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Sugarcane yield response to legume intercropped: a meta-analysis.

Pauline Viaud^{1,2,3,4*}, Benjamin Heuclin^{2,5}, Philippe Letourmy^{2,5}, Mathias Christina^{1,2,5}, Antoine Versini^{3,4},
Alizé Mansuy⁶, Julien Chetty⁶, Krishna Naudin^{2,5}

¹CIRAD, UPR AIDA, F-97743, Saint-Denis, La Réunion, France

²AIDA, Univ Montpellier, CIRAD, Montpellier, France

³CIRAD, UPR Recyclage & Risque, F-97743, Saint-Denis, La Réunion, France

⁴Recyclage & Risque, Univ Montpellier, CIRAD, Montpellier, France

⁵CIRAD, UPR AIDA, F-34398 Montpellier, France.

⁶eRcane, F-97494 Sainte-Clotilde, La Réunion, France

* Corresponding author: pauline.viaud@cirad.fr; 40 Chemin Grand Canal, 97490 Saint-Denis, La Réunion; <https://orcid.org/0000-0002-3133-3321>

Abstract

Intercropping with legumes has attracted much attention worldwide, regarded as a sustainable alternative to chemical N-fertilizer. Many studies have investigated the effects of introducing legumes into sugarcane systems. However, how agro-environmental conditions influence the effect of legumes on sugarcane yield is still unclear. Thus, we performed a meta-analysis to i) quantify the effect of legume intercropping on sugarcane yield, ii) assess how agro-environmental and management conditions influence the response of sugarcane yield to intercropping, and iii) assess the influence of legumes in interaction with weeds on sugarcane yield. We combined data from a systematic literature review and experimental data from a network of trials conducted in the tropical island of La Réunion. 315 observations (one-year x site x intercropping treatment) were analyzed with mixed effects models to assess the effect of legume intercropping on sugarcane yield and factors influencing the response of sugarcane yield. Intercropping with legumes resulted in lower sugarcane yields compared to the monoculture treatment in 63% of cases. Our study highlighted how resource availability (e.g., annual temperature, global radiation, soil organic carbon content) influenced sugarcane yield response to legumes. Late sowing and early destruction date of the legume mitigated the negative effect of legumes

on sugarcane yield. Our study also showed that the negative impact on sugarcane yield increased over years of intercropping, raising questions about legumes' actual contribution to soil fertility. Further studies are needed to optimize legume sowing and destruction dates to find a trade-off between expected services (N enrichment and weed control) and disservices (yield loss, costs, and labor time) in sugarcane agrosystems according to the climate and soil context.

Keywords: Meta-analysis; Fabaceae; Cover crops; Crop association; *Saccharum officinarum*

Highlights:

- Legume intercropping reduced sugarcane yield by an average of 3.34% worldwide.
- Resource availability influenced sugarcane yield response to legumes.
- Legumes sowing and destruction dates drove the competitiveness between species.
- Legumes were twice less damaging than weeds for sugarcane.
- The negative effect on yield increased with the number of years of intercropping

1. Introduction

Under the extensive use of chemical inputs in the 20th century, the intensification of agriculture has led to the emergence of environmental issues such as soil degradation, water pollution, eutrophication, greenhouse gas emissions, biodiversity loss, or weeds' resistance to herbicides (Bengtsson et al., 2005; Heap, 2014; Howarth, 2008; Jie et al., 2002). The environmental cost of intensification raises the question of the sustainability of this agricultural model (Sutton et al., 2013). Therefore, sustainable cropping systems must be designed to ensure food security while improving resource use efficiency and environmental durability (Bommarco et al., 2013).

Sugarcane is a worldwide crop cultivated for sugar, biofuel, and material for electric energy production (Anthunes et al., 2019). The demand for ethanol and electricity will likely increase in the energy sector as it could replace fossil fuels and reduce greenhouse gas emissions (Goldemberg et al., 2014; Leal et al., 2013). Sugarcane is a semi-perennial crop that relies heavily on nitrogen (N) fertilization (FAO 2006). However, the amount of N fertilizer taken up by the sugarcane is particularly low ranging from 10% to 40% of the total amount applied (Otto et al., 2016). As a result, concerns about the low N-use efficiency and environmental impacts of N losses in these systems have been raised (Thorburn et al., 2017; Wang et al., 2020). Therefore, there is a need to develop sustainable agricultural management to maintain economically viable production levels of sugarcane with less reliance on chemical N-fertilizer input.

Legumes are a potential alternative to synthetic fertilizers thanks to their ability to fix atmospheric N. Many studies have considered the positive effect of legumes as a rotation break crop in sugarcane systems to minimize the requirements for N fertilization by the following plantations (Garside & Bell, 1999; Hemwong et al., 2009; Shoko et al., 2007). They showed that legumes could limit mineral N inputs without decreasing sugarcane yield at planting. However, sugarcane is commonly planted every 7 to 15 years, limiting legumes' positive effects as a rotation break crop.

In recent years, many studies have been carried out to investigate the effect of cover crop intercropping, such as legumes, in sugarcane systems. Besides enriching soils with N, legumes may compete with weeds and help reduce herbicide use (Verret et al., 2017). However, excessive interspecific competition can lead to a significant yield loss. As observed in other intercropping systems (e.g., in maize: Sileshi et

al., 2008; in maize, sorghum and pearl millet: Namatsheve et al., 2020), the impact of legumes on the main crop sugarcane yield varies significantly from one study to another (Ambrosano et al., 2013; de Resende et al., 2003; Nadeem et al., 2020; Tian et al., 2020). The impact of legume intercropping on sugarcane yield could vary depending on climate (Waddington et al., 2007), soil (Xu et al., 2020), management practices (e.g., crop species, fertilization, and irrigation regime, crop density, the time and duration of cohabitation, Pelzer et al., 2014; Yu et al., 2016, 2015). The interactions in species mixtures are complex with key issues regarding competition and the timing of N restitution to the main crop (Justes et al., 2014). Apart from sugarcane and cover crops, a third component, the weed community, increases the complexity of these multi-species interactions.

