Title: Effect of crop management and climatic factors on weed control in sugarcane intercropping systems.

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Abstract

Context

Cover crops in intercropping systems have a high potential to manage weeds in tropical agroecosystems as an herbicide alternative. However, it still needs to be better investigated in sugarcane cropping systems.

Objective

This study assesses the weed control ability of cover crops in sugarcane intercropping systems depending on crop management and climate in tropical conditions.

Methods

This study was based on a set of eight experiments, including ten cover crop species, performed from 2012 to 2021 in three areas in Reunion Island (France) and comparing three inter-row management treatments: i) chemical weed control, ii) cover crops sown in the inter-row, and iii) low weed control. Mean weed and cover crop ground cover were measured during the entire crop cycle, and the complementary weed management practices (herbicide, manual weeding) were also recorded. Sugarcane yield and crop management were evaluated to assess the economic impact of a change in practice.

Results

Mean weed ground cover was reduced by 51 % in the cover crop and chemical treatments compared to low control. Additionally, the cover crop treatment had an herbicide treatment frequency index lower by 37% compared to chemical treatment but a higher number of manual weedings. In all treatments, weed cover increased with rainfall and temperature. In the cover crop treatment, a structural equation modeling approach allowed us to highlight the influence of cover crop (sowing date and species) and sugarcane management (crop cycle - plant or ratoon crop) on weed cover. Weed cover decreased with an increase in cover crop ground cover, which was higher for the early sowing date. Additionally, weed cover was

lower in ratoon crops than plant crops but increased over time since intercropping was implemented. Finally, sugarcane yield was lower by 6% in cover crop treatment compared to chemical treatment. The change in operating costs and revenues between these crop management induced a decrease in profits in intercropping compared to chemical cropping systems, variable according to the degree of mechanization.

Conclusions

This study highlights the predominance of management factors, compared with climate, to explain the effectiveness of weed control in sugarcane intercropping systems.

Implications

Due to the change in weed cover over time, there is a need to assess the long-term sustainability of this practice and the potential change in weed communities.

Keywords: *Saccharum officinarum*; companion plants; interplanting; living mulch; weed management

1. Introduction

Over the past few decades, the use of pesticides in agriculture has surged worldwide, mainly due to the expansion of agricultural land and increased application rates (Brühl and Zaller, 2022). However, concerns about pesticides' environmental and health impacts have spurred efforts to explore alternative weed management strategies (FAO, 2019). The emergence of herbicide-resistant weeds is particularly concerning, which poses a significant challenge to weed control (Heap, 2014). In this context, research and development efforts have focused on evaluating non-chemical approaches to weed management (Jacquet et al., 2022).

In tropical and temperate climates, weeds are a significant biotic constraint on agricultural productivity, reducing crop yield and increasing production costs (FAO, 2017; Oerke, 2006). In recent years, the use of cover crops in intercropping systems gained attraction as a promising alternative to herbicides for weed control while also delivering other benefits, such as improved soil fertility and erosion control (Garcia et al., 2018; Gu et al., 2021; Kocira et al., 2020; Scavo et al., 2022; Verret et al., 2017). There is broad agreement that a vigorous cover crop will suppress weeds and reduce herbicide use (Bhaskar et al., 2018; Christina et al., 2021b; Mennan et al., 2020; Ranaivoson et al., 2019).

Sugarcane is a globally significant crop, serving as the primary source of sugar, ethanol, and electric energy in tropical and sub-tropical regions (de Miranda and Fonseca, 2020). Given the increasing demand for ethanol and electricity as potential substitutes for fossil fuels to reduce greenhouse gas emissions (Goldemberg et al., 2014), the sustainability of sugarcane production came under scrutiny (Bordonal et al., 2018), particularly concerning herbicide use. While several studies have highlighted the potential benefits of intercropping sugarcane with cover crops to diversify production (Geetha et al., 2019), increase economic returns per unit of land (Rehman et al., 2014), enhance soil fertility (Solanki et al., 2017), or reduce fertilizer inputs (Prellwitz and Coelho, 2011; Tian et al., 2020), only a limited number have examined the effectiveness of cover crops for inter-row weed management (e.g., Geetha et al., 2019). Although many sugarcane cultivars are now resistant to pests and pathogens (Sundar et al., 2015), weed management remains a major production constraint (Suganthi et al., 2019).

As shown in temperate cropping systems, various climatic and management constraints influence intercropping performance for weed control (Gardarin et al., 2022). In the case of tropical sugarcane cropping systems, climatic factors such as temperature and precipitation could affect the growth and development of both the sugarcane, the cover crop, and the weeds, potentially altering the timing and intensity of weed competition. Also, management factors such as mulching (Carvalho et al., 2017) and cover crop management practices could affect weed control in sugarcane intercropping systems. For example, the choice of cover crop species and the timing of its planting can affect its competitiveness with weeds and its ability to suppress weed growth (Dayoub et al., 2022; Liebman and Dyck, 1993). Additionally, weed control in intercropping systems often relies on complementary pre-emergent herbicide application before cover crop sowing and manual weed control (Mansuy et al., 2019), which must be considered to assess the ability of cover crops to manage weeds in the inter-row. Thus, to optimize the performance of sugarcane intercropping systems for weed control, it is essential to consider and address the range of climatic and technical constraints that may influence their effectiveness.

Sugarcane is the dominant agricultural industry on Reunion Island, with more than half of agricultural land devoted to it, making it a crucial economic, social, and environmental resource (Leung, 2015). The island's tropical climate is favorable to weed growth, with a daily delay in weed control resulting in yield losses of 0.1-0.2 Mg ha^{-1} d^{-1} and an absence of weed control leading to 80% yield loss (Marnotte et al., 2008). As a result, chemical weed control is the primary strategy used to control weeds, making the sugarcane sector the largest consumer of herbicides on the island (Antoir et al., 2016). However, the withdrawal of many chemical herbicides and government incentives to reduce the use of pesticides by 50% by 2025 under the Ecophyto program have prompted the sector to explore alternative weed control methods (Antoir et al., 2016). While the efficacy of cover crops for weed control in sugarcane inter-rows has been recently tested on Reunion Island (Mansuy et al., 2019), the impact of the island's high spatial climate variability remains poorly understood.

A better understanding of the factors influencing weeds x cover crops x sugarcane interactions in intercropping is crucial for developing effective strategies to reduce herbicide use while maintaining yield (Viaud et al., 2023), particularly in tropical islands with diverse environmental conditions. The objectives of this study were to i) assess the weed response to sugarcane intercropping compared to monocropping, ii) assess the changes in herbicide application and manual weeding practices in the intercropping system compared to monocropping, and iii) disentangle the effects of the cover crop, the complementary weed control management, the climate, and the cover crop management on weeds in the sugarcane inter-row. We gathered data from a network of 8 intercrop experiments performed on Reunion Island from 2012 to 2021 to achieve these objectives.

2. Material & Methods

2.1. Experimental network

Reunion Island is located in the Southwest of the Indian Ocean near Madagascar. Sugarcane agricultural areas are located from sea level to 800 m a.s.l, in dry (West Coast) and high rainfall conditions (East Coast, Christina et al., 2021a). Eight field experiments were conducted over nine years (2012-2021) in three locations on Reunion Island (Table 1). Five experiments were conducted on-station in the North of the Island on a Nitisol (WRB classification). Three experiments were conducted on-farm, one in the East on a Ferralsol and two in the West on an Andic Cambisol. The length of each experiment varied between one to seven years. In this study, a trial defines an experiment performed in a specific year (28 trials). Mean annual temperatures (T_{MEAN}) varied from 19.6 to 26.1°C, and annual rainfall varied from 718 to 2611 mm y^{-1}, depending on trials. Soil chemical characteristics were measured at each experiment's beginning and listed in Table A1. The weather variables were obtained from the Meteor software (https://smartis.re/METEOR), which interpolates daily weather variables from the Meteo France and CIRAD weather station network.

