim Barkaoui[9,10] · Benjamin Heuclin[1,2] · Marion Schwartz[2,4] · Sacha Delmotte[7,8,11,12,13,14] · Sandrine Auzoux[2,4] · Alizé Mansuy[3]

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Abstract

Long-term studies are crucial for evaluating how intercropping affects the agronomic, environmental, and socio-economic sustainability of sugarcane systems. Intercropping with cover crops is expected to improve soil fertility and reduce herbicide use; however, its long-term effects on yield, weed dynamics, and production costs remain unclear, particularly under tropical conditions. Weed pressure has been hypothesized to drive yield decline over time, yet the temporal evolution of weed communities and their consequences for system sustainability remain poorly understood. We hypothesized that intercropping would modify ecosystem functions and services by increasing weed diversity and soil fertility, reducing herbicide use, and also increasing labor and production costs. To test this hypothesis, we conducted the first 7-year field experiment on Reunion Island, comparing four sugarcane intercropping systems with conventional chemical and low weed control systems. A multi-criteria approach assessed weed community dynamics, soil fertility, sugarcane yield and quality, herbicide use, labor, and economic performance over a complete crop cycle, including multiple ratoons. We show that weed pressure increased over time in both chemical and intercropping systems due to greater weed cover and species richness. Weed community structure differed during the first 3 years but later homogenized under sugarcane dominance. This increase led to more manual weeding in intercropping systems and to increased herbicide use in chemical ones, resulting in a 61% reduction in herbicide use under intercropping. After 7 years, soil chemical and biological fertility remained unchanged, while physical fertility improved with companion crop and weed development. Sugarcane yield and sucrose content were maintained, but production costs and working hours increased. This study demonstrates that sugarcane intercropping reduces herbicide dependence without compromising yield, though at higher labor costs. Systems maintaining spontaneous flora in inter-rows appear to offer a promising compromise for sustainable weed management. Further research on this system should be conducted in different pedoclimatic conditions.

Keywords Interplanting · *Saccharum officinarum* · Legume · Cover crop · Spontaneous flora · Herbicides · Soil health · Economic analysis · Labor time

1 Introduction

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

Extended author information available on the last page of the article

Sugarcane (*Saccharum officinarum*) is a major source of sugar, ethanol, and a raw material for electricity production (Bordonal et al. 2018). Its cultivation is characterized by a perennial cycle that typically spans 7 to 10 years before replanting, during which ratoon crops are harvested annually. However, conventional sugarcane cropping systems are associated with significant environmental challenges (Martinelli and Filoso 2008), including the intensive use of herbicides to manage weeds (the main sugarcane bio-aggressor) and the persistent issue of soil degradation (e.g., compaction and erosion) due to frequent mechanized harvesting and heavy machinery use (Cherubin et al. 2016). These practices can impact soil chemical, physical, and biological fertility, as well as water quality, raising concerns about the system's long-term sustainability (Hartemink 2008). As global demand for sugarcane products continues to grow (Leal et al. 2013; Goldemberg et al. 2014), there is an urgent need to develop and adopt more sustainable management practices that balance productivity with other ecosystem services.

Sugarcane intercropping with companion crops (sown as an intercrop) has been increasingly studied to improve soil fertility (Li et al. 2013; Tang et al. 2021), weed control (Ali et al. 2017; Soulé et al. 2024), soil bacterial communities (Solanki et al. 2019; Liu et al. 2021b, a; Pang et al. 2022), or to produce cash crops and to improve economic efficiency (Nadeem et al. 2020). However, introducing companion crops with sugarcane can also lead to belowground competition (Christina et al. 2025) and highly variable yield responses (Viaud et al. 2023). Depending on the country and the local context, studies on sugarcane intercropping often focus on specific objectives, such as profitability in India (Singh et al. 2023), soil quality in China (Tang et al. 2021), or reduced herbicide use in France (Mansuy et al. 2019). However, few studies enable a multi-criteria evaluation of this system. In addition, the majority of previous studies have focused on the short-term impact of intercropping (i.e., during the year of growth), whereas the duration of the crop cycle (7 to 10 years before replanting) requires a multiannual evaluation of this system.

Long-term studies are necessary to evaluate the lasting effects of intercropping on soil fertility, crop yield, and overall agricultural sustainability. For example, a positive effect of legume intercropping on soil chemical fertility is expected through an enhancement of soil organic C and N content (e.g., as demonstrated in other crops in temperate climates after 7 years of intercropping, Cong et al. 2015). Nevertheless, the only study examining the effect of legumes on soil properties after 8 years of sugarcane-legume intercropping systems did not find an increase in soil organic carbon content (Wang et al. 2020, in China). In contrast to chemical soil fertility (Lian et al. 2019; Solanki et al. 2019), other aspects of soil fertility, such as physical or biological fertility, have been less studied. Some short-term studies have suggested that intercropping can improve soil biological (e.g., through bacterial abundance and diversity, Pang et al. 2022) or physical fertility (e.g., through infiltration, Singh et al. 2008), but such responses are not consistently observed (Singh et al. 2021). To our knowledge, the multiannual impact of intercropping on soil biological and physical fertility has not yet been assessed, despite being a potential response to the issue of soil degradation in conventional sugarcane cropping systems.

The long-term productivity of sugarcane intercropping systems has become a significant concern, as a recent meta-analysis has highlighted that intercropping can have a negative impact on sugarcane yield, which becomes more pronounced over time (Viaud et al. 2023). Based on an observed increase in weed pressure in intercropping systems, a recent study has hypothesized that yield decline could be explained by a change in the weed community (Soulé et al. 2024), by selecting weed species that are more harmful. Indeed, companion crops can potentially reduce the abundance of weed species that are competitively inferior, as observed in other cropping systems (Smith and Gross 2007); however, this may not be the case for highly competitive species commonly found in tropical environments, such as lianas (Lakhia et al. 2023). Despite this observation, the response of weed communities to sugarcane intercropping systems has not been studied in the literature. As cover plants are increasingly proposed as a system for reducing herbicides in sugarcane (Mansuy et al. 2019; Djian-Caporalino and Lavoir 2024; Soulé et al. 2024), it is becoming urgent to assess their impact on the dynamics of these communities.

Yield reductions, associated with an increase in weed pressure, requiring more weed control interventions, can have serious implications for labor and economic costs. The economic impact of these systems is bound to be highly context-specific (Linked to input and labor costs, e.g., Singh et al. 2008; Kaur et al. 2016). However, weed management in these systems has been shown to require increased costs for weed control (Soulé et al. 2024). Consequently, research needs to consider the economic efficiency of sugarcane cultivation under ecologically intensified cropping systems over extended periods.

Understanding the multiannual implications of sugarcane intercropping across the different dimensions of sustainability is crucial for designing sustainable practices and advising farmers and policymakers on the consequences of agroecological transition. This study aimed to perform a multi-criteria analysis of sugarcane intercropping over an entire crop cycle (including both plant and multiple ratoon crops), compared to conventional (chemical) and low weed control (spontaneous weed community in the inter-row) cropping systems (Fig. 1). We hypothesized that (i) intercropping will impact ecosystem functions (increase in plant biodiversity and soil fertility), ecosystem services (decrease

Fig. 1 Comparison of sugarcane grown in a conventional chemical system (left) and in an intercropping system with Abyssinian mustard (*Brassica carinata*, right) during a planting year without sugarcane mulch. Photocredit: Christina Mathias.

in yield and increase in weed control), their benefits (decrease in herbicide use), and socio-economic efficiency (increase in working hours and costs) compared to conventional chemical or low weed control systems, and (ii) the annual change in weed community will increase these impacts over multiple annual cycles in sugarcane intercropping systems. To test these hypotheses, we conducted a 7-year sugarcane experimental trial on Reunion Island.

2 Material and methods

2.1 Study site

This study was carried out on the research station of La Mare, located on the northern coast of Reunion Island (20°54 S, 55°31 E, 69 m a.s.l., Indian Ocean) over seven sugarcane cropping seasons (i.e., seven years, one plant crop and six ratoon crops). The climate was tropical, with a rainy season from January to March and a dry season from May to November. The mean annual rainfall was approximately 1800 mm, and the mean annual temperature was 24 °C (means over 10 years). Daily climatic data were measured in a nearby Campbell meteorological station (100 m from the trial). The soil of the experimental site was a Hypereutric Nitisol according to the WRB classification (IUSS Working Group WRB 2015) with 17% of clay, 55% of silt, and 28% of sand in the 0–30 cm layer. Soil chemical characteristics within the 0–30 cm soil layer were determined prior to sugarcane plantation using a composite of nine samples spread across the experimental trial (see section 2.5.1 for details on the analyses). At the beginning of the experiment, the soil had a pH of 6.2 and a soil organic C, total N, and Olsen-P content of 24.2, 2.0, and 0.088 g kg^{-1}, respectively, for the top 30 cm soil layer. The soil had a cation exchange capacity (CEC) of 8.8 cmol kg^{-1} and K, Ca, Mg, and Na content of 1.0, 6.64, 3.04, and 0.10 cmol kg^{-1}, respectively.