The diversity of the results observed in sugarcane yield response to legume grown as a cover crop in the inter-row highlights the need for a comprehensive and quantitative analysis. To our knowledge, the impact of climate, soil, and management practices variability on sugarcane yield response to legume intercropping has never been analyzed in a quantitative study. The objectives of this study were i) to quantify the effect of legume intercropping on sugarcane yield, ii) to assess how agro-environmental and management conditions influence the response of sugarcane yield to intercropping, and iii) to assess the influence of legumes in interaction with weeds on sugarcane yield. We performed a meta-analysis by combining data from a literature review and experimental data from a network of trials conducted in the tropical island of La Réunion.

2. Materials and methods

2.1. Complementarity of the two data sets

A meta-analysis was performed to assess the sugarcane yield response to legume intercropping compared to sugarcane grown as a monocrop. The database included two complementary data sets. The first data set was based on a systematic literature review (section 2.2, Table 1). This data set had the advantage of covering a wider range of agro-pedo-climatic conditions but the disadvantage of having less information on crop and legume management. The second data set included data from a network of

92 trials performed in the Island of La Réunion (section 2.3, Table 1). This data set had the advantage of
 93 providing more information than the first one (e.g., actual temperature and rainfall, and
 94 destruction/disappearance day of the cover crop, ground cover by legume and weeds).

95
 96 **Table 1. Variables used in the meta-analysis from the two data sets. The number of observation (obs) or**
 97 **mean (minimum and maximum) values in the datasets are presented.** The characteristics of the climate
 98 types are shown in Table A1. DASP/H: Day after sugarcane planting or harvesting. NA: Not available for
 99 the data set.

Explanatory variables	Levels	Dataset 1: Literature	Dataset 2: Reunion
Climate	Desert	30 obs	
	Semi-arid	25 obs	
	Oceanic	48 obs	4 obs
	Subtropical	94 obs	
	Tropical	42 obs	72 obs
Altitude		479 m (10-1671)	103 m (69-545)
Mean annual temperature		23.3 °C (19-28.7)	24 °C (20.3-26)
Mean annual rainfall		1254 mm y ⁻¹ (200-2674)	1353 mm y ⁻¹ (718-2008)
Soil texture	Fine	78 obs	76 obs
	Medium	104 obs	
	Coarse	57 obs	
Soil organic carbon		10.6 % (3.5-33)	33.5 % (17-33.5)
Applied N fertilizer rate		174 kg N/ha (0-525)	168 kg N/ha (132-287)
Irrigated trial	Irrigated	177 obs	60 obs
	Rainfed	122 obs	16 obs
Legume species		21 species	5 species
Growth habit	Creeping	10 obs	10 obs
	Semi-erected	25 obs	6 obs
	Erected	105 obs	
	Semi-twining	82 obs	60 obs
	Twining	17 obs	
Legume sowing date		14.5 DASP/H (0-90)	51 DASP/H (0-119)
Legume destruction/ disappearance date		NA	282 DASP/H (125-365)
Width of the inter-row (m)		1.2 m (0.45-3.6)	1.5 m
Crop cycle	Plantation	203 obs	12 obs
	Ratoon	36 obs	64 obs
Number of years of IC		1,9 year (1-10)	2,8 years (1-6)
Type of trial	On-station	218 obs	63 obs
	On-farm	21 obs	13 obs
Global mean ground cover		NA	34 % (6-81)
Weeds mean ground cover		NA	10 % (1-45)
Legume mean ground cover		NA	35 % (1-65)

2.2. Literature review

A literature search was performed using the online database Scopus (Elsevier) in June 2021. The search equation was (an asterisk being a replacement for any starting/ending of the respective term) : (legum* OR faba* OR pulse* OR "cover crop" OR "green manure*" OR Arachis OR Cajanus OR Canavalia OR cicer OR crotalaria OR glycine OR lens OR phaseolus OR Pisum OR vicia OR vigna) AND (*cane OR "Saccharum officinarum") AND (intercrop* OR "crop association" OR "associated crops" OR "companion crop*" OR "mixed crop*" OR mixtures OR "multiple crops*" OR companion crop*) in the title, abstract or keywords. The database searches were increased with searches in library resources for relevant papers from citations in retrieved papers.

Studies had to meet the following selection criteria to be included in the meta-analysis: (i) studies report sugarcane yield from a field experiment in which a monoculture treatment (CT) was compared with at least one legume-intercropped treatment (IC), (ii) the mean and number of replicates were directly reported as numerical or graphical data, (iii) full-text articles were available. Data reported as an average across years, locations, or factors were excluded. We did not include treatments with more than one legume species (e.g., legume mixture or two species planted one after the other in the same crop cycle). Studies were excluded if crop management practices other than intercrop practices differed between CT and IC, except for weed management. If data from the same experiment were reported in several papers, the data were included from the article that reported the data in the most significant degree of detail. The literature search and the selection procedure were presented in a Prisma diagram (Appendix A, Fig. A1).

A total of 31 papers fit our selection criteria for the meta-analysis (Table 2). The resulting database included 239 observations (one-year x site x IC treatment) from the literature review.

123 **Table 2. Selected studies for the meta-analysis, from both data set: Reunion and Literature.** Details on references are available in Appendix A.