2.2. Experimental design, sugarcane management and yield

Each experiment consisted of a randomized block sugarcane (*Saccharum officinarum*) to compare three inter-row management treatments: a treatment with chemical weed control in the whole plot (CH), a treatment with a cover crop sown each year in the inter-row (CC), and a weedy treatment with low weed control in the sugarcane inter-row (LC). Depending on the experiments, each treatment was repeated in two to four blocks, with each elementary plot varying from 60 to 780 m² (Table A2). The sugarcane was planted with a 1.5m row distance in all experiments. All experiments were planted with the sugarcane R579 cultivar except for the "P12" experiment using the R587 cultivar (Table A2). All experiments were irrigated except for "Canecoh_OF", located in the East rainy part of the island. Mineral NPK fertilization was supplied to reach the optimum yield according to recommendations provided by the Serdaf software based on soil analysis (Versini et al., 2018). NPK fertilization varied depending on trials, with an average of 180 kg N ha^{-1}, 100 kg P ha^{-1}, and 250 kg K ha^{-1}. In most trials, fertilization has been split with a first application one month after planting or harvest and a second at 2-3 months (details available in the data paper Ngaba et al., 2023). Sugarcane stalk fresh mass (hereafter sugarcane yield) was measured at harvest by sampling all sugarcane stalks on the two rows in the middle of the plot (Ngaba et al., 2023). Part of the yield data (only legume intercropping treatments) were included in the meta-analysis of Viaud et al. (2023).

Table 1. Description of the experimental network used in this study with the experiment location, trial harvest year (including crop cycle), cover crop species sown in the trial and their sowing dates (months after planting or harvest, MAP/H), mean temperature (T_{MEAN}, °C) and rainfall (mm y^{-1}) over the sugarcane cycle, and trial identification (ID). Different sowing dates in the same trial indicated different sowing date treatments. In the cover crops species, "Mixture" indicated a mixture of cover crops (detailed in Table A3).

Location, Experiment (Latitude, Longitude, Altitude)	Harvest year	Cover crop species	Sowing date (MAP/H)	T_{MEAN} (°C)	Rainfall (mm y^{-1})	ID
North "P12" (-20.903, 55.532, 70m a.s.l)	2018 (P)	*Vigna unguiculata*	2.8	26.0	1421	1
	2019 (R1)	*V. unguiculata*	1.6	25.0	1260	2
	2020 (R2)	*V. unguiculata*	1.6	23.9	1284	3
North "P41" (-20.903, 55.528, 68m a.s.l)	2015 (P)	*Desmodium intortum, Canavalia ensiformis*	1.1/ 2.3/ 3.3	24.0	2008	4
	2016 (R1)	*D. intortum, C. ensiformis*	2.3	24.2	1117	5
	2017 (R2)	*Guizotia abyssinica, C. ensiformis, Avena sativa, V. unguiculata, Crotalaria juncea, Crotalaria spectabilis*	2.3	24.2	1350	6
	2018 (R3)	*G. abyssinica, C. ensiformis, Brassica carinata, V. unguiculata, C. juncea, C. spectabilis*	1.6	25.0	1528	7
	2019 (R4)	*G. abyssinica, C. ensiformis, B. carinata, V. unguiculata, C. juncea, C. spectabilis*	1.1	25.6	1327	8
	2020 (R5)	*G. abyssinica, C. ensiformis, B. carinata, V. unguiculata, Raphanus sativus*, Mixture	2.6	25.0	718	9
	2021 (R6)	*G. abyssinica, C. ensiformis, B. carinata, V. unguiculata, R. sativus*, Mixture	1.38	24.1	1070	10
North "P25_montagne" (-20.902, 55.531, 50m a.s.l)	2018 (P)	*C. ensiformis,* Mixture	2,7	24.4	1527	11
	2019 (R1)	*C. ensiformis,* Mixture	1.3	25.6	1310	12
	2020 (R2)	*C. ensiformis,* Mixture	1.3	25.0	736	13
North "P25_LEG" (-20.902, 55.531, 50m a.s.l)	2012 (P)	*V. unguiculata, C. ensiformis, Dolichos lablab, D. intortum, Cajanus cajan*	0.4 /1.9	23.9	1569	14
	2013 (R1)	*V. unguiculata, C. ensiformis, D. intortum*	0.7 /1.8	24.4	1418	15
	2014 (R2)	*V. unguiculata, C. ensiformis, D. intortum*	0.5 /2	24.4	1023	16
	2015 (R3)	*V. unguiculata, C. ensiformis, D. intortum*	0.7 /1.6	24.3	1941	17
	2016 (R4)	*V. unguiculata, C. ensiformis*	1.8	24.1	1063	18
North "P25_ITK" (-20.902, 55.531, 50m a.s.l)	2013 (R1)	*V. unguiculata*	0.8	24.2	1103	19
	2014 (R2)	*V. unguiculata*, Mixture	0.6 /2.3	24.5	1033	20
	2015 (R3)	*B. juncea*, Mixture	0.7 /1.6	24.4	1974	21
East "Canecoh_OF" (-21.047, 55.682, 170m a.s.l)	2016 (R4)	*V. unguiculata, C. ensiformis*	1.5	22.8	1218	22
	2017 (P)	*C. ensiformis,* Mixture	3	22.8	1505	23
	2018 (R1)	*C. ensiformis,* Mixture	1.6	22.6	1289	24
	2019 (R2)	*C. ensiformis,* Mixture	2.1	22.9	2501	25
	2020 (R3)	*C. ensiformis,* Mixture	1.5	22.4	2611	26
West "Ecocanne_AC" (-21.067, 55.280, 545m a.s.l)	2015 (R1)	*D. intortum, C. ensiformis*	0 /1.3	20.3	1241	27

West “Ecocanne_OB” (-21,066, 55,285, 575m a.s.l)	2014 (R2)	*D. intortum, C. ensiformis*	0.3 /1.4	19.6	860	28

* Crop cycle: P = plant crop, R1 = first ratoon crop, R2 = second ratoon crop…

2.3. Weed management, HTFI, and manual weedings

Weed management of all treatments included: the application of a pre-emergent herbicide after sugarcane planting or harvest in the whole plot, a manual or chemical weeding of the sugarcane row to limit the impact on sugarcane production (throughout the crop cycle), and a specific manual weeding of the weeds considered as the most harmful in the whole plot (in particular, tall grasses: *Panicum maximum* and *Rottboellia cochinchinensis*). In the chemical control treatment, 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 cover crop treatment when ground cover by weeds exceeded 30%. 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 (Halberg, 1999). The HTFI was only available in 81% of trials. Details of the chemical compounds used for herbicides are available in the data paper (Ngaba et al., 2023), and are summarized in Table A6. Information regarding manual weedings included: manual weeding in the row only, manual weeding in the inter-row only, and manual weeding in the whole plot. In the present study, the number of manual weedings in the inter-row (MW_{IR}) was considered as the sum of those in the whole plot and the inter-row, while the number of manual weedings in the row (MW_R) was considered as the sum of those in the whole plot and sugarcane row. The number of manual weedings was only available in 89% of trials. In most cases, when an herbicide was applied, or a manual weeding was performed during the trials, all plots from the same inter-row management treatment were concerned. Consequently, the mean values per treatment and trial were used in the following analyses.

2.4. Cover crop management

The experimental network tested ten cover crop species (Table 2). They included six Fabaceae, three Brassicaceae, and one Asteraceae plant, as well as mixtures (Table A3). Cover crops were sown manually or mechanically in two to three lines depending on trials (Table A3). The sowing date depended on trials (Table 1, Table A3). At the end of their development, cover crops died gradually with sugarcane closure or were mechanically destroyed before canopy closure in a few treatments (14% of treatments, Table A3). The sowing densities were determined based on previous studies and literature (Christina et al., 2021b; Table A3). In mixtures, the sowing density of each cover crop was its density in pure crop divided by the number of present species (Négrier et al., 2023).

Table 2. Cover crop species sown in the experimental network: species, common name, family, area of origin, and the number of trials including these species (Ntrial) is indicated.