2.2 Experimental design and weed control management

The experiment consisted of a randomized sugarcane trial with six inter-row conditions considered treatments, repeated into four blocks with 60 m^2 elementary plots (6 m wide and 10 m long):

- A conventional sugarcane cropping system with chemical weed control of both the sugarcane row and the inter-row (hereafter referred to as the chemical condition)
- Four intercropping conditions with companion crops sown each year in the sugarcane inter-row with manual weed control on the sugarcane row. Companion crop species sown in the intercropping changed over time. The four intercropping conditions included either *Canavalia ensiformis* or *Desmodium intortum* in the first 2 years (Table S1) and differed afterwards: mainly *Brassica carinata* (Brass.CC condition), mainly *Vigna unguiculata* (Vigna.CC condition), mainly *Crotalaria* species (Crota.CC condition), or a mix of *Crotalaria* and *Raphanus sativus* (Mixt.CC condition).
- A low weed control condition (LWC) with spontaneous flora in the sugarcane inter-row, with manual or chemical weed control on the sugarcane row.

Weed management of all conditions included (i) the application of a pre-emergent herbicide after sugarcane planting or harvest in the whole plot, (ii) a manual or chemical weeding of the sugarcane row to limit the impact on sugarcane production (throughout the crop growth), and (iii) a specific manual weeding of the weeds considered the most harmful in the whole plot (in particular, tall grasses: *Panicum maximum* and *Rottboellia cochinchinensis*). In the chemical condition, additional post-emergent herbicides were systematically applied to limit ground cover by weeds below the threshold of 30% ground cover (sugarcane sector recommendations). Additional manual weedings were occasionally performed in the intercropping conditions when ground cover by weeds exceeded 30% in the inter-row. An Herbicide Treatment Frequency Index (HTFI) was calculated as the sum of the ratio of the herbicide dose applied divided by the recommended dose across each herbicide application in a specific plot (https://agriculture.gouv.fr/indicateur-de-frequence-de-traitements-phytosanitaires-ift). Details of the chemical compounds used for herbicides are available in the data paper (Ngaba et al. 2023). The number of manual weedings was recorded.

2.3 Sugarcane and companion crop management

The R579 sugarcane cultivar was planted with a 1.5 m inter-row in April 2014 and harvested annually in October. A non-limited split NPK fertilization was applied during the whole experiment in all conditions, with 240 kg N ha^{-1}, 130 kg P ha^{-1}, and 380 kg K ha^{-1} in the plant crop, and 170 kg N ha^{-1}, 140 kg P ha^{-1}, and 190 kg K ha^{-1} on average in the ratoon crop (see Ngaba et al. 2023 for details). The whole experiment was irrigated with sprinklers. Sugarcane stalk fresh mass (hereafter sugarcane yield, Mg ha^{-1}) was measured at harvest by sampling all sugarcane stalks from the two central rows out of four in each plot. Sugarcane was harvested manually in the plant and first ratoon crops, and mechanically in the following years. Sucrose content in the stalks (%) was measured based on near-infrared spectroscopy of extractable sucrose. Sugar yield (Mg ha^{-1}) was calculated as the product of sugarcane yield and sucrose content. In ratoon crops (2015–2021), the sugarcane mulch was left on the soil surface and homogenized after harvest. Depending on inter-row conditions and years, different companion crops were sown in the inter-row each year (Table S1). The sowing densities were determined based on previous studies and literature (Christina et al. 2021b) and are detailed in the data paper (Ngaba et al. 2023). Sowing dates varied from 1 to 2.5 months after sugarcane harvest, depending on the year. From the plant crop (2014–2015) to the fourth ratoon crop (2018–2019), the companion crops were sown manually. In the last two ratoon crops, the companion crops were sown with a micro-tractor power harrow. In both cases, the sugarcane mulch was removed before sowing and then re-spread (except for the plant crop with bare soil).

2.4 Ground cover by companion crops and weeds

The ground cover by companion crops and weeds was estimated in each elementary plot (excluding borders) using a visual notation method according to a rating scale ranging from 0 to 100%, used in previous studies (Christina et al. 2021b; Soulé et al. 2024). This method enables the assessment of ground cover by species in multi-species crops. In each plot, ground cover was estimated for (i) all plants (companion crops and weeds), (ii) companion crops only, (iii) weed community only, and (iv) weed species every month during the first 6 months and then every 2 months up to the sugarcane harvest. The ground cover was then linearly interpolated between two measurement dates to calculate the mean ground cover between two sugarcane harvest dates. The description of the weed species observed in the experiment is provided in Table S2, which includes the mean abundance and frequency of observation in the experiment plots.

2.5 Soil fertility

2.5.1 Indicators of soil chemical fertility

Bulk soil was sampled at the end of the experiment (after the 2021 harvest) in three of the four blocks for soil chemical analysis (0–30 cm depth). Three cores were sampled per plot between the sugarcane row and the middle of the inter-row, and a composite was made for chemical analysis. Before analysis, the soils were dried at 65 °C and then sieved to 2 mm. Standard soil chemical analyses were carried out in the CIRAD soil laboratory in Saint-Denis de La Réunion. Due to the absence of carbonates, soil organic carbon and total soil nitrogen were quantified using the Dumas combustion method (ISO 106994:1995) with an elemental analyzer (VarioMax Cube CNS, Elementar, Hanau, Germany). The phosphorus content of the soil was measured using the Olsen-Dabin method (Dabin 1968), historically used in La Réunion. Cation exchange capacity (CEC), as well as the content of exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, Na^+), were quantified by a solution of cobaltihexamine trichloride as an extraction reagent, following standard ISO 23470:2018 (Fallavier 1984). Finally, pH was quantified using the water and KCl method (ISO 10390:2021).

The chemical fertility indicators included nitrogen, phosphorus, and potassium availability provided by Serdaf, a soil-specific nutrient management expert system developed for sugarcane fertilization in La Réunion (Versini et al. 2018). Briefly, nitrogen availability corresponding to the soil N mineralization over the crop growth (N_{min}) was calculated in each plot based on total soil nitrogen, bulk density, stoniness, and infield mineralization rate. Phosphorus deficiency ($P_{deficiency}$) was assessed using the fertilizer doses of P recommended by Serdaf in each plot. The expert system considers the soil P content, pH, and the fixing capacity of the soil to establish a P recommendation for sugarcane. The more soil P is available for the crop, the lower the recommendation and $P_{deficiency}$. In addition, the exchangeable potassium content was considered a direct indicator of potassium availability for crops ($K_{availability}$). Finally, in each plot, a soil chemical fertility index (SFI_{Chem}) was aggregated from the three indicators following a method adapted from Obriot et al. (2016), where indicator values were normalized based on desirability criteria: "more is better" for N_{min} and $K_{availability}$, and "less is better" for $P_{deficiency}$:

$$SFI_{Chem} = \frac{1}{3}\left(\frac{N_{min}}{\max(N_{min})} + \frac{\min(P_{deficiency})}{P_{deficiency}} + \frac{K_{availability}}{\max(K_{availability})}\right) \quad (1)$$

This index represented the chemical fertility of the soil in the 0–30 cm soil layer, which is the agronomic reference layer for determining fertilization needs for sugarcane (Versini et al. 2018).

2.5.2 Indicators of soil biological fertility

Three indicators adapted from Biofunctool®, a set of indicators selected to assess soil health in tropical contexts (Thoumazeau et al. 2019), were used to describe the soil biological fertility. The measurements and soil sampling were performed after the last harvest in the same plots as the soil chemical fertility indicators, between the sugarcane rows and the middle of the inter-rows. Soil mesofauna and little macrofauna activity were assessed by examining substrate degradation using bait-laminas sticks (van Gestel et al. 2003). The sticks were planted vertically in two groups of 7 per plot, with an additional strip serving as a control to assess the degradation rate, spaced 30 cm apart. The sticks were made of perforated plastic and initially filled with a commercial organic substrate (70% cellulose, 27% bran flakes, and 3% active coal; Terra Protecta GmbH, Berlin). The turnover of the soil carbon pool (0–10 cm depth) was investigated using the permanganate oxidizable carbon method (POXC) to inform on the available energy of the system originating from biological activity (Culman et al. 2012). Basal soil respiration was assessed using Situresp® (Thoumazeau et al. 2017), an incubation method that measures the quantity of carbon emitted by microorganisms over 24 hours. Following the same aggregation method described in the previous section, a soil biological fertility index (SFI_{Biol}) was calculated:

$$SFI_{Biol} = \frac{1}{3}\left(\frac{Lamina}{\max(Lamina)} + \frac{Situresp}{\max(Situresp)} + \frac{POXC}{\max(POXC)}\right) \quad (2)$$

This index represented biological fertility in the 0–10 cm soil layer, capturing biological activity (Thoumazeau et al. 2019).