Reference	Country	Duration (years)	Legume cover crop species	Soil texture	Mean annual precipitation (mm)	Mean annual temperature (°C)
Trial 1	La Réunion (-20.903, 55.532)	2	<i>Vigna unguiculata</i>	Fine	1344	26.3
Trial 2	La Réunion (-20.903, 55.532)	6	<i>Canavalia ensiformis</i> , <i>Crotalaria juncea</i> , <i>Crotalaria spectabilis</i> , <i>Desmodium intortum</i> , <i>V. unguiculata</i>	Fine	1344	26.3
Trial 3	La Réunion (-20.903, 55.532)	3	<i>C. ensiformis</i>	Fine	1344	26.3
Trial 4	La Réunion (-20.903, 55.532)	5	<i>C. ensiformis</i> , <i>D. intortum</i> , <i>V. unguiculata</i>	Fine	1344	26.3
Trial 5	La Réunion (-20.903, 55.532)	1	<i>V. unguiculata</i>	Fine	1344	26.3
Trial 6	La Réunion (-21.047, 55.682)	3	<i>C. ensiformis</i> , <i>V. unguiculata</i>	Fine	1603	22.6
Trial 7	La Réunion (-21.067, 55.280)	1	<i>C. ensiformis</i> , <i>D. intortum</i>	Fine	816	20.1
de Souza Filho and de Andrade 1985	Brazil	3	<i>Phaseolus vulgaris</i>	Fine	1797	22
Parsons and Khubone 1999	South-Africa	1	<i>Arachis hypogaea</i> , <i>P. vulgaris</i>	Fine	1123	21.9
Gana and Busari 2001	Nigeria	2	<i>Glycine max</i> , <i>Sesbania rostrata</i> , <i>V. unguiculata</i> ,	Coarse	1075	28.4
Nazir et al., 2002	Pakistan	1	<i>Lens culinaris</i> , <i>Pisum sativum</i>	Coarse	346	24.2
de Resende et al., 2003	Brazil	2	<i>C. ensiformis</i> , <i>C. juncea</i> , <i>C. spectabilis</i> , <i>Mucuna pruriens</i>	Coarse	1354	23.5
Parsons 2003	South-Africa	1	<i>G. max</i> , <i>P. vulgaris</i> , <i>V. unguiculata</i>	Fine	1123	21.9
Saini et al., 2003	India	3	<i>P. sativum</i>	Coarse	769	23.9
Berry et al., 2009	South-Africa	1	<i>A. hypogaea</i> , <i>M. pruriens</i> , <i>Phaseolus lunatus</i>	Coarse	861	20
Manimaran et al., 2009	India	1	<i>Vigna mungo</i>	Coarse	1048	28.7
Rasool et al., 2011	Pakistan	1	<i>Cicer arietinum</i> , <i>L. culinaris</i>	Coarse	941	21.3
Prellwitz and Coelho 2011	Brazil	1	<i>C. juncea</i>	Fine	1073	24.4

Ambrosano et al., 2013	Brazil	1	<i>Cajanus cajan</i> , <i>C. ensiformis</i> , <i>Crotolaria brevifolia</i> , <i>C. juncea</i> , <i>Crotolaria mucronata</i> , <i>M. pruriens</i>	Fine	1255	20.8
Rehman et al., 2014	Pakistan	2	<i>C. arietinum</i> , <i>G. max</i>	Medium	346	24.2
Teshome et al., 2015	Ethiopia	1	<i>G. max</i>	Fine	200	28.7
Kaur et al., 2015	India	2	<i>P. sativum</i>	Coarse	1363	22.5
Córdova-Gamas et al., 2016	Mexico	2	<i>C. cajan</i> , <i>C. ensiformis</i>	Fine	1646	26.3
Khippal et al., 2016a	India	2	<i>Cyamopsis tetragonoloba</i> , <i>V. mungo</i> , <i>Vigna radiata</i> , <i>V. unguiculata</i>	Medium	772	24.1
Khippal et al., 2016b	India	2	<i>C. arietinum</i> , <i>L. culinaris</i> , <i>P. sativum</i>	Medium	766	24.4
Nadiger al., 2017	India	1	<i>G. max</i> , <i>P. sativum</i>	Medium	602	25.2
Pereira et al., 2017	Brazil	1	<i>C. cajan</i>	Fine	1341	20
He et al., 2018	China	2	<i>V. radiata</i>	Medium	1363	22.5
She et al., 2019	China	2	<i>A. hypogaea</i>	Medium	1727	22.2
Yasin et al., 2018	Pakistan	1	<i>L. culinaris</i>	Medium	346	24.2
Zarekar et al., 2018	India	1	<i>A. hypogaea</i> , <i>V. radiata</i>	Medium	2674	26
Salazar Cajas 2019	Australia	2, 1	<i>G. max</i>	Medium	1457	19.8
Solanki et al., 2019	China	1	<i>A. hypogaea</i> , <i>G. max</i>	Medium	1363	22.5
Geetha et al., 2019	India	1	<i>C. juncea</i> , <i>G. max</i> , <i>L. culinaris</i> , <i>V. unguiculata</i>	Coarse	618	26.3
Jhansi 2020	India	1	<i>A. hypogaea</i> , <i>C. juncea</i> , <i>C. tetragonoloba</i> , <i>G. max</i> , <i>V. mungo</i> , <i>V. radiata</i> , <i>V. unguiculata</i>	Medium	1108	28.2
Tian et al., 2020 ; Luo et al., 2016	China	10	<i>G. max</i>	Medium	1727	22.2
Nadeem et al., 2020	Pakistan	2	<i>L. culinaris</i>	Coarse	346	24.2

2.3. Network trials in La Réunion

2.3.1. Study site

A network of eight trials was carried out to assess the ability of legume cover crops intercropped with sugarcane to control weeds in the inter-row and their impact on sugarcane yield. These trials were managed by the sugarcane research center in Reunion Island (eRcane institute) on three sites in Reunion Island from 2012 to 2019 (Table 2) as part of the CanécoH and AgriécoH projects. Most of the trials were conducted in the north of the island on an experimental research station (Sainte-Marie, 69m a.s.l.). Two trials were also conducted on-farm in the east (Saint-Benoit, 150m a.s.l.) and in the west of the island (Saint-Paul, 545m asl).

The resulting database contained 76 observations (one-year x site x treatment) from the Reunion network trials.

2.3.2. Experimental design and crop management

All trials compared one or several sugarcane-legume intercropping treatments (IC) to a control treatment (CT) where sugarcane grown as a monoculture with chemical weeding. Depending on trials, different legume species, legume sowing dates, and destruction dates have been tested. Treatments were replicated two to four times with plots ranging from 60 to 780 m² depending on the trials. Details on trial's experimental design and crop management are available in Table A2 to A5.

In all trials, sugarcane was planted with a 1.5 m inter-row. Legume was sown in the inter-row mechanically or manually. Five legume species were tested (*Canavalia ensiformis*, *Crotalaria juncea*, *Crotalaria spectabilis*, *Desmodium intortum*, *Vigna unguiculata*). The sowing date of the legumes (expressed in day after planting - DASP or harvest - DASH) varied between trials and treatments. At the end of their development, legumes were destroyed or left in the field, gradually disappearing thanks to the sugarcane canopy closure.