Species	**Common name**	**Family**	**Origin**	**Ntrial**
Brassica carinata	Abyssinian mustard	Brassicaceae	Temperate	4
Brassica juncea	Brown mustard	Brassicaceae	Temperate	1
Canavalia ensiformis	Jack bean	Fabaceae	Tropical	19
Crotalaria juncea	Sunn hemp	Fabaceae	Tropical	2
Crotalaria spectabilis	Showy crotalaria	Fabaceae	Tropical	2
Desmodium intortum	Greenleaf	Fabaceae	Tropical	6
Dolichos lablab	Hyacinth bean	Fabaceae	Tropical	1
Guizotia abyssinica	Niger	Asteraceae	Temperate	4
Raphanus sativus	Radish	Brassicaceae	Temperate	2
Vigna unguiculata	Cowpea	Fabaceae	Tropical	13
Mixture of cover crops	Detailed in Table A3			10

2.5. Ground cover by cover crop and weeds

The ground cover by cover 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% and described in Table A4. This method makes it possible to assess the ground cover by species in multi-species crops and was used in previous studies (Christina et al., 2021b; Mansuy et al., 2019; Marnotte, 1984; Négrier et al., 2023). In the trial plots, ground cover by i) cover crops and ii) weeds was performed every month during the first six months and then every two months up to the sugarcane harvest. Ground cover was then linearly interpolated between two dates of measurement to calculate a mean ground cover by cover crops (COV_{CC}) or weeds (COV_{WEED}) between two sugarcane harvest dates. The current study will not present the ground cover results by weed species. Nonetheless, a description of weed species observed in the trials is available in Table A5.

2.6. Economic assessment

An economic analysis of the three systems (chemical, cover crop, and low control) was carried out to assess the impact on profits of a change in practices. The economic analysis was carried out 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/wakka.php?wiki=RechercheFacette&q=otecas&facette=). This software, developed specifically for the sugarcane industry in La Réunion, calculates revenue and operating costs according to crop management and yields. Three types of farms were considered: i) a farm managed manually (weeding with a backpack sprayer and manual sowing of cover crops), ii) a farm managed with a micro-tractor for weeding and sowing, iii) a farm managed with a tractor for weeding and sowing. These three types of farms currently exist in La Réunion.

Only the variable operating costs across the cropping systems were considered in the expenses: the purchase of herbicides (Table A6) and seeds (Table A7), as well as labor and mechanization costs (taking account of equipment depreciation, Table A8). For each plot in the trial network, the costs of herbicide purchase, seed purchase, number of chemical weeding operations, and number of manual (and some mechanical) weeding operations were calculated. Each farm's labor and mechanization costs for herbicide application were calculated differently, considering the number of weed control operations (in the trials) and the type of weed control (backpack sprayer, micro-tractor, or tractor). The costs of sowing cover crops were calculated differently for the three farms, taking into account the type of sowing (manual, micro-tractor, or tractor) as well as the mulch management in the row spacing, which must be removed for manual or micro-tractor sowing. The revenue from sugarcane production in each trial was calculated with OTECAS based on the fresh stalk yield, sugarcane richness, and additional subsidies in La Réunion. For this calculation, we considered the same size of 5 ha for all three types of farms with manual harvest. The profits were calculated as the difference between revenue and operating costs.

2.7. Data analysis

Prior to analysis, a few elementary plots were removed due to cover crop failure due to untested factors: accidental herbicide application in the inter-row (14 out of 607 plots), no emergence due to irrigation failure or excessive water stress (60 out of 607 plots), cover crop destruction due to bio-aggressors (6 out of 607 plots). All analyses were performed using R 4.1 (R Development Core Team, 2022).

For all statistical analyses, the following procedure was made. If necessary, to ensure residue normality, the target variable was transformed using the Box-Cox function (powerTransform function from car R package, Fox et al., 2023) based on a Gaussian law. Then, the identification of the random effects (among trial identification, location, year, and nested effects) was realized by comparing the linear mixed model (lme function, nlme R package, Pinheiro et al., 2022) and the only fixed model (gls function, nlme R package) fitted using the restricted maximum likelihood (REML) estimation and compared using the Bayesian information criterion (BIC). Then, the fixed effect selection was performed using a stepwise downward procedure based on BIC from the model with all fixed effects and interactions (lme function) and fitted using the maximum likelihood (ML) estimation (Zuur et al., 2009). Finally, the model parameters of the resulting model were fitted using REML estimation. The assumptions of homogeneity and normality were checked graphically using histograms of residuals, quantile-quantile plots of Pearson's residuals versus standardized Gaussian sample, and plots of residuals against fitted values. Pairwise comparisons among treatments were performed using the emmeans function with a Tukey p adjustment method and a 0.05 probability threshold (emmeans R package, Lenth et al., 2023). The models' mean predicted and confidence interval values depending on factors were calculated using the emmeans function.

In the first step, the influence of the inter-row treatment (low control, cover crop, or chemical), the experiment identification, the mean temperature (T_{MEAN}), the cumulated rainfall over the crop cycle, the crop cycle (plant or ratoon crop), the irrigation management, and their interaction on COV_{WEED} (transformation λ=0.39) were tested as fixed effects using a linear mixed model with the trial identification (ID) as a random effect. The same analysis was performed for HTFI (transformation λ=0.46) and the number of manual weedings in the inter-row (MW_{IR}, transformation λ=0.46) and in the row (MW_R, transformation λ=0.50). Note that analyses on MW_{IR} and MW_R were also realized without transformations with a generalized linear mixed model (glmer function) with a Poisson law which gave the same results. The linear analyses with a Gaussian law and transformation were chosen for these two variables to be applied in the following structural equation model. Similarly, the influence of the inter-row treatment on the different operating costs and revenue was assessed with the same mixed analysis with the trial identification as a random effect. The average predicted values by the statistical models for costs and revenue depending on the inter-row treatment were presented.

In the cover crop treatment, COV_{WEED} could result from the influence of different weed control management: COV_{CC}, MW_{IR}, and HTFI, as well as other biotic and abiotic factors. COV_{CC}, MW_{IR}, and HTFI could themselves be influenced by climate and management through weed pressure. Consequently, the influence of climate (T_{MEAN} and Rainfall), sugarcane management (crop cycle, irrigation, number of years since the implementation of intercropping - Y_{IC}), cover crop (CC) management (CC species - $CC_{species}$ and sowing date – CC_{Sowing_date}), MW_{IR}, and HTFI on COV_{CC} and COV_{WEED} was tested using a mixed structural equation model (SEM, psem function from the piecewiseSEM R package, Lefcheck, 2016) to take into account the indirect effect of factors on COV_{WEED} through COV_{CC}, HTFI, and MW_{IR}. The initial SEM included four submodels (hypotheses):

$$COV_{WEED} \sim COV_{CC} + MW_{IR} + HTFI + Y_{IC} + T_{MEAN} + Rainfall + CC_{species} + CC_{Sowing\_date} + Cycle + Irrigation, \qquad random = 1|ID$$

$$COV_{CC} \sim MW_{IR} + Y_{IC} + T_{MEAN} + Rainfall + CC_{species} + CC_{Sowing\_date} + Cycle + Irrigation, \quad random = 1|ID$$

$$HTFI \sim Y_{IC} + T_{MEAN} + Rainfall + CC_{species} + CC_{Sowing\_date} + Cycle + Irrigation, \quad random = 1|ID$$

$$MW_{IR} \sim Y_{IC} + T_{MEAN} + Rainfall + CC_{species} + CC_{Sowing\_date} + Cycle + Irrigation, \quad random = 1|ID$$

Following a similar procedure to the linear mixed model (Box-Cox transformation, ML estimation for fixed effect selection, and REML estimation for the final parameter estimations), insignificant effects ($\alpha > 0.05$), as well as unlinked variables, were progressively removed up to reach the global goodness-fit-criteria (Fisher's C test).

2.8. Data availability

All the data, including observations and sugarcane management, were described in a companion paper (Ngaba et al., 2023), and are freely available in the CIRAD dataverse "Agroecological Practices to reduce wEED infestAtion in the tropIcS" (APEEDAIS, https://dataverse.cirad.fr/dataverse/APEEDAIS). The dataset links separated per trial were listed in supplementary materials.