2.5.3 Indicators of soil physical fertility

Three indicators adapted from Biofunctool® (Thoumazeau et al. 2019) were used to describe the soil physical fertility. The measurements and soil sampling were conducted simultaneously with those for soil biological and chemical fertility between the sugarcane row and the middle of the inter-row. Aggregate stability at 0–10 cm depth ($Agg_{SoilSurf}$), which informs the soil's capacity to resist erosion, was assessed on six dried aggregates selected for sizes ranging from 6 to 8 mm (Le Bissonnais 2016). Water infiltration, providing information on infiltration rate, runoff, and erosion processes, was assessed using the Beerkan method (Lassabatère et al. 2006). Visual Evaluation of Soil Structure (hereafter VESS), which informs on soil compaction, was estimated at 0–20 cm depth using the method proposed by Guimarães et al. (2011), where the VESS index is a score ranging from 1 (good soil structure) to 5 (poor soil structure). Finally, a soil physical fertility index (SFI_{Phys}) was aggregated following the same method previously described, considering 1 as an optimal value for VESS:

$$SFI_{Phys} = \frac{1}{3}\left(\frac{Agg_{SoilSurf}}{\max(Agg_{SoilSurf})} + \frac{Beerkan}{\max(Beerkan)} + \frac{1}{VESS}\right) \quad (3)$$

2.6 Economic and working hour assessment

The different inter-row conditions were compared based on weed control operating costs, revenue from sugarcane sales, and working hours. All these variables were calculated each year in each plot using the OTECAS software developed by the eRcane Institute as part of the agricultural innovation and transfer network (2022 version, https://coatis.rita-dom.fr) and used in previous studies (Soulé et al. 2024). This software, developed specifically for the sugarcane industry in Reunion Island, calculates revenue and operating costs based on crop management and yields. Only the variable operating costs across the cropping systems were considered in the expenses: the purchase of herbicides and seeds (Table S3) and labor and mechanization costs, taking into account equipment depreciation (Table S4). For each plot in the trial network, the costs of herbicide purchase, seed purchase, the number of chemical weeding operations (backpack sprayer), and the number of manual and mechanical weeding operations were calculated. The costs of sowing companion crops were calculated differently, considering manual sowing (from plant to fourth ratoon crops), sowing with a micro-tractor (two last ratoon crops), and the mulch management in the row spacing. The revenue from sugarcane production in each trial was calculated based on the fresh stalk yield, sugarcane richness, and additional subsidies in La Réunion. The number of working hours for weed control operations was determined using the references in the OTECAS software, which provided the number of working hours per type of operation (expressed per ha) rather than the actual time spent in the experimental trial (Table S4). The first year of the trial was excluded from the analysis as weed control operations were not recorded.

2.7 Data analysis

2.7.1 Temporal variation analysis and inter-row condition effect

All statistical analyses were performed using R 4.3 (R Development Core Team 2023) according to the following procedure. If necessary, to ensure normality of the residue, the target variable was transformed using the Box-Cox function (*powerTransform* function from the *car* R package, Fox and Weisberg 2019) based on a Gaussian distribution. For all variables, a mixed linear analysis was performed using the year (qualitative variable) as a random effect (*lme* function, *nlme* R package, Pinheiro et al. 2025). The influence of the inter-row condition (IR), the crop class (CropClass, plant or ratoon crop), the number of years since the beginning of the experiment ($Y_{NB,}$ 1 to 7), and their interaction were tested as fixed effects using a type III Fisher variance analysis:

$$Variable \sim CropClass + Y_{NB} + IR + CropClass : IR + Y_{NB} : IR + 1|Year \quad (4)$$

As no data on manual weedings were available for the plant crop, only the interaction between Y_{NB} and the inter-row condition was tested for the number of manual weedings, costs, and working hours. Considering soil indicators and soil fertility indexes at the end of the experiment, the influence of the inter-row condition was tested without a random effect. The assumptions of homogeneity and normality were checked graphically using histograms of residuals, quantile-quantile plots of Pearson's residuals versus a standardized Gaussian sample, and plots of residuals against fitted values. Pairwise comparisons of slope response to Y_{NB} among treatments were performed using the *emtrends* function with a Tukey *p*-adjustment method and a 0.05 probability threshold (*emmeans* R package, Lenth 2025). Pairwise comparisons of means among treatments were performed using the *emmeans* function with the same Tukey *p*-adjustment method. The models' mean predicted and confidence interval values, depending on factors, were calculated using the *emmeans* function. The marginal (only fixed effects, R_m^2) and conditional R^2 (both fixed and random effects, R_C^2) were calculated with the *performance* package.

2.7.2 Weed community analysis

The weed species richness was calculated as the number of weed species occurring in a plot each year. A non-metric multidimensional scaling (NMDS) was performed to examine the changes in weed species composition in response to cultivation year and inter-row conditions using the *metaMDS* function (*vegan* package). The influences of climate (annual precipitation and mean temperature) and the number of years since the beginning of intercropping were tested using the *envfit* function (*vegan* package). The influence of the interaction between cultivation year and inter-row conditions on community structure was tested with a permutational ANOVA (*adonis2* function, *vegan* package, with the Bray-Curtis distance calculation method) paired with a post hoc test (*pairwise.adonis2* function from the *pairwiseAdonis* package, Martinez Arbizu 2020) to test for significant differences among cultivation years and inter-row conditions. We finally used the *multipatt* function from the *indicspecies* package (Cáceres and Legendre 2009) to identify weed species significantly associated with each cultivation year and/or inter-row conditions.

3 Results and discussion

3.1 Increase in weed pressure over years in intercropping

Similar to previous studies on sugarcane (e.g., Kaur et al. 2016; Geetha et al. 2019; Soulé et al. 2024) or other cropping systems (Verret et al. 2017; Gu et al. 2021), sugarcane intercropping reduced ground cover by weeds by 47% compared to low weed control on average across the 7-year experiment (Fig. 2a), at a level even lower than conventional chemical weed control. Mix.CC companion crop sequences showed the lowest ground cover by weeds, but this was mainly due to differences in plant crop (Fig. 3a), where this sequence included *Canavalia ensiformis*, known to be highly efficient regarding weed control (Mansuy et al. 2019; Christina et al. 2021b). Nonetheless, after the decrease from plant (1st year) to first ratoon crop (2nd year), due to sugarcane mulch (Carvalho et al. 2017), ground cover by weeds increased annually in all intercropping conditions, reaching ground covers close to low weed control systems at the end of the experiment (Fig. 3a). In the chemical weed control condition, ground cover by weeds also increased annually but the rate of increase was 47% lower than in intercropping (except for Brass.CC condition). The change in weed pressure over time in intercropping systems remains poorly understood, as it has only recently been highlighted by Soulé et al. (2024) for sugarcane and remains unclear even in other diversified cropping systems (Adeux et al. 2019a). This increase could result from an enrichment of the weed seed bank and/or the selection of highly competitive weeds, as observed in other temperate

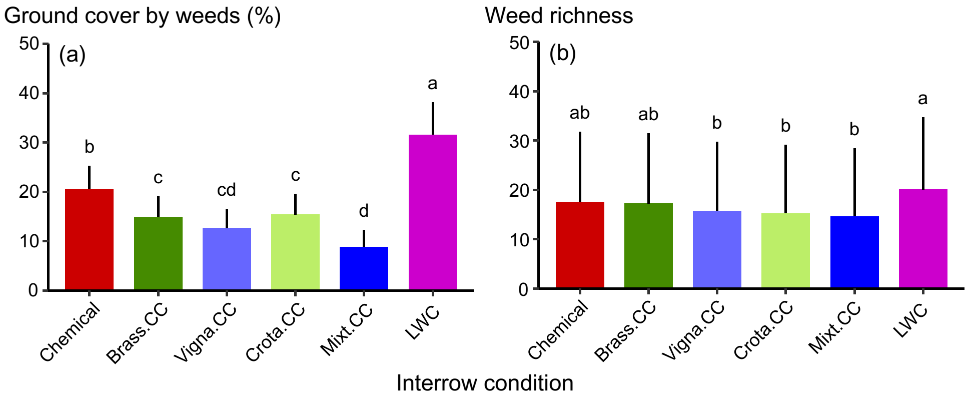

Fig. 2 Average annual ground cover by weeds (**a**) and weed richness (**b**) over the 7-year experiment depending on the inter-row condition: chemical weed control (chemical), companion crops sown in the inter-row (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC). Mean values predicted by the statistical model (Table S5) and 95% confidence intervals are presented. Letters indicate significant differences in the pairwise comparisons.