Recommended non-limiting fertilizer rates were applied to sugarcane for all trials (Table A4). All trials were irrigated, except for those in Saint-Benoît with enough annual rainfall. A pre-emergence herbicide was applied after sugarcane planting or harvesting and before legume sowing. Afterward, weeding

interventions were performed when weeds reached 30% soil ground cover (chemically for CT and manually for IC).

2.3.3. Field measurements

Ground cover by legume—was measured using a visual notation method used in previous studies (Christina et al., 2021a) described in Table A6. Global ground cover by legume species and weeds, considered as a whole, was measured monthly in the inter-row. Respective ground covers by legume species and weeds were calculated by multiplying the global ground cover by the respective proportion of each pool. The measure was extrapolated between two measurement dates to estimate a mean ground cover over the sugarcane crop cycle. 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 (i.e., a minimum of 30 m² areas).

2.4. Database

We compiled and harmonized the data from the literature and the Reunion network trials in a database. We collected the means sugarcane yield of the control treatment (CT) and the intercropped treatment (IC), their standard deviation, and replicate numbers. Standard deviations were calculated from standard errors, coefficients of variation, 95% confidence interval, or least significant differences in cases where they were not reported in the papers.

To explain the variability in sugarcane yield responses due to legume intercropping, we considered several explanatory variables related to climate, soil, and management practices. The explanatory variables used in the meta-analysis are shown in Table 1. Information for these variables was extracted from the text, tables, or figures using a web-based image analysis, Webplotdigitizer v4.5 (Rohatgi, 2018). When soil organic matter was reported, we converted it to soil organic carbon by dividing the value by 2 (Pribyl, 2010). If not reported, average annual rainfall and annual temperature data were retrieved using the New_LocClim 1.10 database (Grieser, Gommès, and Bernardi 2006). The legume species were classified according to their usual growth habit (creeping, erected, semi-erected, semi-twining, and twining) as identified by the Useful Tropical Plants (<https://tropical.theferns.info/>) and the PROTA4U (<https://www.prota4u.org/>) databases (Table A7).

Some variables had a few missing data (< 15%). We used single imputation method to include them in the analysis (Scheffer 2002). The country's median was imputed when the applied N fertilizer rate for sugarcane was missing (31/315 observations). The mean value according to soil texture was imputed when the initial soil carbon content of the topsoil layer (%) was missing (46/315).

Some of the variables initially considered were omitted for the analysis of the literature data because there were too many missing values (actual rainfall and temperature during the experiment, applied NPK fertilizer for legumes, applied PK fertilizer for sugarcane, use of herbicide with IC, legume' destruction/disappearance day of legume).

2.5. Data analysis

2.5.1. Linear mixed model

Three mixed-effect models were built to estimate the effect of legumes and explanatory variables on sugarcane yield for each subset of the database:

- Model 1: Full data set (Literature + Reunion)
- Model 2: Literature data set
- Model 3: Reunion data set

As the observations from La Réunion were over-represented in the database, comparing models 1 and 2 allowed us to verify that these observations did not induce a bias in our analysis. The third model was built to consider the variables not or not widely available in the literature. The approach used to build these models is described in the following sections.

2.5.2. Effect size

The natural logarithm of the ratio of IC-to-CT sugarcane yields was used as the effect size in the meta-analysis. The natural logarithm linearized the metric and provided a more normal sampling distribution in small samples (Hedges, Gurevitch, and Curtis 1999). The results were back transformed and presented as the percent change in sugarcane yield of the IC treatment compared to the CT treatment in the figures and results.

2.5.3. *Weight of the observations*

In meta-analysis, observations were commonly weighted by the inverse of their variance (i.e., observations with low variance were considered more reliable and received a higher weight in the meta-analysis). Unfortunately, this information was missing in many selected studies (86 obs from 8 papers). In addition, some of the selected studies had a very low coefficient of variation ($< 5\%$) compared to those usually reported for sugarcane yields (Fig. A2). We doubted that the values reported in these articles represent the existing variability in these trials. As a comparison, the average coefficient of variation of the Reunion network trials was $11.91 \pm 1.05 \%$. Therefore, we decided to weight observations using the number of replicates to ensure robustness and statistical significance by keeping a sufficient sample size.

2.5.4. *Preliminary analysis*

A first exploration showed that the full data set and the literature had a non-Gaussian residuals distribution. To correct it, observations with a Cook distance greater than $4/n$ were considered suspect and eliminated from the data set (with n =number of observations) (Viechtbauer and Cheung 2010). The new full data set contained 281 observations (212 from the literature data set and 69 from the Reunion data set). A new literature data set was extracted from it. Alone, the Reunion data set showed a Gaussian residuals distribution and did not require a selection based on Cook distance. Finally, the full, literature and Reunion data sets contained respectively 281, 212, and 76 observations. The residual diagnostics before and after outlier removal were presented in Fig. A3. The observations from He et al. (2018) had a unique behavior compared to other studies regarding nitrogen fertilization effect on the response variable (Fig. A4). An indicator variable “He2018” was created to take it into account, which takes the value 1 for this study and 0 for the others.

2.5.5. *Identification of the best random structure*

The best random structure was identified by comparing models with different random structures and the same fixed structure with all variables included (model beyond the optimal). Models were fitted using the restricted maximum likelihood (REML) estimation, and comparisons were made using Akaike’s information criterion (AIC) (Zuur et al., 2009). The “trial” (ensemble of individual IC

observations from the same trial) and “trial_control” factors (ensemble of individual IC observations with the same control treatment) were tested as random effects to account for the hierarchical dependence between multiple observations within a study (Lajeunesse 2011). A first-order autocorrelation structure AR(1) was also tested to account for repeated observations not being independent over the years within one trial. The random structure minimizing the AIC, including only the random effect “trial_control” was used in following analyses.

2.5.6. Identification of the best-fixed structure

We extended the models to determine the influence of explanatory variables (Table 1) on the yield response ratio. The fixed effect selection was performed using a stepwise forward procedure based on Akaike's information corrected criteria (AICc). During the selection, models were fitted using the maximum likelihood (ML) estimation (Zuur et al., 2009). The best-fitted models were presented in Table 3.