3. Results

3.1. COV_{WEED} response to inter-row treatment, climate, and sugarcane management

Mean annual ground cover by weeds (COV_{WEED}) varied from 0 to 75% depending on trial and inter-row treatment (Fig. 1). COV_{WEED} was influenced by the inter-row treatment ($p<0.0001$), T_{MEAN} ($p=0.0091$), the total rainfall ($p=0.0127$), the crop cycle ($p=0.0021$), the interactions between the treatment and the rainfall ($p<0.0001$), and the interaction between the experiment and the inter-row treatment ($p=0.0068$, Table A9). On average, COV_{WEED} was reduced by 51% in both cover crop and chemical treatments, compared to low control treatment (Table A10, Fig. 1a). Nonetheless, COV_{WEED} was not influenced by the inter-row treatment in two experiments (P25_ITK and Ecocanne_OB) out of eight, and all treatments were similar in both experiments (Table A11). COV_{WEED} was 43% lower in ratoon crops than in plant crops, with mean values of 13% and 23% in ratoon crops (characterized by a sugarcane trash mulch cover) and plant crops (a first-year without mulch cover), respectively (Table A9, Fig 1b). COV_{WEED} increased with the total rainfall over the crop cycle in both low control and chemical treatment but not in the cover crop treatment (Table A9, Fig. 1c). COV_{WEED} increased with T_{MEAN} in all treatments (Table A9, Fig. 1d).

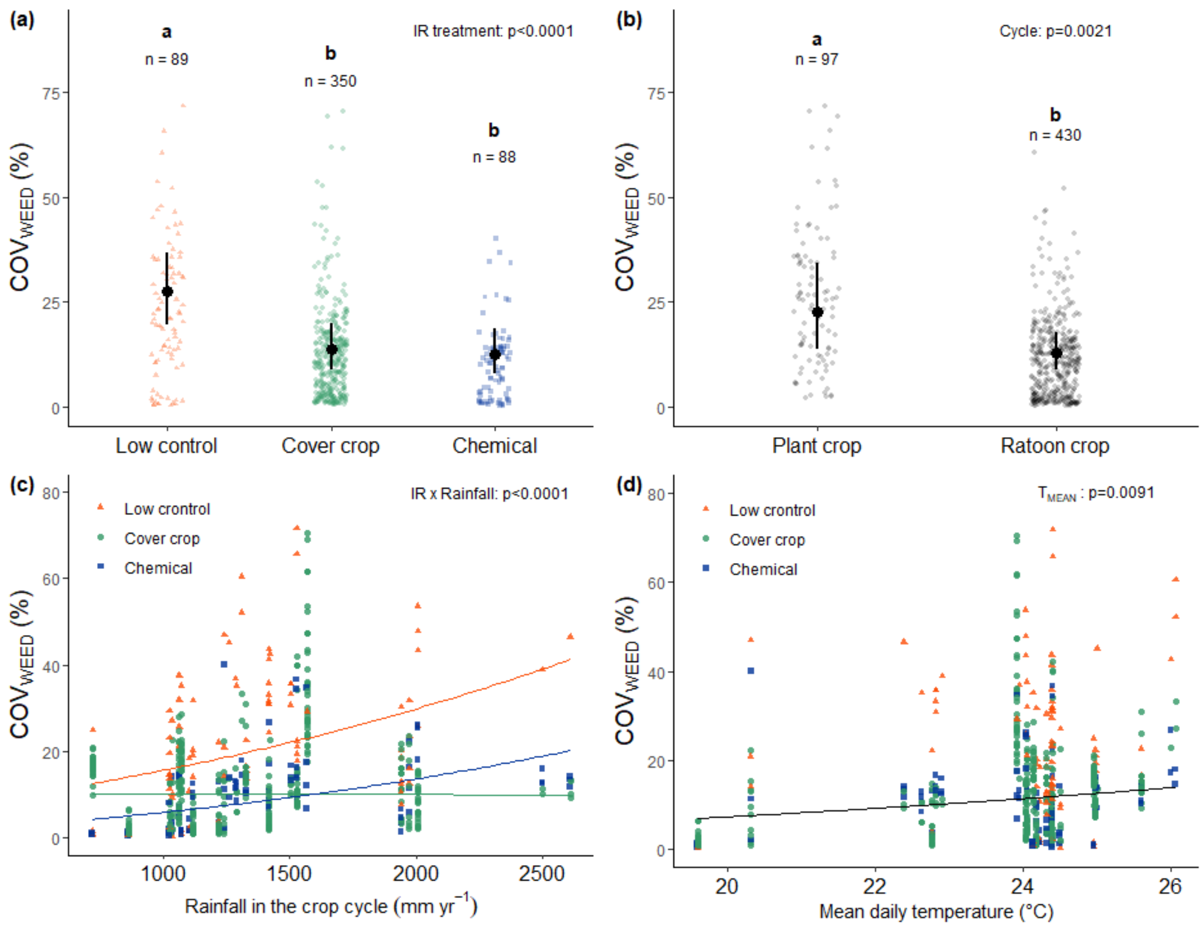

Fig. 1. Mean ground cover by weeds (COV_{WEED}) response to inter-row management treatment (IR, a), sugarcane crop cycle (plant or ratoon crop, b), rainfall (c), and mean daily temperature (T_{MEAN}, d) during the crop cycle. In (a) and (b), the mean values (black point) and confidence intervals (black line) predicted by the mixed model with the trial as a random effect are presented. The number of measurements in each category is indicated by "n". Letters indicated significant differences in the pairwise comparisons (Table A10). In (c) and

(d), the lines represented the predicted response by the model after back-transformation. P values of the fixed effects in the variance analysis are indicated (Table A9).

3.2. $Yield_{SC}$, HTFI and manual weedings response to inter-row treatment

The sugarcane yield ($Yield_{SC}$), the herbicide frequency treatment index (HTFI) and the number of manual weedings in the sugarcane inter-row (MW_{IR}) and in the row (MW_R) were influenced by the inter-row treatment (Fig. 2, Table A9, A10). Average $Yield_{SC}$ across trials were 135, 127, and 128 Mg FM ha^{-1} in chemical, cover crop, and low control treatments, respectively (Fig. 2a). $Yield_{SC}$ was significantly lower by 6% in the cover crop treatment compared to chemical one. The HTFI was reduced by 37% in the cover crop and low control treatments compared to chemical treatment (Fig. 2b). Nonetheless, the number of manual weedings in the cover crop treatment increased by 86% and 34% in the inter-row and row, respectively (Fig. 2c,d), compared to both low control and chemical treatments. No climate or sugarcane management influences were observed on HTFI, MW_{IR}, and MW_R.