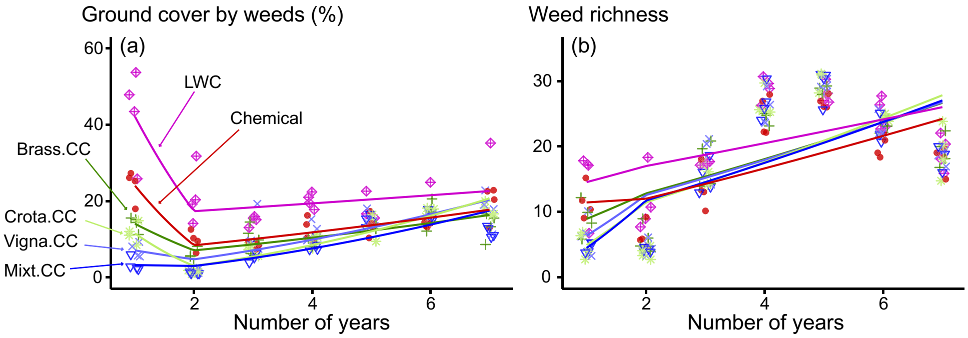

Fig. 3 Change in ground cover by weeds (**a**) and weed richness (**b**) with the number of years since the beginning of the experiment, depending on the inter-row condition: chemical weed control (chemical), companion crops sown in the inter-row (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC). The lines represent the marginal predictions by the statistical models (Table S5), and the symbols represent the observed values.

cover cropping systems, particularly under rotations (Graziani et al. 2012; Mohler et al. 2018; Nichols et al. 2020). The question of whether weed pressure has reached a stable state in our intercropping systems after 7 years remains unsolved based on our observations. The year after the trial ended, the sugarcane was replanted with conventional management (chemical sugarcane destruction and soil tillage). Observations made during the year of this new planting in 2022–2023 show coverage levels similar to those observed in 2014–2015, with 49% coverage in the low weed control conditions and 18% in the chemical condition (data not shown), suggesting that a new plantation would act as a re-initialization filter for weed pressure.

In parallel with the change in ground cover, an increase in weed species richness over the years was observed in intercropping (Fig. 3b). The increase in weed richness was also observed in low weed control, but the rate of increase was higher by 70% in intercropping. Consequently, while weed richness was 58% lower in intercropping than in low weed control in the first 2 years of the experiment, weed richness reached a similar level in all inter-row conditions at the end of the experiment. On average, across the 7 years of the experiment, weed richness was significantly lower than in low weed control in three out of four intercropping conditions, with 21% lower richness (Fig. 2b). Nonetheless, the fixed effects explained only 38% of richness variability, and a larger part was explained by the random effect (i.e., climate, Table S5) in our analysis, in line with previous studies highlighting the predominant role of climate in weed species richness variations (Peters et al. 2014). Our results illustrate the complex effects of intercropping practices on weed richness and why there is no clear consensus in the literature (Poggio 2005; Mohammadkhani et al. 2023; Namatsheve et al. 2024). Indeed, weed richness can be impacted by long-term interspecific competition (Restuccia et al. 2020) and, perhaps predominantly, by climate or management (Pyšek et al. 2005).

3.2 Climate and sugarcane shape weed community structure more than intercropping

The inter-row practices influenced the weed community structure during the first 2 years of the experiment, but weed communities became homogenized afterward under the predominant influence of climate and sugarcane management (Fig. 4). Permutational analysis of variance highlighted how the change in the weed community was mainly affected by the cultivation-year effect compared to the interaction between the inter-row condition and the year (Table S6). The annual change in community structure resulted in a homogenization of plots over time in all inter-row conditions (Fig. 4a). This homogenization was strongly related to the number of years (Y_{NB}) since the beginning of the experiment ($R^2 = 0.87$, $p < 0.001$), followed by the change in total rainfall during the crop growth ($R^2 = 0.47$, $p < 0.001$) and the average temperature ($R^2 = 0.34$, $p < 0.001$, Table S7). In our experiment, Y_{NB} was not significantly correlated with rainfall or the mean temperature, and these two climatic variables were not correlated with each other either. These results suggest that, in our context, sugarcane crop management had a greater impact on weed community structure than climate, highlighting how crop management can lead to homogenized weed communities despite climate variability (Derrouch et al. 2021). Similar observations have been made in other cropping systems, such as oilseed rape, where tillage intensity was a main factor, closely followed by rainfall (Hanzlik and Gerowitt 2011). In the case of sugarcane, straw management (sugarcane leaf mulching after harvest) is known to impact the weed community (Carvalho et al. 2017). Sugarcane straw can limit the emergence of weeds with low seed resources (Ferreira et al. 2010) or, conversely, stimulate the germination of other species, such as *Ipomoea* or *Merremia* species (Azania et al. 2002; Correia and Durigan 2004; Correia and Kronka 2010).

Pairwise comparisons of weed communities revealed how the inter-row conditions affected the weed communities in the first two cultivation years, with little impact afterward (Fig. 4b). In both years, the chemical and low weed control conditions did not differ in weed communities ($p = 0.16$ in 2014–2015, and $p = 0.18$ in 2015–2016), while all intercropping conditions significantly modified weed communities compared to low weed control in both of the first cultivation years. As illustrated by the indicator weed species (Fig. 5), intercropping limited the growth of various small broad-leaf weed species (such as *Amaranthus* species or *Solanum americanum*), as well as small ligneous (e.g., *Senna occidentalis*) during the first cultivation year. Indeed, companion crops have the potential to reduce the abundance of weed species that are competitively inferior (Smith and Gross 2007), such as small species, which are more sensitive to light competition. Another explanation is that some species regulated by companion crops (e.g., *Argemone* species) are known to grow better in the cold season, making them less competitive in summer (as illustrated by Poggio (2005) on the effect of intercropping depending on the weed emerging season in tropical climates). In addition, except for 1 year, liana species were not species indicators, suggesting that cover crops fail to control liana weeds in most cases. Thanks to

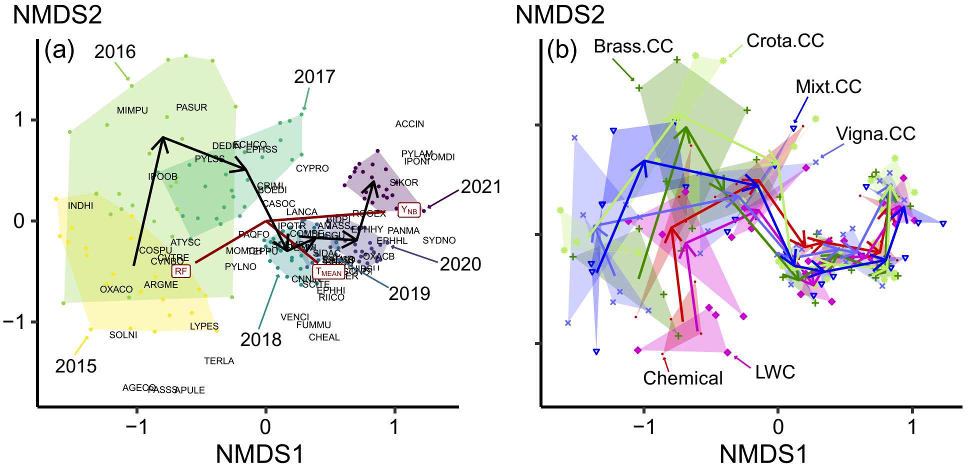

Fig. 4 Non-metric multidimensional scaling (NMDS, $k = 2$, stress $= 0.19$) ordination of weed communities by (**a**) cultivation year and the interaction between inter-row conditions and year (**b**): chemical weed control (Chemical), companion crops sown in the inter-row (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC). Data points represent communities (plots), and colored polygons delimitate the space of each cultivation year (**a**) or inter-row x year levels (**b**). Black arrows represent the annual change between community centroids. Red vectors in (**a**) represent the direction and magnitude of correlations between annual rainfall (RF), mean daily temperature ($\mathrm{T}_{\mathrm{MEAN}}$), the number of years since the beginning of the experiment (Y_{NB}), and the ordination axis scores representing the change in weed community (Table S7). Species are projected and indicated with EPPO codes (Table S2).