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, respectively (Fig. A5 to A7).

2.5.7. Publication bias

Publication bias was assessed by drawing funnel plots, in which standard errors were plotted against the effect size log-ratio (Fig. A8, Duval and Tweedie 2000). Publication bias was tested on data with a reliable coefficient of variation (>5%). Funnel plot asymmetry was tested with a rank correlation test (Begg and Mazumdar 1994).

2.5.8. Analyses

All analyses were performed in R 4.1.1 (R Core Team, 2021) except the test of the autocorrelation structure performed in SAS 9.3 (SAS Institute, Cary NC) using the PROC MIXED procedure. In R, linear regressions with mixed-effects models were performed with the function lme() from the package nlme (Pinheiro et al., 2021). For categorical variables, pairwise comparisons were performed with the

function `lsmeans()` from the package `emmeans` (Lenth et al., 2018). The rank correlation tests were performed with the function `ranktest()` from the package `metafor` (Viechtbauer 2010).

The data used in this study are available from the Dataverse repository in Viaud et al. (2022).

3. Results

3.1. Sugarcane yield response to intercrop treatment

The effect of legumes intercrops on sugarcane yields varied widely, ranging from a 65% increase to a 47% decrease compared to the monoculture treatment (Fig. 1). In the full data set, the mean IC-to-CT yield ratio was -3.3 % (confidence interval (CI): [-1.9, -4.8]). In 22% of observations, legumes had a strong depressive effect on sugarcane yield (IC-to-CT yield ratio < -10%). The mean IC-to-CT yield ratio was lower in the Reunion data set (-5.8%, CI: [-3.3, -8.3]) than in the literature data set (-2.5%, CI: [-0.7, -4.2]). Several outliers were found in the full data set with Cook's distances. When outliers were removed, the mean IC-to-CT yield ratios were -2.2, -1.0, and -5.8 %, respectively, for the full, literature, and Reunion data set (Appendix B, Fig. B1).

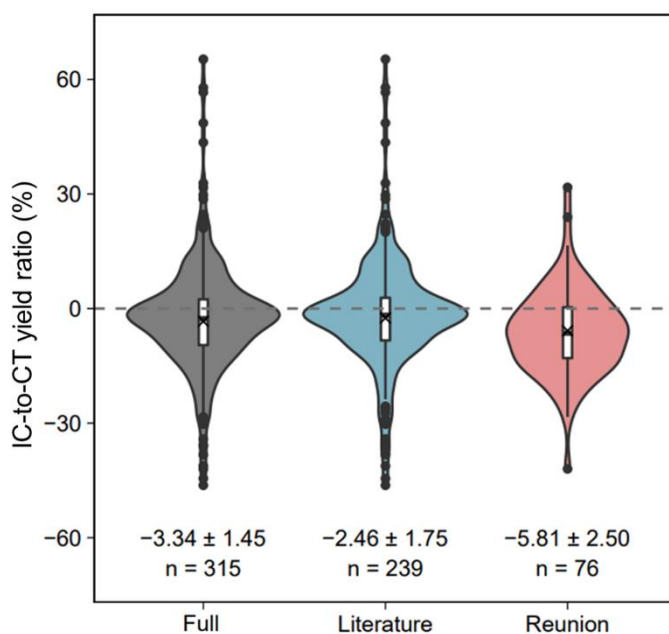


Fig. 1. The IC-to-CT yield ratio depending on the data sets. The violin plots represent the data distribution. The horizontal lines within boxes indicate medians and the crosses indicated the mean.

The upper and lower edges of boxes indicate 75th and 25th percentiles, whiskers below and above the boxes indicate the 10th and 90th percentiles. Outliers are plotted as individual points. The mean value, confidence intervals (\pm) and the number of observations (n) are indicated below the violin plots.

3.2. Explanatory variables selected for the three models

All three models explained a significant proportion of the IC-to-CT yield ratio variability with conditional coefficient of determination values (R^2) of 0.74, 0.77 and 0.77 in model 1, 2 and 3, respectively (Table B1 to B3). Selected explanatory variables differed between models (Table 3).

Table 3. Analysis of variance (ANOVA) of the random-effects models built to assess the influence of explanatory variables on the IC-to-CT yield ratio for the three data sets. P = p-value, NA = not available for the data set, boxes left blank = variables not selected based on the AICc criteria.

Variables	Full Model 1	Literature Model 2	Reunion Model 3
Climate	P = 0,0002	P = 0,0057	
Mean annual temperature	P = 0,0650	P = 0,0001	
Climate x Temperature	P = 0,0001		
Mean annual rainfall			
Altitude	P = 0,0633		
Soil texture		P = 0,0762	NA
Soil organic carbon		P = 0,1383	P = 0,0074
Applied N fertilizer rate			
Irrigated trial			
Legume species			
Growth habit	P = 0,0798		
Sowing date of CC	P = 0,0728	P = 0,1093	
Destruction date of CC	NA	NA	P = 0,0071
Width of the interrow	P = 0,0799		NA
Crop cycle		P = 0,0831	
Number of years of IC	P = 0,0823	P = 0,1364	
Type of trial			
Global mean ground cover	NA	NA	
Weeds mean ground cover	NA	NA	P = 0,0098
Legume mean ground cover	NA	NA	P = 0,0206

3.3. Climate and soil effects

The interaction of temperature and climate significantly influenced the IC-to-CT yield ratio in the full data set (Model 1, $F = 6.59$, $P = 0.0001$, Table 3). The IC-to-CT yield ratio increased with the temperature

in all climates except for tropical climate (Fig. 2a). The yield ratio response in desert (5 studies, 28 obs), semi-arid (4 studies, 23 obs), and oceanic climates (2 studies, 52 obs) should be interpreted carefully due to limited observations. In the subtropical climate, the IC-to-CT yield ratio increased up to 24°C. Above 24°C, in the tropical climate, the yield ratio did not change with temperatures. While the interaction between temperature and climate was not selected in the literature data set (Model 2, Table 3), the temperature (Model 2, $F = 18.12$, $P = 0.0001$) and the climate (Model 2, $F = 3.95$, $P = 0.0057$) significantly influenced the IC-to-CT yield ratio. The effects of these variables were similar to the results obtained in the full data set (Fig. B2).