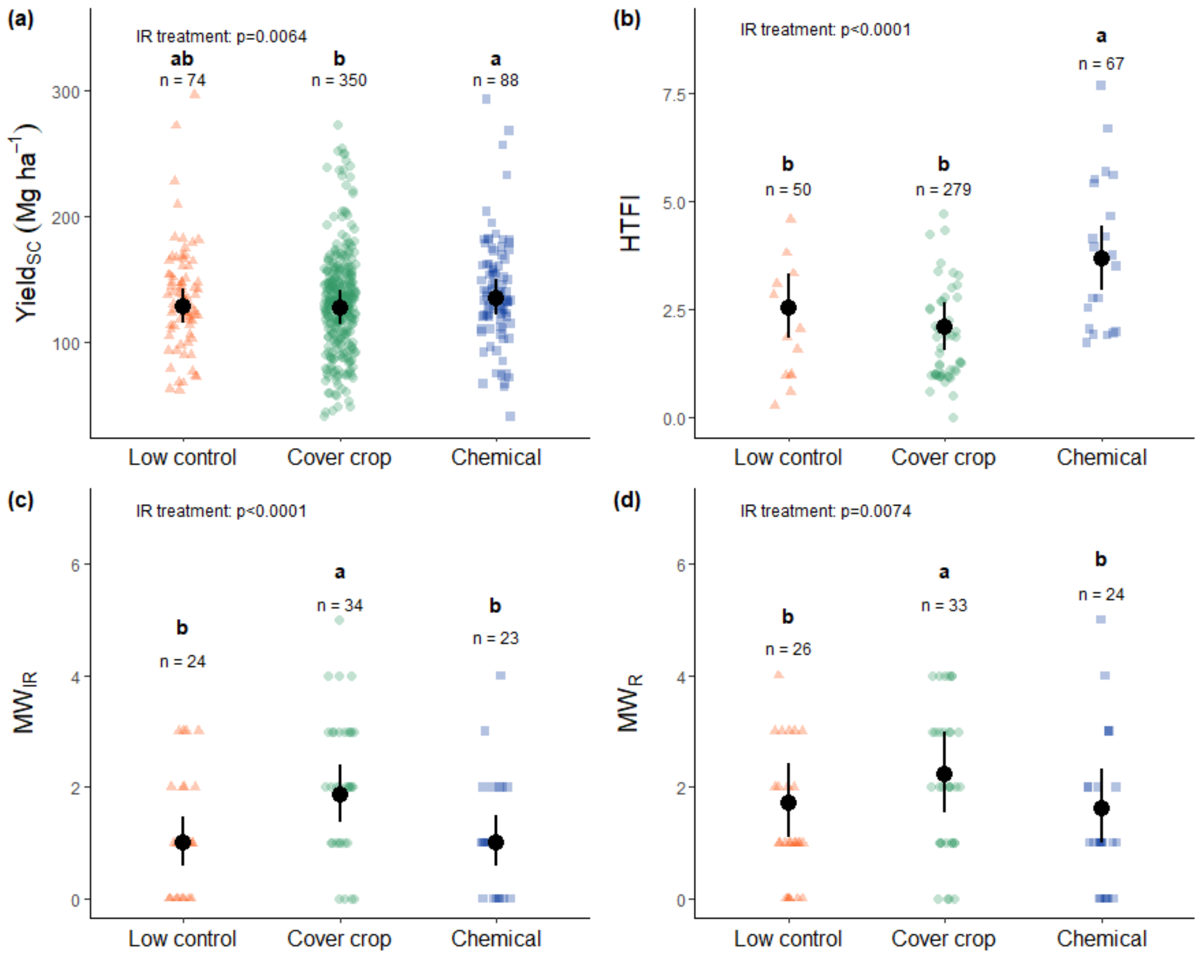

Fig. 2. Sugarcane yield (Yield$_{SC}$, a), herbicide treatment frequency index (HTFI, b), and number of manual weedings in the inter-row (MW$_{IR}$, b) and row (MW$_R$, c) depending on the inter-row management treatment. The mean values (black point) and confidence intervals (black line) predicted by the linear mixed models with the trial as a random effect are presented. The number of measurements in each category is indicated by "n". Letters indicated significant differences in the pairwise comparisons (Table A10). P values of the fixed effects in the variance analysis are indicated (Table A9).

3.3. Structural equation models on COV_{CC} and COV_{WEED}

In the cover crop treatment, COV_{WEED} was directly influenced by COV_{CC}, the crop cycle, the number of years since the implementation of intercropping (Y_{IC}), the cover crop sowing date and species, and COV_{CC} was directly influenced by cover crop sowing date, species, and crop cycle (Fig. 3b, Table A12, A15). COV_{WEED} was also indirectly influenced by cover crop sowing date and species through COV_{CC}. These retained paths respected the Fisher global goodness-of-fit criteria in the SEM with all the data (Fischer C = 0.76, p=0.94, Table A12) as well as in SEM using only plant crop data (Fischer C = 2.9, p=0.23, Table A13) or ratoon crop data (Fischer C = 3.9 p=0.42, Table A14). These fixed factors explained 49% and 34% of COV_{WEED} and COV_{CC} variability, respectively (Fig. 3b). Nonetheless, the respective influence of each factor depended on the crop cycle (Fig. 3c,d). In plant crops, the cover crop sowing date affected COV_{CC} while not in ratoon crops, and this factor had a prominent effect on COV_{WEED} in plant crops compared to ratoon crops (see estimates in Table A13 and A14). The cover crop species directly influenced COV_{WEED} in ratoon crops but not plant crops.

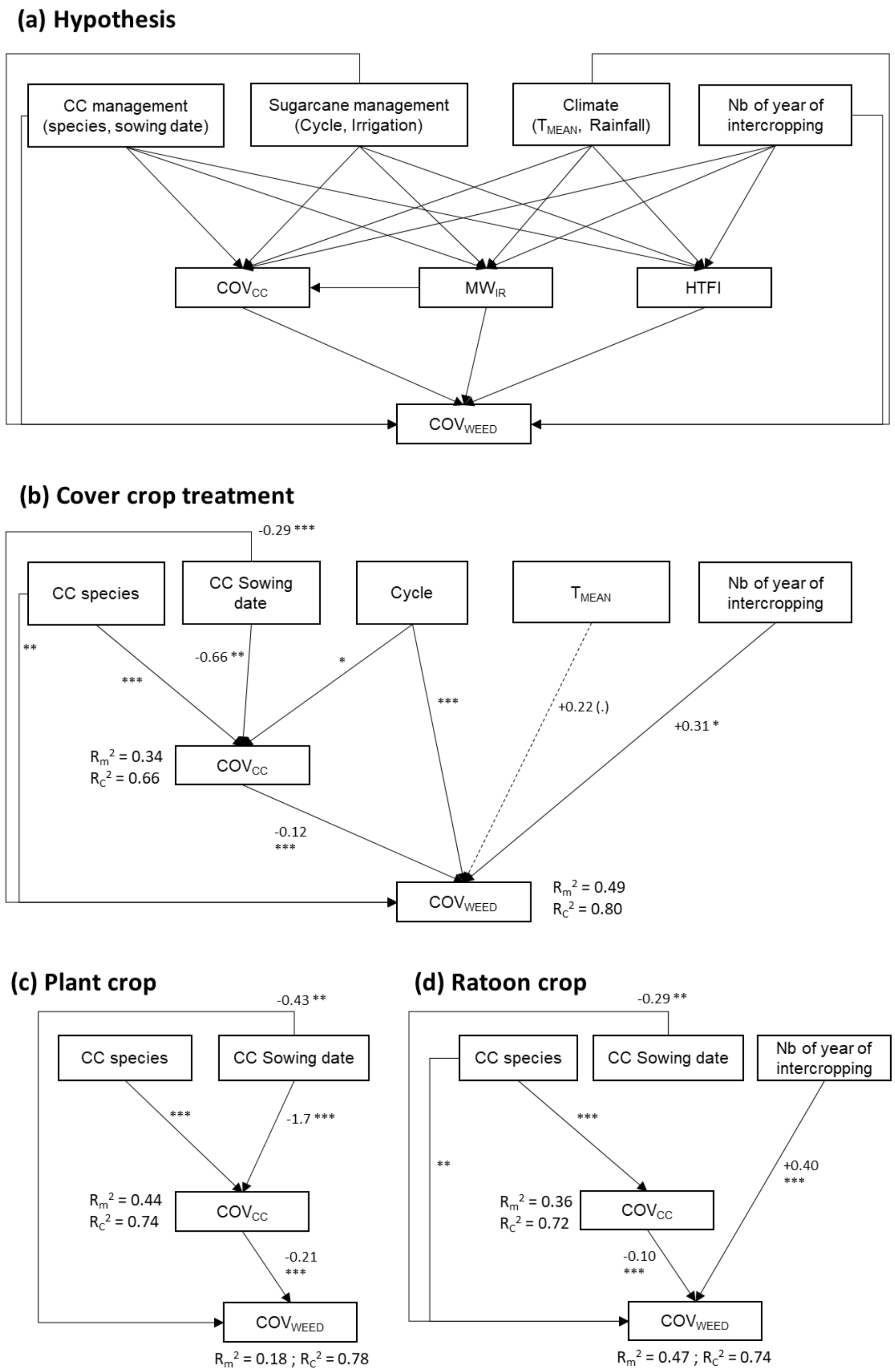

Fig. 3. Structural equation model (SEM, a) showing direct and indirect effects of cover crop management, weed management, and environmental conditions on the ground cover by weeds (COV_{WEED}) and cover crop (COV_{CC}) in the cover crop treatment considering the hypothesis (a), final SEM with all data (b), plant crop data (c) or ratoon crop data (d). Arrows represent the structural equation with variables: mean annual temperature (T_{MEAN}), rainfall, crop cycle,

irrigation management, cover crop (CC) species, and sowing date, number (nb) of years since the implementation of intercropping, the number of manual weedings in the inter-row (MW_{IR}), and the herbicide treatment frequency index (HTFI). In (b), (c), and (d), the arrows represent the significative result of the analysis. The mode estimates are given for quantitative variables (after Box-Cox transformation), and p values are indicated by ***, **, *, and (.) when lower than 0.001, 0.01, 0.05, and 0.1, respectively. Marginal R^2 (R_m^2) and conditional R^2 (R_C^2) are given. Details on model estimates for qualitative variables and variance analyses are given in Supplementary Material (Table A12 to A14).