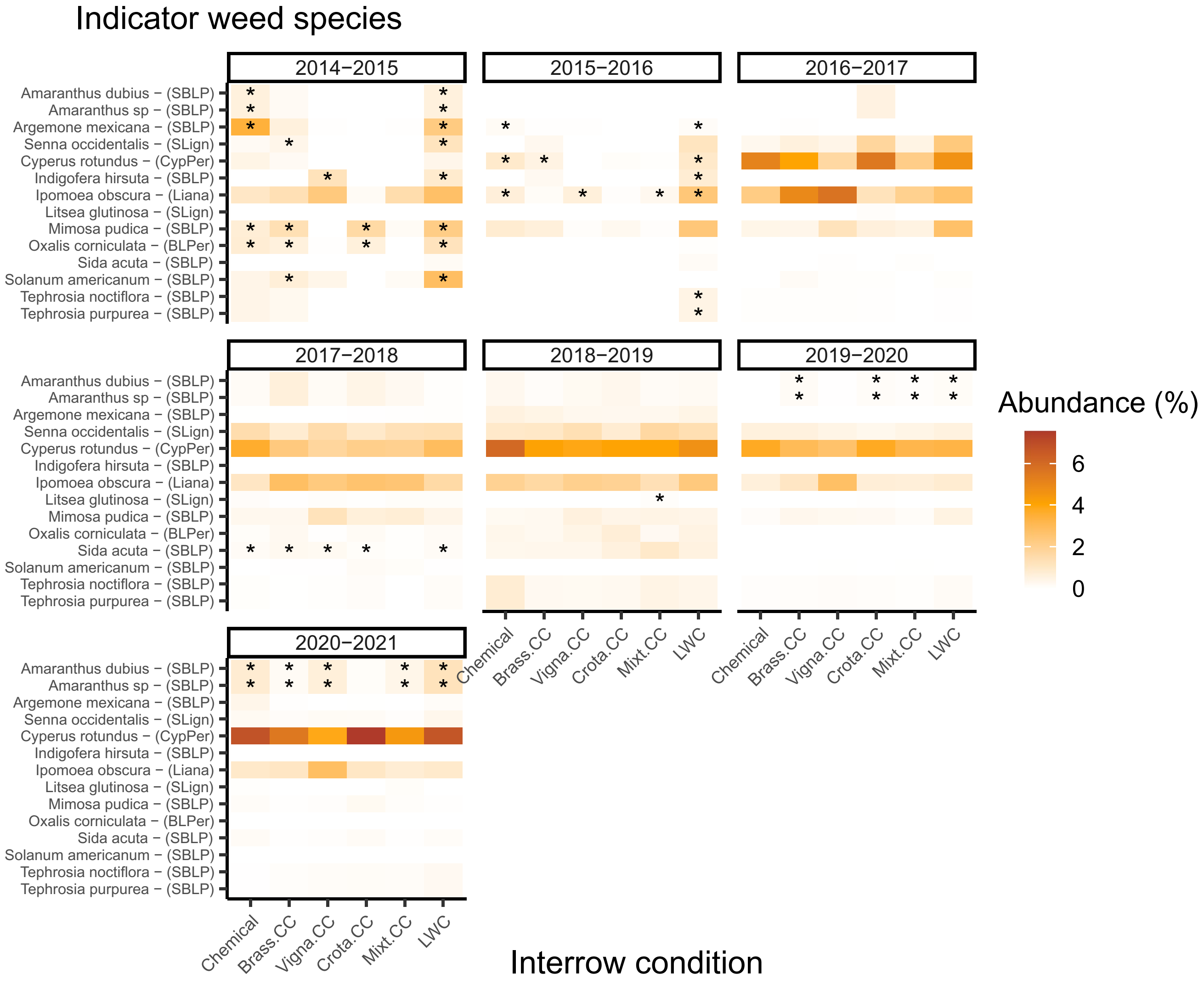

Fig. 5 Change in indicator weed species abundance (mean ground cover) depending on inter-row conditions in each cultivation year: chemical weed control (Chemical), companion crops sown in the inter-row (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC). Indicator species (statistically associated with a condition, $p < 0.05$) are indicated by "*". Weed species growth habits are indicated: broad-leaf perennials (BLPer), small ligneous (SLign), small broad-leaf plants (SBLP), liana, and perennial sedges (CypPer).

their ability to use other plants as support to grow, lianas are less sensitive to competition for light and can grow despite shading (Martin et al. 2012). In 2015–2016, the companion crop *Desmodium intortum*, itself a liana, was able to limit the growth of *Ipomoea obscura* (Fig. 5), potentially due to its similar growth type or its potential allelopathic effect (Hooper et al. 2015).

3.3 Lower chemical but higher manual weedings

Sugarcane intercropping systems make it possible to reduce herbicide use compared to monocropping at the cost of increased manual weeding (Fig. 6). In Reunion Island, the average HTFI in grower conditions was 3.43 at the beginning of the trial (similar to our chemical weed control condition), with significant variations from 1 to 7, depending on the fields (DAAF La Réunion 2016). In our study, the average observed decrease in herbicide use in intercropping (−61%, Fig. 6a) is higher than previous observations in an experimental network in Reunion Island (Soulé et al. 2024) but similar to other countries (Kaur et al. 2016) suggesting that the herbicide reduction will be highly influenced by local conditions such as natural flora, soil, and climate. No difference was observed among companion crop sequences, in accordance with previous studies suggesting that the choice of companion crop species has little influence on weed control compared to crop management that favors companion crop development (Soulé et al. 2024). Nonetheless, an increasing number of manual weedings over the years was required to limit weed growth (Fig. 7b), which could be

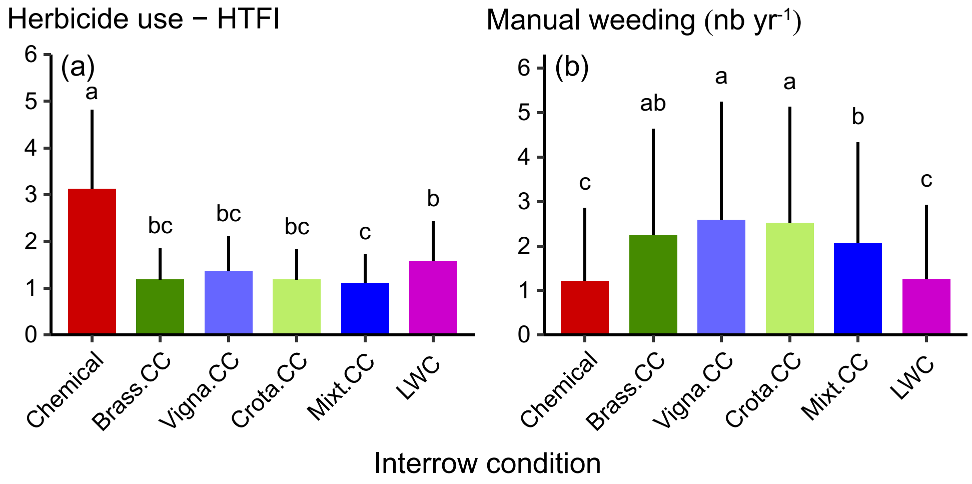

Fig. 6. Average herbicide use (expressed as herbicide treatment frequency index – HTFI (**a**)) and number of manual weedings (**b**) over the 7-year experiment depending on inter-row condition: chemical weed control (Chemical), companion crops sown in the inter-row (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC). Mean values predicted by the statistical model (Table S5) and 95% confidence intervals are presented. Letters indicated significant differences in the pairwise comparisons.

explained by the increasing weed pressure (Fig. 3a). This impact regarding manual work has been studied little in the sugarcane international literature (Bhullar et al. 2006), which mainly focuses on using complementary herbicides. However, such consequences have been highlighted in other cropping systems, such as conservation agriculture in the tropics (Lee and Thierfelder 2017). In the chemical cropping system, little change in manual weedings was observed over the years (Fig. 7b), but an increase in herbicide use was required to limit weed growth (Fig. 7a).

Despite being poorly investigated in the literature, low weed control in the inter-row could be a promising system to reduce herbicide use with no impact on manual weeding (Fig. 6). Nonetheless, it tends to require a slightly higher use of herbicide than some companion crop conditions due to the complementary use of herbicide on the sugarcane row. The choice of areas to be left colonized by weeds must be carefully considered in this practice, as the presence of weeds throughout the whole plot can lead to a yield loss of 0.1–0.2 Mg ha^{-1} per day of weed control delay, and the absence of weed control can lead to an 80% of yield loss (Marnotte et al. 2008). Nonetheless, this practice is worth pursuing as it is starting to be adopted in other perennial cropping systems, such as vine (Fernández-Mena et al. 2021), and is increasingly being studied in banana cropping systems (Achard et al. 2018) as a substitute for companion crops.