The IC-to-CT yield ratio significantly decreased with the altitude in the full data set (Model 1, $F = 3.5$, $P = 0.0633$, Table 3, Fig. 2b). On the contrary, the average rainfall was not a significant covariate. However, the IC-to-CT yield ratio increased with the mean annual rainfall in the rainfed trials, while it tended to decrease in the irrigated trials (Fig. B3).

The IC-to-CT yield ratio was also significantly influenced by the initial amount of C in the topsoil layer in both the literature (Model 2, $F = 2.24$, $P = 0.1383$, Table 3) and the Reunion data sets (Model 3, $F = 8.88$, $P = 0.0074$, Table 3). In both cases, the IC-to-CT yield ratio increased with the soil organic carbon (Fig. 2c). This increase was higher in the Reunion data set than in the Literature data set.

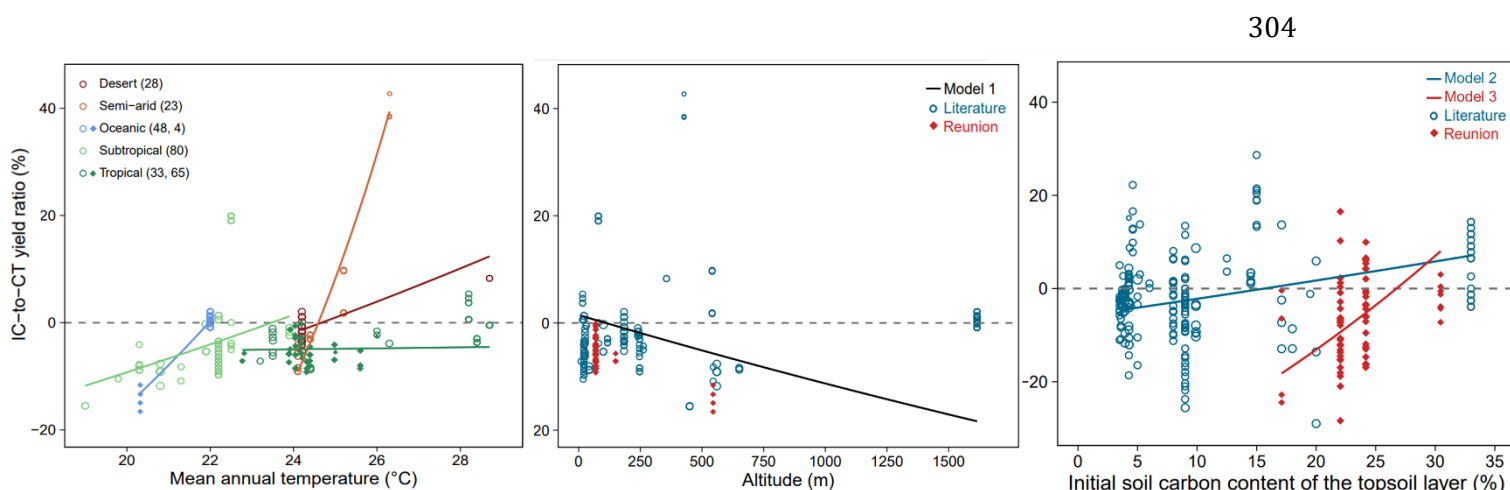


Fig. 2. The IC-to-CT yield ratio depending on (a) the mean annual temperature (°C) in interaction with the climate, (b) the trial altitude (m) and (c) the initial soil carbon content of the topsoil layer (%). Lines in (a) represent the fitted random effects model regression in the model 1. Black, blue

and red lines in (b) and (c) represent the fitted random-effects model regression in models 1, 2 et 3, respectively. The open circles and filled points represent the literature and Reunion predicted values, respectively.

3.4. Management effects

Depending on data sets the IC-to-CT ratio was significantly influenced by the legume sowing date, the destruction or disappearance date of the legume and the width of the sugarcane inter-row (Table 3). The sowing date of the legume was a significant covariate in the full data set (Model 1, $F = 3.26$, $P = 0.0728$) and literature data set (Model 2, $F = 2.6$, $P = 0.1093$) but was not selected in the Reunion data set. In both cases, our results showed a strong negative effect of legumes on sugarcane yield for early sowing (Fig. 3a and Fig. B4). The destruction/disappearance date of the legume was a significant covariate in the Reunion data set (Model 3, $F = 7.87$, $P = 0.0071$) but was not available in the literature. The IC-to-CT yield ratio decreased with the destruction date (Fig. 3b). Finally, the IC-to-CT yield ratio decreased with an increase in the inter-row width in the full data set (Model 1, $F = 3.11$, $P = 0.0799$, Fig. 3c).

The legume species growth habit and the type of sugarcane cycle (plantation vs. ratoon crop) were selected in both the full data set (Model 1, $F = 2.13$, $P = 0.0798$) and the literature data set (Model 2, $F = 3.08$, $P = 0.0831$). However, the pairwise comparison conducted on these variables showed no significant difference between the different growth habits (Fig. B5), and between plantation and ratoon crop cycles (Fig. B6).