3.4. Weeds response to cover crops growth and species

A negative impact of COV_{CC} on COV_{WEED} was shown in the structural equation model in both plant and ratoon crops (Fig. 3). The SEM predicted a decrease in COV_{WEED} from 39 to 14% in plant crops, and 14 to 5% in ratoon crops, with increasing COV_{CC} (Fig. 4a). COV_{CC} was influenced by the cover crop species in both plant and ratoon crops (Fig. 3, 5a). In contrast, COV_{WEED} was only influenced by the cover crop species in the ratoon crops (Fig. 3, 5b). In plant crops, the highest COV_{CC} were found in cover crop mixture (56%), and *V. unguiculata* (49%), followed by *C. ensiformis* (42%), and the lowest COV_{CC} was found in *D. intortum* (29%, Fig. 5a). In ratoon crops, cover crop species with the highest COV_{CC} was *C. ensiformis* (35%) followed by *C. juncea* (33%), *C. spectabilis* (29%) and *R. sativus* (28%). The lowest COV_{CC} were found for *G. abyssinica* (11%), *V. unguiculata* (13%), and *B. juncea* (near 0%). In ratoon crops, COV_{WEED} was similar among all CC species except for *C. ensiformis,* which has a lower COV_{WEED} (8%) than *V. unguiculata* (11%, Fig. 5b).

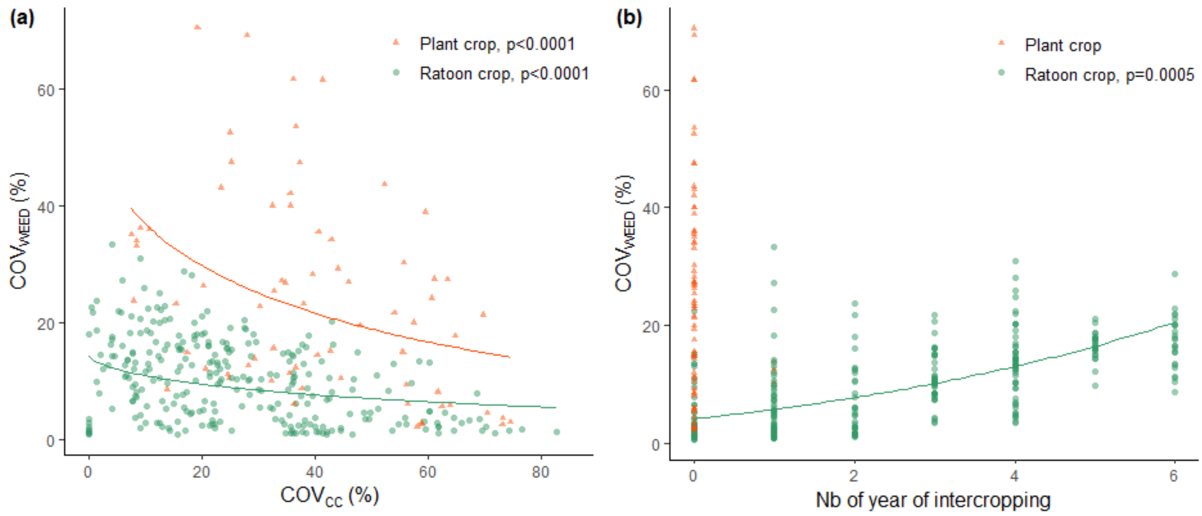

Fig. 4. Mean ground cover by weeds (COV_{WEED}) in the cover crop treatment in the inter-row in response to the mean ground cover by cover crop (COV_{CC}, a) and the number (Nb) of years since the implementation of intercropping (b). The lines represented the predicted response by the SEM models after back-transformation, and the P values are indicated.

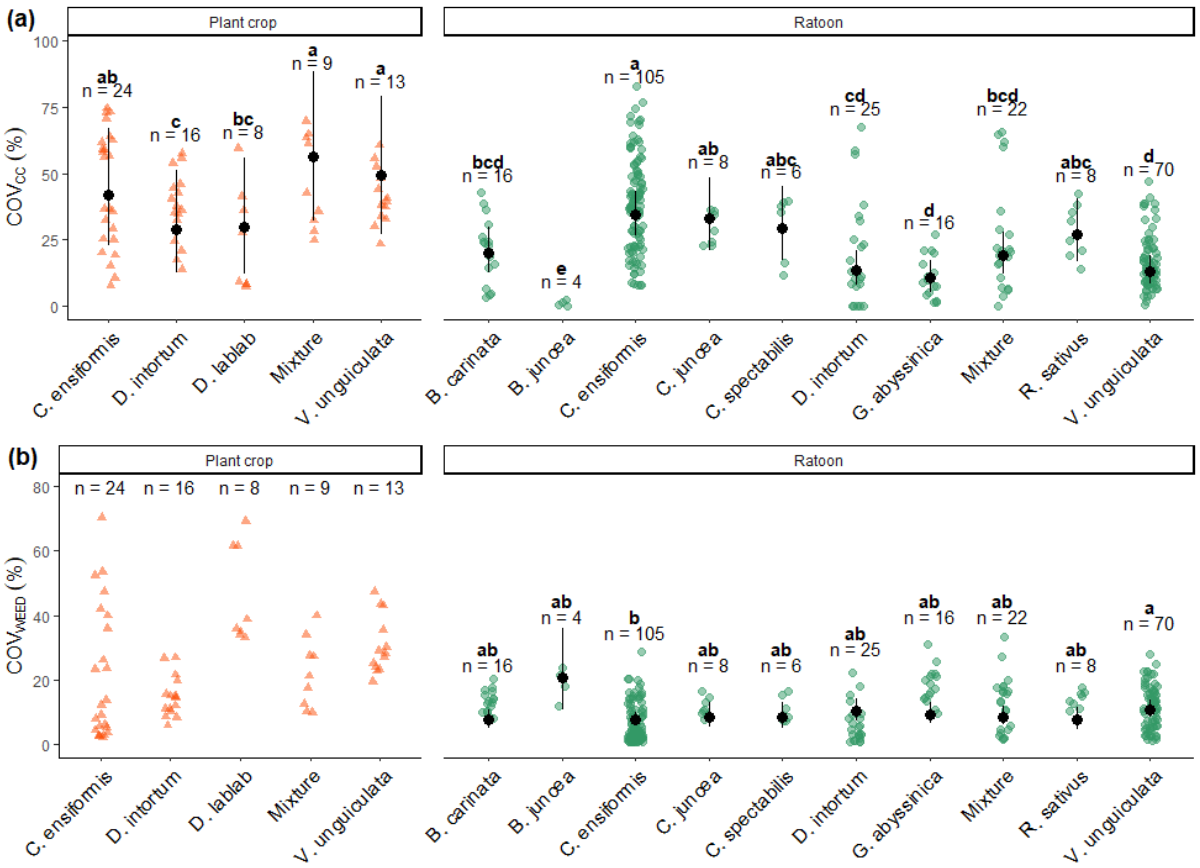

Fig. 5. Mean ground cover by cover crop (COV_{CC}, a) and weeds (COV_{WEED}, b) in the cover crop treatment depending on the cover crop species in plant and ratoon crops. The mean values (black point) and confidence intervals (black line) predicted by the SEM are presented depending on cover crop species. The number of measurements in each category is indicated by "n". Letters indicated significant differences in the pairwise comparison with a Tukey p-adjustment method.