3.4 Soil fertility response and erosion protection

Intercropping with companion crops has the potential to improve soil fertility and soil protection against different abiotic factors, such as rainfall or wind, as observed in other cropping systems (Cong et al. 2015; Sharma et al. 2017). In sugarcane conventional cropping systems, straw mulching after harvest already plays a role in erosion protection, but is not always enough to limit erosion (Thomaz et al. 2022) due to its decomposition during sugarcane growth. In our study, intercropping resulted in a higher ground cover of 62

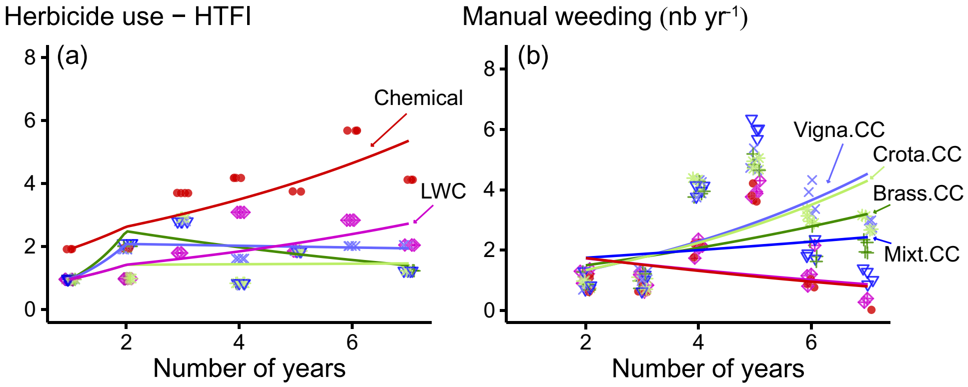

Fig. 7 Change in herbicide use (expressed as herbicide treatment frequency index – HTFI (**a**)) and number of manual weedings (**b**) with the number of years since the beginning of the experiment, depending on inter-row condition: chemical weed control (Chemical), companion crops sown in the inter-row (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC). The lines represent the marginal predictions by the statistical models (Table S5), and the symbols represent the observed values.

to 157% compared to chemical systems, on average, during the 7 years of growth (Fig. S1). Low weed control systems also achieved a higher ground cover of 63% compared to chemical systems. Still, it remained lower than in the highest companion crops. Nonetheless, not all companion crop sequences achieved the same level of ground cover, with sequences including crotalaria species exhibiting slightly lower ground cover than others (Fig. S1).

Despite 7 years of intercropping, including legumes, little effect could be observed on soil fertility, particularly regarding chemical and biological fertility indicators (Fig. 8), even if physical fertility increased with the plant development in the inter-row (Fig. 9). At the end of the experiment, no statistical differences were found among inter-row conditions for all soil health indicators or soil chemical characteristics (Table 1). The absence of significant differences could be attributed to the low number of repetitions in our study and, for the chemical fertility index, to the large soil layer sampled (0–30 cm), which is the reference layer for determining sugarcane nutrient requirements (Versini et al. 2018). Nonetheless, chemical and physical fertility indices tended to be higher in the most productive legume companion crop sequences, particularly Vigna.CC (Fig. 8).

The low chemical and biological fertility response is not inconsistent with previous studies on sugarcane intercropping systems. Although short-term experiments have shown that there is a higher soil NPK availability after legume dies in intercropping systems (Lian et al. 2019; Solanki et al. 2019), the only studies that examined the multiannual effect of sugarcane legume intercropping did not report any positive effect on soil properties, e.g., soil organic carbon content in the 0–30 cm layer, even after 7 years (Wang et al. 2020),

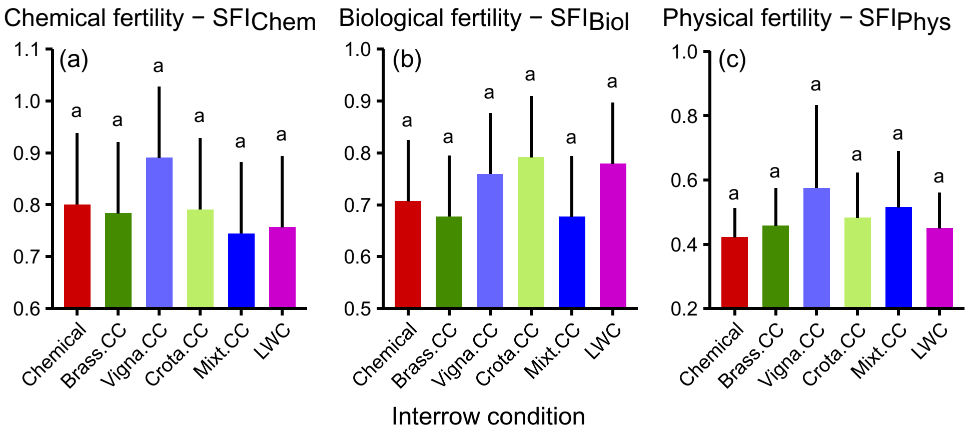

Fig. 8 Comparison of soil fertility index (SFI) after 7 years of the experiment in terms of chemical (SFI_{Chem}, **a**), biological (SFI_{Biol}, **b**), and physical fertility (SFI_{Phys}, **c**), depending on the inter-row condition: chemical weed control (Chemical), companion crop sequences (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC). Mean values and confidence intervals (bars) predicted by the linear models are presented. The letter "a" indicates non-significant differences in the pairwise comparisons.

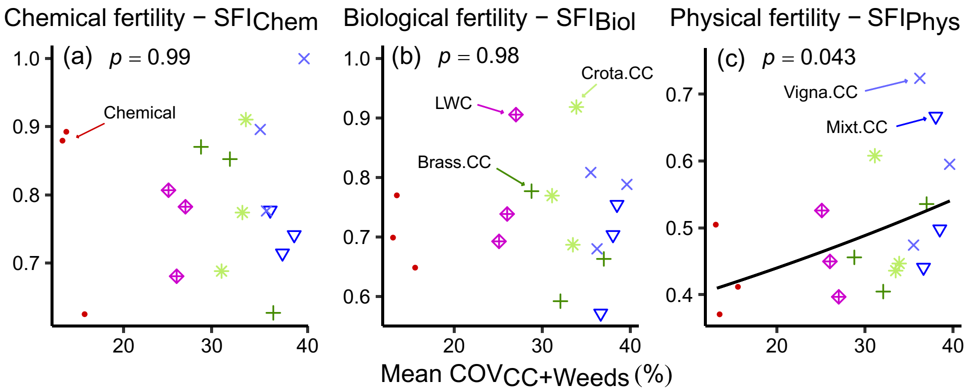

Fig. 9 Change in soil fertility index (SFI) after 7 years of the experiment in terms of chemical (SFI_{Chem}, **a**), biological (SFI_{Biol}, **b**), and physical fertility (SFI_{Phys}, **c**) with mean ground cover by both companion crops and weeds ($COV_{CC+Weeds}$). Colored dots indicate the inter-row condition: chemical weed control (Chemical), companion crop sequences (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC). *p*-values indicate a significant response of the SFI to $COV_{CC+Weeds}$.

Table 1 Main soil characteristics and soil fertility indicators measured after 7 years of inter-row conditions: chemical weed control (Chemical), intercropping (Brass.CC, Vign.CC, Crota.CC, and Mixt.CC), and low weed control (LWC). Soil characteristics include organic N (N_{org}), organic C (C_{org}), N mineralization over the crop growth (N_{min}), P deficiency ($P_{deficiency}$), K availability ($K_{availability}$), soil mesofauna and little macrofauna activity index (Lamina), basal soil respiration index (Situresp), turnover soil carbon index (POXC), soil structure index (VESS), water infiltration rate index (Beerkan), aggregate stability index ($Agg_{SoilSurf}$). Mean values and standard deviation are presented. The letter "a" indicates non-significant differences in the pairwise comparisons.