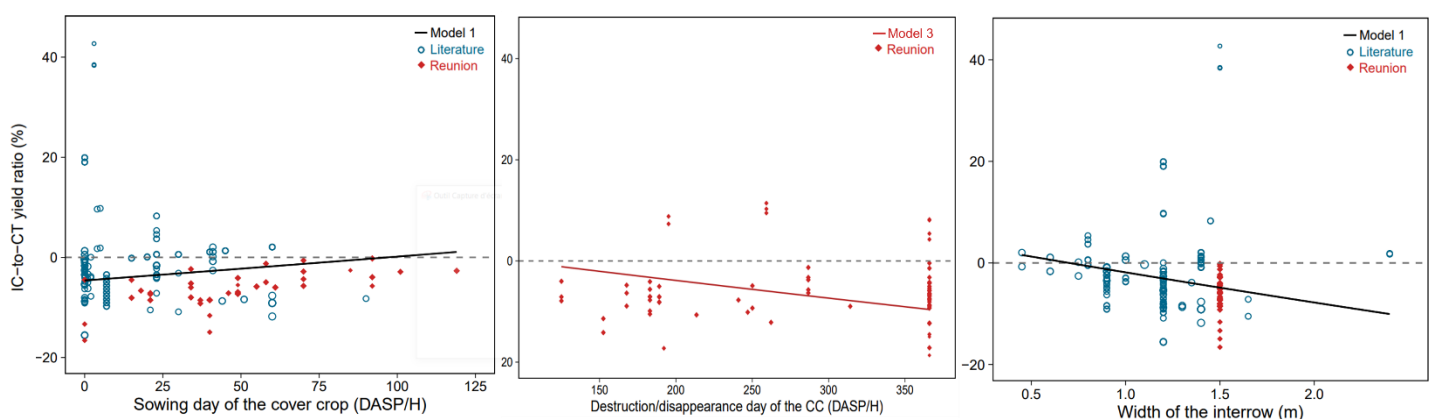


Fig. 3. The IC-to-CT yield ratio depending on (a) the legume sowing date (in days after planting or harvest DASP/H), (b) the legume destruction or disappearance date (DASP/H) and (c) the width of the inter-row (m). The black and red lines represent the fitted random-effects model regression of the model 1 and 3, respectively. The blue open circles and red filled points represent the literature and Reunion predicted values, respectively.

3.5. Effect of intercropping with legume over the years

The number of years of intercropping was a significant covariate in the full data set (Model 1, $F = 3.18$, $P = 0.0823$) and the literature data set (Model 2, $F = 2.27$, $P = 0.1364$) but it was not selected in the Reunion data set. In the full data set, the IC-to-CT ratio decreased by 0.7% per year of intercropping (Fig. 4).

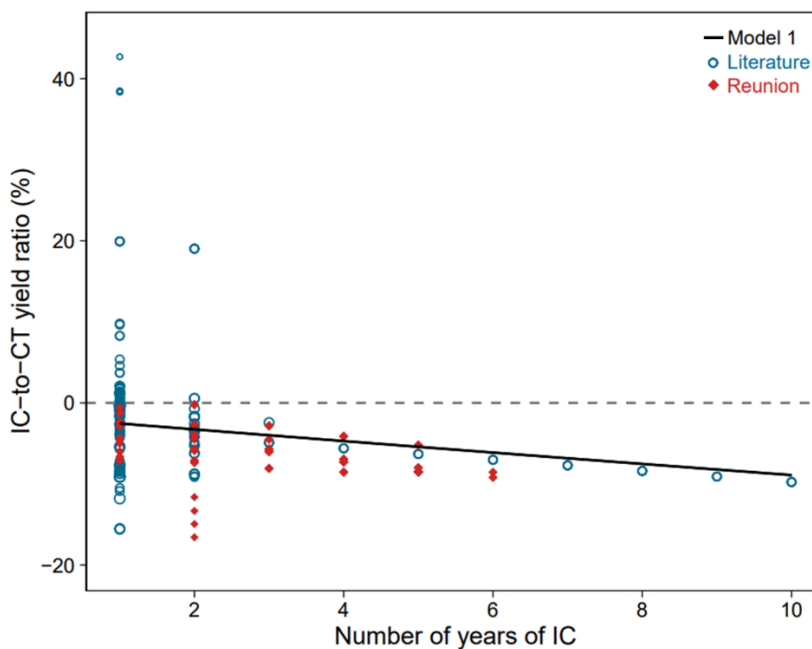


Fig. 4. The IC-to-CT yield ratio depending on the number of years since the implementation of the IC treatment (years). The black line represents the fitted random-effects model regression in the model 1. The blue open circles and red filled points represent the literature and Reunion predicted values, respectively.

3.6. Legumes and weed effects on cane yield

We used the Reunion data set to quantify the impact of legume and weed development on sugarcane yield (Table 3). The IC-to-CT yield ratio decreased with the global mean ground cover (Fig. B7). The analysis showed that weeds had an effect two times stronger than legumes on sugarcane yield when respective ground covers were used in the model. The IC-to-CT yield ratio decreased with weeds' mean ground cover (slope = -0.33, Model 3, $F = 7.19$, $P = 0.0098$), while it increased with legume mean ground cover (slope = 0.15, Model 3, $F = 5.71$, $P = 0.0206$, Fig. 5). Nonetheless, when using the global ground cover by both weeds and legume, the IC-to-CT yield ratio decreased with an increase in the global ground cover of the inter-row.