3.5. Weeds response to cover crop management

The structural equation model showed a direct effect of cover crop sowing date on COV_{WEED} in plant and ratoon crops (Fig. 3, 6a) and a direct effect of the number of years of intercropping on COV_{WEED} (Fig. 3, 4b). COV_{CC} was also influenced by the sowing date but only in plant crops (Fig. 3, 6b). In plant crops, the impact of the sowing date on COV_{WEED} was higher than in ratoon (see coefficient in Fig. 3c,d). COV_{WEED} decreased in plant crops by around 5% per month after sugarcane planting and by around 2% in ratoon (Fig. 5a). Similarly, COV_{CC} decreased by around 13% per sowing month after planting in plant crops (Fig. 5b). COV_{WEED} also increased with the number of years since the implementation of intercropping by around 3% per years (Fig. 4b).

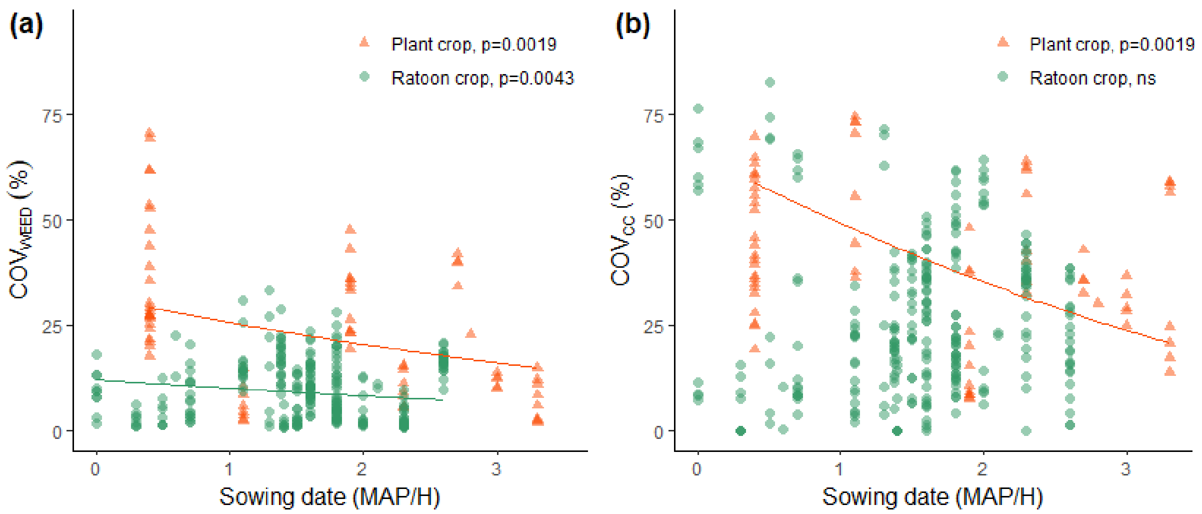

Fig. 6. Mean ground cover by weeds (COV_{WEED}, a) and cover crop (COV_{CC}, b) in the cover crop treatment depending on the sowing date of the cover crop (in months after sugarcane planting or harvest, MAP/H). The lines represented the predicted response by the SEM models after back-transformation, and the P values are indicated.

3.6. Changes in costs, revenue, and profits

Total operating costs in the cover crop treatment increased by 1762, 1149, and 196 € ha^{-1} compared to chemical treatments in manual farms, farms with micro-tractors, and farms with tractors, respectively (Table 3). This increase was mainly due to the additional cost of sowing and mulch management. The decrease in operating costs for chemical weeding (herbicide purchase and herbicide application) in CC compared to CH was relatively similar to the increase in costs due to seed purchase and additional manual weed weeding. By opposition, the costs in LC were slightly lower than CH due to decreased herbicide use. Nonetheless, in both CC and LC, the revenue was lower by 884 and 609 € ha^{-1}, respectively, compared to CH due to decreased sugarcane yield. Consequently, the profits were lower in CC and LC treatments than in CH. While the type of farm had little impact on costs in the LC treatment, the highest profit reductions were observed in manual farms and farms with micro-tractors for the CC treatment.

Table 3. Average operating costs and revenue (€ ha^{-1}) depending on the cropping systems: chemical weeding (CH), cover crop sown in the inter-row (CC), or low control in the inter-row (LC), for three types of farms (manual, with micro-tractors or tractors). The change in costs, revenue, and profits (difference between revenue and costs) between CC or LC compared to CH are presented.

		Manual farms			Farms with micro-tractors			Farms with tractors		
		CH	CC	LC	CH	CC	LC	CH	CC	LC
Operating costs (€ ha^{-1})	Herbicide	160	87	92	160	87	92	160	87	92
	Herbide application	1056	838	952	569	452	513	246	196	222
	Additional weeding	381	451	352	381	451	352	381	451	352
	Seed purchase	0	172	0	0	172	0	0	172	0
	Sowing	0	1130	0	0	416	0	0	77	0
	Mulch management	0	681	0	0	681	0	0	0	0
	Total costs	1597	3359	1396	1110	2259	957	787	983	666
Revenue (€ ha^{-1})	Yield revenue	13862	12978	13253	13862	12978	13253	13862	12978	13253
Change (€ ha^{-1})	Change in costs		1762	-201		1149	-153		196	-121
	Change in revenue		-884	-609		-884	-609		-884	-609
	Change in profits		-2646	-408		-2033	-456		-1080	-488

4. Discussion

4.1. Weed control by cover crops in sugarcane intercropping systems

In our cover crop treatments, weed control was performed by combining preliminary herbicide application (whole plot), cover crop development, and manual weedings (particularly for the tall grasses considered as strongly harmful). Nonetheless, our approach highlights the prominent role of cover crop development in reducing weed infestation in our tropical conditions at the same level as chemical treatments.

Despite having a limited number of studies in the sugarcane literature examining the effectiveness of cover crops for inter-row weed management, these findings agree with previous studies showing that cover crops showed weed suppression efficiency higher than 30% in India (Geetha et al., 2019), and that sugarcane intercropping allow to limit weed biomass at the same level than chemical treatments (Kaur et al., 2016, 2015; Mahadevaswamy and Martin, 2002). Similar observations were made in other intercropping systems in temperate climatic conditions, with a decrease in weed biomass by 56% compared to non-weeded cropping systems in a meta-analysis on various cash crops (mainly wheat, maize, and barley, Verret et al., 2017).

The negative relationship between the weeds and cover crop ground covers observed in our study highlights how the ability of cover crops to limit weed growth is directly linked to its development in the inter-row. These results agree with the broad agreement on cover crop fallow or intercropping that high biomass, cover, or a fast ground cover by cover crops increases weed control (Gardarin et al., 2022; Osipitan et al., 2019). Even if only the mean ground cover by cover crops was tested in this study, the main species used in intercropping are known to have high biomass and rate of increase in ground cover in Reunion Island (Christina et al., 2021b; Négrier et al., 2023).

While the choice of cover crop species appeared important regarding cover crop development in our study, the impact on weed growth was relatively constant. Such a statement on weed growth can result from the impact of complementary manual weedings, even if we did not see a link between MW_{IR} and COV_{WEED} in our SEM approach. Both legumes (*C. ensiformis*, *Crotalaria* species) and non-legume species (*R. sativus*) showed high covering ability. In particular, *C. ensiformis* have a high growth rate and biomass production, which can explain its smothering effect (Lawson et al., 2006). Soares et al. (2022) also showed that *C. ensiformis* reduced the diversity of weed species. *C. juncea* has a potential allelopathic effect that can suppress weeds and the main crops (Skinner et al., 2012). The weed-smothering efficiency of sunn hemp (*C. juncea*) and cowpea (*V. unguiculata*) was also observed in previous studies in India (Geetha et al., 2019). *B. carinata* and the mixtures of cover crops were also adapted to limit weed growth. Nonetheless, other species, such as *D. intortum* or *G. abyssinica*, were less adapted to intercropping.

4.2. Climate, resource, and weed control in intercropping systems

In our climatic conditions, rainfall and temperature influenced weed development. Such a response was expected in our tropical conditions (Peters et al., 2014). Nonetheless, while COV_{WEED} increased in the low control and chemical treatments with rainfall, it did not change in the cover crop treatments. These results suggest that other factors limit weed development in the cover crop treatments.