Indicator	Unit	Layer (cm)	Chemical	Brass.CC	Vigna.CC	Crota.CC	Mixt.CC	LWC
pH	unitless	0–30	6.00 (± 0.22) a	5.79 (± 0.65) a	6.04 (± 0.23) a	5.89 (± 0.21) a	5.65 (± 0.26) a	5.89 (± 0.69) a
N_{org}	g kg^{-1}	0–30	1.76 (± 0.08) a	1.83 (± 0.07) a	1.85 (± 0.13) a	1.79 (± 0.13) a	1.79 (± 0.14) a	1.86 (± 0.08) a
C_{org}	g kg^{-1}	0–30	21.12 (± 0.92) a	21.53 (± 0.96) a	22.29 (± 0.96) a	21.73 (± 2.21) a	21.40 (± 1.21) a	21.86 (± 0.85) a
N_{min}	kg ha yr^{-1}	0–30	36.43 (± 0.53) a	35.54 (± 3.89)	37.54 (± 2.02) a	34.23 (± 1.32) a	38.06 (± 1.54) a	37.28 (± 2.09) a
$P_{deficiency}$	mg kg^{-1}	0–30	104.64 (± 7.91) a	105.22 (± 11.55) a	97.77 (± 15.08) a	104.75 (± 10.67) a	114.64 (± 5.27) a	99.79 (± 7.08) a
$K_{availability}$	$cmol^{+}$ kg^{-1}	0–30	0.58 (± 0.32) a	0.56 (± 0.28) a	0.73 (± 0.14) a	0.60 (± 0.21) a	0.46 (± 0.07) a	0.42 (± 0.08) a
Lamina	d^{-1}	0–10	0.44 (± 0.10) a	0.47 (± 0.14) a	0.43 (± 0.15) a	0.52 (± 0.01) a	0.46 (± 0.07) a	0.49 (± 0.05) a
Situresp	unitless	0–10	0.18 (± 0.03) a	0.15 (± 0.06) a	0.22 (± 0.04) a	0.23 (± 0.10) a	0.14 (± 0.01) a	0.24 (± 0.06) a
POXC	mg kg^{-1}	0–10	530.35 (± 30.43) a	490.38 (± 30.16) a	558.75 (± 48.06) a	507.94 (± 95.14) a	521.39 (± 87.24) a	504.95 (± 65.44) a
VESS	unitless	0–20	4.19 (± 0.76) a	3.71 (± 0.26) a	3.97 (± 0.62) a	3.89 (± 0.19) a	4.09 (± 0.40) a	3.99 (± 0.41) a
Beerkan	mL min^{-1}	NA	4.16 (± 4.52) a	4.83 (± 5.91) a	16.28 (± 8.91) a	7.86 (± 6.67) a	11.15 (± 8.31) a	4.05 (± 4.78) a
$Agg_{SoilSurf}$	unitless	0–10	5.11 (± 0.34) a	5.42 (± 0.35) a	5.15 (± 0.13) a	5.34 (± 0.32) a	5.30 (± 0.12) a	5.57 (± 0.10) a

like our results. Similarly, short-term experiments have highlighted how intercropping can improve biological fertility by enhancing soil bacterial abundance and diversity (Pang et al. 2022), particularly diazotrophs (Solanki et al. 2019). However, to our knowledge, no multiannual effect has been reported. Such an absence of response could be linked to the relatively low biomass produced by companion crops in intercropping systems compared to rotation, or to significant losses of legume-N after their death through NH_3 volatilization and N_2O emissions, as recently suggested by Viaud (2023) and shown for NH3 volatilization by Glasener and Palm (1995) and Nett et al. (2016) and for N_2O emissions by Peyrard et al. (2016). Those losses are favored by sugarcane mulch (Pinheiro et al. 2018). In our system, a low amount of C inputs (approximatively 1 Mg ha^{-1} from companion crops, Viaud 2023), combined with low soil C stabilization ability (Feller and Beare 1997) and higher mineralization rate in tropical conditions (Ogle et al. 2005) may explain why the effect of legume on soil chemical fertility was not noticeable (Fujisaki et al. 2018).

Studies in other cropping systems have shown that intercropping can improve soil structure in tropical conditions by increasing soil porosity and infiltration rates and reducing runoff (e.g., in cotton, Blaise et al. 2021). Compared with chemical fertility, the impact of sugarcane intercropping on soil physical fertility has been poorly investigated. A few studies suggest that intercropping can reduce bulk density and improve infiltration (e.g., Singh et al. 2008 in India), but such a response is not always observed, even in the same experimental site (e.g., Singh et al. 2021). In our experiment, even if the soil physical fertility index did not differ significantly among inter-row conditions, it was positively correlated with plant development (companion crops and weeds) in the inter-row (Fig. 9c), suggesting that the effect of intercropping on soil decompaction is worth pursuing, particularly in mechanized sugarcane cropping systems with highly compacted soils (Cherubin et al. 2016).

3.5 Impact on yield, working hours, costs, and revenue

Despite the potential for interspecific competition among sugarcane, companion crops, and weeds, intercropping and low weed control systems showed minimal impact on overall system productivity. Sugarcane yield (fresh stalk mass) was only weakly influenced by the fixed experimental factors ($R_m^2 = 0.21$), and no significant yield trend was observed over the 7 years of the experiment (Fig. 10a, Table S5). A unique statistical difference was detected in plant crops between Crota.CC and Mixt.CC conditions ($p = 0.0287$), but ratoon crop yields were unaffected by inter-row conditions. This absence of a clear intercropping effect contrasts with findings from a global meta-analysis by Viaud et al. (2023), which reported yield reductions of 3% worldwide and 6% in La Réunion under sugarcane-legume intercropping. In our study, the mean yield difference between intercropping and monocropping was −8%, although this was not statistically significant, likely due to high variability in fresh yield measurements. Another explanation is the relatively high proportion of companion crops compared to weeds in the early years of the experiment (Fig. 3a, Fig. S1), a factor that has been previously shown to mitigate yield losses (Viaud et al. 2023). Similarly, the sucrose content remained largely unaffected by inter-row conditions (Table S5), aligning with previous studies indicating that intercropping or weed competition has limited effects on sugarcane juice quality (Yang et al. 2013).

Interestingly, unlike trends observed in other sugarcane-producing countries (Park et al. 2005), no yield decline was observed over successive ratoon crops in La Réunion. This stability may stem from the low levels of mechanization and the quality of the island's volcanic soils (Dlamini and Zhou 2022). Increasing weed pressure over time did not significantly affect yields under either monocropping or intercropping, contradicting Soulé et al. (2024) and Viaud et al. (2023), who hypothesized a cumulative negative effect of weed competition over time. Two main explanations may account for this discrepancy: first, more severe impacts may occur in regions that are more vulnerable to yield decline (Wang et al. 2020); second, regular weeding in the sugarcane row may have buffered the competitive effects of inter-row vegetation. Indeed, recent studies have shown that companion crops or weeds in the inter-row can have little impact on the above-ground part of the harvested sugarcane, despite their impact on the sugarcane roots (Christina et al. 2025). However, such systems do require increased weeding efforts within the sugarcane row.

Following sugarcane yield and sucrose trends, inter-row conditions poorly affected revenue (Fig. 10b). The revenue was significantly affected by the interaction between inter-row conditions and the number of years since the beginning of the experiment (Table S5), but no differences in trends emerged from pairwise comparisons. Nonetheless, intercropping systems required approximately twice the total weed control costs and working hours compared with chemical monocropping or low weed control systems (Fig. 10c, d). This difference was primarily driven by sowing activities, which were manual until 2019 and subsequently performed with micro-tractors. Although herbicide-related costs and labor were lower in intercropping systems than in weed control systems, these savings were offset by increased manual weeding requirements. One way to reduce working hours and costs in our system would be to use mechanized sowing with tractors (Soulé et al. 2024), an option not employed in our experiment and only applicable to large and relatively flat areas, as opposed to micro-tractors (Chetty et al. 2024). In contrast to our study, studies from India (Kaur et al. 2016), Pakistan (Nadeem et al. 2020), and China (Tang et al. 2021) have shown higher net profits from intercropping, attributed to the harvest and market value of