In fertilized tropical conditions, one hypothesis is that light partitioning is a primary factor determining the competition between weeds and cover crops (Christina et al., 2021b; Tardy et al., 2015). Light competition can explain the differences in weed cover observed in our study in response to cover crop ground cover and between the plant (slow sugarcane canopy closure, around six months after planting) and ratoon crops (fast sugarcane canopy closure, around 3-4 months after harvest), even if a strong effect of mulch should also be expected (Carvalho et al., 2017). The plant or ratoon crop cycle also influenced cover crop growth in our study, illustrating the importance of light competition between sugarcane and cover crops (Viaud et al., 2023). Previous studies have also shown that cover crops limit the emergence of weeds due to a decrease in the quantity and quality of light transmitted through the cover (Benvenuti et al., 2001; Juroszek and Gerhards, 2004). Accordingly, the cover crop sowing date strongly influenced crop development in plant crops in our study compared to ratoon crops, where the sugarcane dominancy limits cover crop growth. Nonetheless, as suggested by our SEM results, the response of weeds to cover crop sowing dates is more complex. In our study, when the cover crop sowing date was delayed, chemical weeding was performed before sowing, thus decreasing the mean weed ground cover over the crop cycle (direct effect). An opposite effect also occurred; mean cover crop cover decreased by delaying the sowing date (and so increased weed ground cover over the crop cycle, indirect effect).

Our spatially limited study did not allow us to assess the influence of soil characteristics on the weed-cover crop competition in sugarcane intercropping systems. Nonetheless, Viaud et al. (2023) showed a higher impact of intercropping on sugarcane yield with lower soil carbon content in our tropical conditions, suggesting that soil nutrient competition could occur despite fertilization. The influence of soil resource availability on the weeds x cover crops x main crop competition process has to be further investigated as it is still poorly understood and often limited to nitrogen (Corre-Hellou et al., 2011; Hauggaard-Nielsen et al., 2001). Crop modeling could give helpful insights into understanding how and when competition for resources occurred between plants over the sugarcane growth cycle and also help disentangle the effects of these competitions regarding climate or crop management effects.

4.3. Sugarcane intercropping management.

As shown in our study, the combination of cover crops and manual weedings makes it possible to reduce by 37% the frequency of herbicide application in sugarcane cropping systems. However, intercropped species must be carefully selected, and their management adapted because of the risk of excessive inter-specific competition on sugarcane yield depending on soil and climatic conditions (Viaud et al., 2023).

Considering cover crop species selection and management, our study suggests that many species would be adapted to sugarcane intercropping regarding weed control. Nonetheless, irrigation failure can affect cover crop emergence and development, highlighting the need to select drought-resistant species such as *C. ensiformis*. Some species, such as *C. juncea*, can also be infested by aphids limiting their development. Cover crop mixtures could help maintain ground cover in case of choosing one sub-optimal species (Négrier et al., 2023) and increase mixture resilience to unexpected events (Elhakeem et al., 2021). Regarding sowing management, our study suggests that early sowing will provide higher cover crop development in plant crops. However, a meta-analysis suggested that early sowing will also induce a higher sugarcane yield reduction in intercropping compared to conventional management (Viaud et al., 2023). Our analysis did not allow us to accurately compare cover crop sowing management, such as the number of sown lines or the sowing method (manual vs. mechanical). Nonetheless, cover crop sowing geometry should be assessed further as previous studies have shown that it can increase cover crop growth with little impact on sugarcane yield (Nadeem et al., 2020; Tian et al., 2020).

While using cover crops limits weed growth in the inter-row, weeding sugarcane row remains a major issue. Herbicides can be sprayed in the sugarcane row to control weeds but with a high risk of affecting cover crop development. Consequently, to limit weed growth in the row and very harmful weed species in the inter-row, more manual weedings were performed in the sugarcane row and inter-row compared to chemical control. Such interventions increase weed control costs, but these are, on average, offset by lower herbicide costs. Adding all the costs and changes in revenue linked to yields, profits from intercropping would be lower than for chemical farming in La Réunion. The main reason for this is the cost of sowing and the decrease in yield. Consequently, our results suggest that by adapting the crop management to reduce the impact on yield (Viaud et al., 2023) and favoring sowing directly through the sugarcane mulch (as in farms with tractors), the profits could be less impacted by a change of practice from chemical to intercropping. In other countries, some studies have shown that additional returns from the intercrop could also increase the net profits compared to sugarcane monocropping (Kaur et al., 2015; Nazir et al., 2002; Singh et al., 2008). Therefore, harvesting the cover crop in La Réunion could be evaluated to see the impact on the economic balance (considering additional labor and mechanization costs). Finally, while this study focused on weed control in sugarcane intercropping systems, crop diversification is known to have the potential to provide various ecosystem services (Beillouin et al., 2021; Isbell et al., 2017; Tamburini et al., 2020), some of which have already been studied in sugarcane intercropping systems: associated soil biodiversity (Pang et al., 2022), soil fertility and greenhouse gas emissions (Luo et al., 2016), or soil erosion (Wang et al., 2022). One way of encouraging the adoption of intercropping by improving its profitability would be to work on payments for ecosystem services (Mota et al., 2023; Schomers and Matzdorf, 2013).

In opposition to the long-term effect of legume intercropping on soil fertility (Luo et al., 2016), the long-term effect of intercropping on weed pressure has not been investigated in sugarcane intercropping systems. Our results highlighted how the increase in weed cover with years of intercropping questioned the long-term sustainability of this practice. Indeed, they can explain the previous results of increased sugarcane yield loss through years in sugarcane-legume intercropping systems compared to monocropping (Viaud et al., 2023). The authors' hypothesis to explain such an impact was an increasing weed pressure over time. This increase could result from a weed seed bank enrichment and/or the selection of highly competitive weeds, as seen in other temperate cover cropping systems mainly under rotations (Graziani et al., 2012; Mohler et al., 2018). Nonetheless, while some studies attempted to assess the response in weed communities in short-term intercropping (Gomez and Gurevitch, 1998; Poggio, 2005; Stefan et al., 2021), the long-term impact of intercropping on change in weed communities still need to be assessed.

Conclusions

Sugarcane intercropping in Reunion Island allowed reducing weed cover by 51% compared to low control treatments and reduced herbicide treatment frequency index by 37% compared to chemical treatments, at the cost of an increased number of manual weedings and a 6% decrease in sugarcane yield. In intercropping, crop management significantly influences weed cover more than the climate in our tropical conditions. Changes in operating costs and revenue led to a reduction in profits compared with chemical treatment, which varied according to the type of farm (manual or mechanized). The lack of a relationship between manual weedings and weed cover suggests investigating the effects of further reduction of costly manual weedings in future research. Additionally, the increase in weed cover with years of intercropping highlights the need to assess the long-term impact of intercropping on weed communities to assess this practice's sustainability.

Acknowledgments

This work was supported by the Ecophyto plan's action program (French Ministry of Agriculture and Food Sovereignty) and the ODEADOM for funding the CanécoH V2 and AgriécoH projects. This work was supported by the Conseil Regional de La Reunion, the French Ministry of Agriculture and Food, the European Union (Feader program, grant n◦ AG/974/DAAF/2016-00096 and Feder program, grant n◦ GURTDI 20151501-0000735) for funding. This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101081973 - IntercropValuES. We thank all the eRcane institute technicians who help with the experiment establishment and monitoring.

Author contributions

Mathilde Soulé: Investigation, Data Duration, Writing - Original Draft, Vizualisation. **Alizé Mansuy**: Conceptualization, Methodology, Investigation, Project administration, Funding acquisition. **Julien Chetty**: Conceptualization, Methodology, Investigation. **Sandrine Auzoux**: Data Curation, Visualization. **Pauline Viaud**: Formal analysis, Data Curation, Visualization. **Marion Schwartz & Aude Ripoche**: Resources, Visualization. **Benjamin Heuclin:** Formal analysis. **Mathias Christina**: Methodology, Formal analysis, Data Curation, Writing - Original Draft, Visualization, Supervision. **All authors**: Writing - Review & Editing.

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