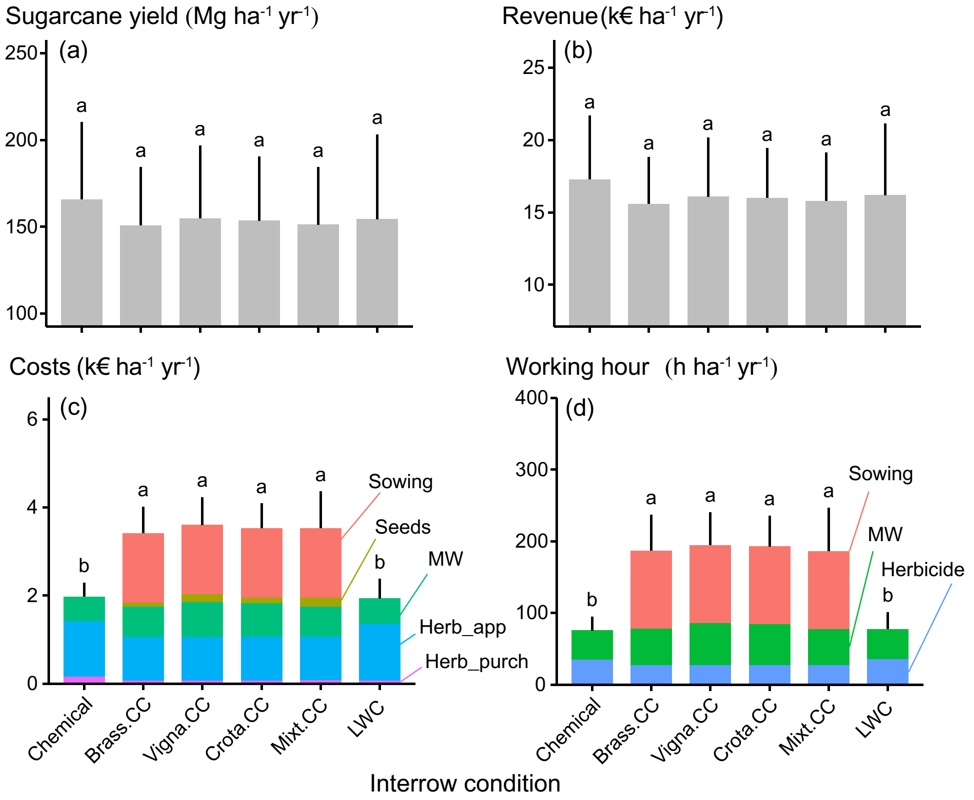

Fig. 10 Average sugarcane yield (**a**), revenue from sugar (**b**), weed control costs (**c**), and weed control working hours (**d**) depending on the inter-row condition: chemical weed control (Chemical), companion crop sequences (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC) over the 7 years of growth. The mean observed values and standard deviations are presented for categories: seed purchase (Seeds), sowing price or working hours (Sowing), manual weeding (MW), herbicide purchase (Herb_purch), and herbicide application price (Herb_app) or working hours (Herbicide). The letters "a" and "b" indicate significant differences in the pairwise comparisons.

companion crops. In Reunion Island, companion crops were used solely for weed suppression within the ECOPHYTO framework and were not harvested for revenue. Additionally, local economic conditions, such as higher labor costs and standardized sugarcane pricing, further differentiate our findings from those of other regions. However, recent work as part of the IntercropValues project has highlighted farmers' interest in a complementary harvest in Reunion Island (https://intercropvalues.eu/case-studies/cics-07/).

3.6 Sustainability of low-herbicide sugarcane cropping systems

Our analysis confirmed that intercropping is an appropriate practice to reduce herbicide use and is relevant to reducing pesticide use by 50% by 2025 in the agricultural sector (national ECOPHYTO II program in France, Fig. 11). Additionally, this practice could provide increased protection against erosion in tropical islands subject to regular extreme storms that affect sugarcane production (Christina et al. 2021a). Nonetheless, because of increased costs and working hours, as illustrated by our study (Fig. 11), farmers would likely adopt such intercropping practices only with financial incentives, which could take various forms, including labels for sale, payment for ecosystem services (Schomers and Matzdorf 2013), or the harvest of the companion plant for additional return (Kaur et al. 2016). Although this technical option has been largely ignored in the international literature, our analysis also suggests that a fine-tuned regulation of spontaneous weeds in the inter-row could be another promising practice to limit the environmental impacts of herbicides without additional costs or working hours. Recent studies suggest that diversified weed communities could limit the negative effects of competitive and dominant species on crop productivity, while potentially promoting ecosystem functions provided by subordinate species (Storkey and Neve 2018; Adeux et al. 2019a, b). Nonetheless, such an assumption is not always observed in tropical cropping systems (Ripoche et al. 2024), and this practice will likely face common perceptions of weeds as "crop enemies" among several stakeholders, including sugarcane growers, agricultural advisors, and researchers (Merfield 2022). To effectively regulate weed species in diversified sugarcane systems, a more detailed evaluation of their harmfulness (MacLaren et al. 2020) or their benefits regarding ecosystem function (Mézière et al. 2015) is now required, which remains a significant knowledge gap at the species level in tropical contexts.

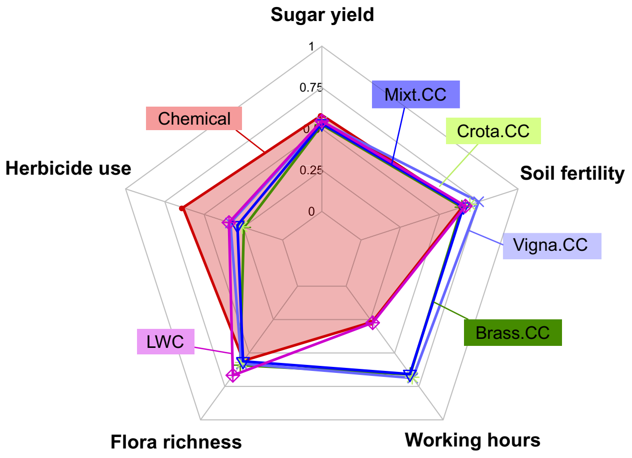

Fig. 11 Comparison of 7-year average sugar yield (product from sugarcane yield and sucrose content), soil fertility index (average over SFI_{Chem}, SFI_{Biol}, and SFI_{Phys}), working hours, flora richness (weed richness), and herbicide use (herbicide treatment frequency index) depending on the inter-row conditions: chemical weed control (Chemical), companion crop sequences (Brass.CC, Vigna.CC, Crota.CC, Mixt.CC), and low weed control (LWC). Variables were normalized by the maximum observed value during the experiment.

4 Conclusion

This study provides the first multi-criteria assessment of sugarcane intercropping systems over a complete cycle under tropical conditions. As expected, our results demonstrate that intercropping can substantially reduce herbicide use without compromising sugarcane yield or quality, while simultaneously enhancing soil physical fertility and providing erosion protection. These findings confirm the potential of intercropping as a sustainable practice in the agroecological transition of intensive sugarcane systems. However, we also reveal significant trade-offs, notably the higher production costs and labor requirements associated with companion crop management. A key result of this study is the observation of increasing weed pressure and shifts in weed community composition over time. This dynamic evolution, which could compromise the agronomic performance of intercropping systems, underscores the need to better understand the trajectories of weed communities and the implications of their long-term management. In addition, a low weed control system that combines chemical management within the crop rows with spontaneous flora in the inter-rows emerged as a promising alternative. This system could deliver ecosystem services comparable to those of intercropping while limiting additional costs and labor. Further research should evaluate its performance across diverse pedoclimatic conditions and weed communities to determine its potential for reducing herbicide dependence and sustaining productivity in tropical sugarcane systems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-026-01085-y.

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Authors' contributions Conceptualization: M.C, J.C, and A.M.; methodology: M.C, J.C, A.R, A.V., K.B., M.S., B.H, and A.M.; validation: S.A.; formal analysis: M.C., K.B., and B.H.; investigation: M.C., J.C., A.V., M.S., S.D., and A.M.; resources: A.M.; data curation: S.A.; writing—original draft: M.C.; writing—review and editing: all authors; funding acquisition: A.M and A.V.

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Data availability All data were described in a companion paper (Ngaba et al. 2023) and referred to as "P41 experiment", and are freely available in the CIRAD dataverse "Agroecological Practices to reduce wEED infestAtion in the tropIcS" (APEEDAIS, https://dataverse.cirad.fr/dataverse/APEEDAIS).

Code availability R scripts used in this study are available from Christina (2025).

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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Authors and Affiliations

Mathias Christina[1,2] · **Julien Chetty**[3] · **Aude Ripoche**[2,4,5,6] · **Antoine Versini**[7,8] · **Karim Barkaoui**[9,10] · **Benjamin Heuclin**[1,2] · **Marion Schwartz**[2,4] · **Sacha Delmotte**[7,8,11,12,13,14] · **Sandrine Auzoux**[2,4] · **Alizé Mansuy**[3]

✉ Mathias Christina
mathias.christina@cirad.fr

[1] CIRAD, UPR AIDA, F-34398 Montpellier, France

[2] AIDA, Univ Montpellier, CIRAD, Montpellier, France

[3] eRcane, F-97494 Sainte-Clotilde, Réunion, France

[4] CIRAD, UPR AIDA, 97743 Saint-Denis Cedex 9, La Réunion, France

[5] CIRAD, UPR GECO, 97743 Saint-Denis Cedex 9, La Réunion, France

[6] GECO, Univ Montpellier, CIRAD, Montpellier, France

[7] CIRAD, Recyclage et risque, 97400, UPR78 Saint-Denis, La Réunion, France

[8] Recyclage et Risque, Univ Montpellier, CIRAD, Montpellier, France

[9] UMR AMAP, CIRAD, F-34398 Montpellier, France

[10] AMAP, Univ Montpellier, CIRAD, CNRS, INRAE, Montpellier, IRD, France

[11] CEFE, Univ Montpellier, CNRS, EPHE, Montpellier, IRD, France

[12] INRAE, IRD, Eco&Sols, Univ Montpellier, CIRAD, Institut Agro, Montpellier, France

[13] CIRAD, UPR HortSys, F-97455 Saint-Pierre, Reunion, France

[14] HortSys, Univ. Montpellier, CIRAD, Montpellier, France