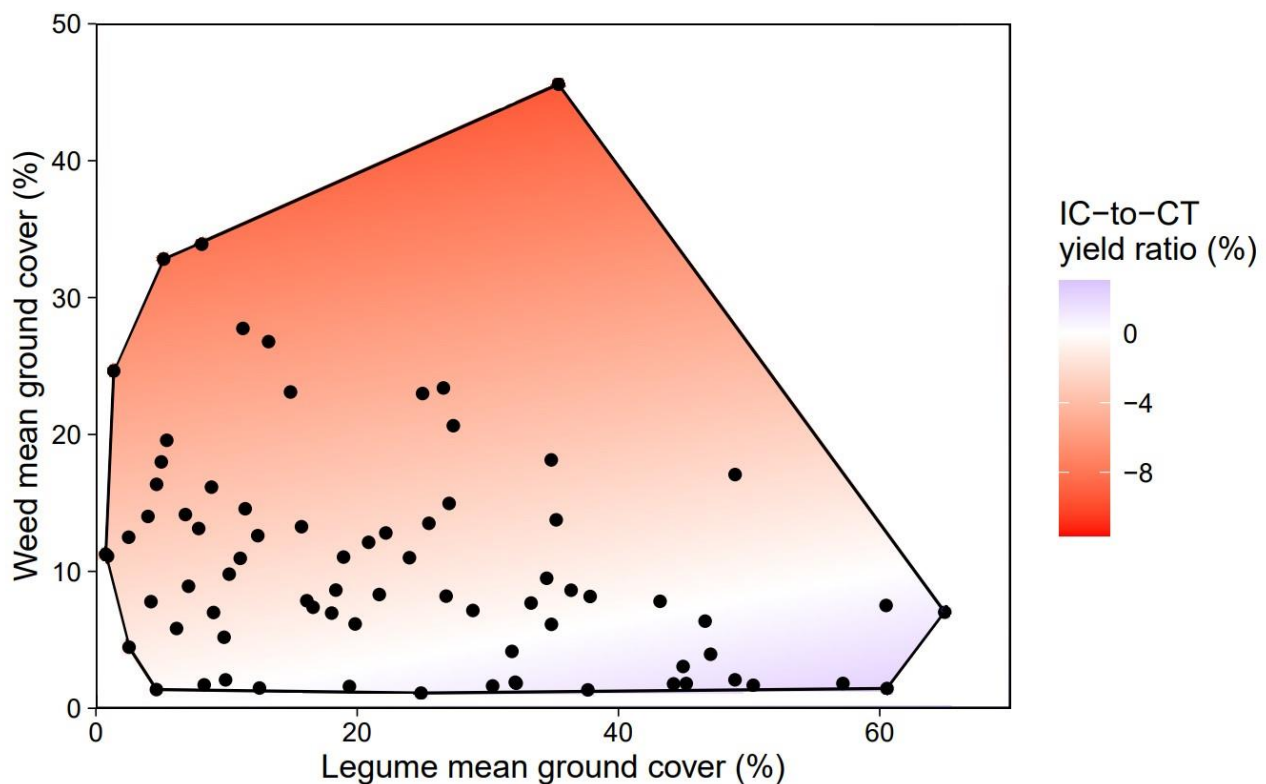


Fig. 5. The IC-to-CT yield ratio (% , red to purple gradient) depending on the ground cover by legume (x-axis) and weeds (y-axis). The IC-to-CT was predicted based on Model 3 (Reunion data set). The black line delimited the area of observed ground cover values in the Reunion data set. The red filled points represent the Reunion predicted values.

361

362 4. Discussion

363 4.1. Variable effect of legume cover crops on sugarcane yield

364 Our meta-analysis showed that legumes intercrops had on average a slightly negative effect on
365 sugarcane yield compared to the monoculture treatment. However, the effect varied widely among the
366 studies, negatively affecting sugarcane yield in 63% of cases. Such variability was not unexpected
367 considering the wide range of climate, soil, and management practices considered in this meta-analysis.
368 These results are similar to those obtained by Verret et al. (2017) in a worldwide meta-analysis on
369 intercropping systems with annual cash crops (mainly maize and straw cereals) and legumes. They
370 found a negative effect of legumes on cash crop yield in 56% of cases compared to the monoculture
371 weeded treatment. Similar to our results, the IC-to-CT yield ratio in Verret et al. (2017) varied from -49
372 to 317%.

373 The negative effect on sugarcane yield was larger in data issued from Reunion studies than in the
374 literature. There is no apparent reason related to the experimental conditions that could explain such a
375 difference. A publication bias may explain this difference and lead to underestimating the effect of
376 legumes on sugarcane yield in the literature. Publication bias may be due to unpublished studies with
377 negative results and the preferential publication of significant results compared to non-significant
378 results (Makowski et al., 2019). The symmetrical funnel plot suggested no publication bias in our study
379 (Fig. A8). However, this result must be considered cautiously because we could draw the funnel plot
380 only on a restricted part of the data (99/315), excluding data for which the variance was unknown and
381 data with a coefficient of variation <5%.

382 4.2. Influence of resource availability in sugarcane-legume competition

383 Identifying which factors influence sugarcane yield response was the second objective of the meta-
384 analysis. Our results showed that sugarcane yield varied with resource availability related to climatic
385 conditions, soil types, management conditions, and legume establishment.

The current study highlighted how legume competition was stronger at lower temperatures. Such observation is explained by the fact that sugarcane is a tropical crop sensible to low temperatures (Mongelard and Mimura, 1972). In addition, the ratio decreased with altitude, which is also associated with a decrease in global radiation (Chopart, Mézino, and Nativel 2003). Temperature and global radiation are key factors explaining variability in sugarcane yield on a regional scale (Christina et al., 2021b; Marin and Carvalho 2012). Sugarcane competitiveness is stronger when environmental conditions (e.g., temperature and global radiation) ensure favorable sugarcane development.

Our study also highlighted how light access by the legume was an important factor in the competitive interactions between sugarcane and legume. An increase in the distance between sugarcane rows induced a greater and longer light accessibility to the legume. Similar results have been shown with other crops such as cotton, soybeans, corn, and rice, where low row spacing reduced weed density and its impacts on yield (Bradley 2006; Chauhan and Johnson 2011; Tursun et al., 2016). However, row spacing can be difficult to change as it responds to local technical constraints and can only be achieved at planting time.

In this study, mean annual rainfall or irrigation did not significantly affect sugarcane-legume competition. However, the sugarcane yield ratio tended to increase with rainfall in the non-irrigated trials (Fig. B3). Several studies have shown that an increase in water availability reduces inter-species competition (Daellenbach et al., 2005; Roy et al., 2015; Waddington et al., 2007). Our study also showed that the ratio increased with soil fertility, even if no significant effect of the amount of nitrogen fertilizer was found. These results are consistent with other meta-analyses on intercropping systems (Pelzer et al., 2014; Xu et al., 2020), showing that the effect of nitrogen fertilizer is not significant but appeared to be highly variable, stressing the need for deeper analysis.

4.3. Trade-off in sugarcane-legume intercropping

Our study highlighted legume's sowing and destruction date as key factors driving the competitiveness of sugarcane and legume. An early sowing date of the cover crop resulted in a decrease in sugarcane yield in the present study, supporting the assumption that sugarcane is highly sensitive to competition during early growth. It can be assumed that the legume can over-compete sugarcane for light, water,

413 and nutrients when established early. Thus, delaying the sowing of the cover crop relative to the
414 sugarcane planting/harvest day should give the sugarcane a competitive advantage. These results are
415 in agreement with a meta-analysis on cereal-legume intercropping systems (Yu et al., 2016). Yu et al.,
416 (2016) also showed that this effect was more significant when the first sowed species was fertilized.
417 Although no interaction between sowing date and nitrogen fertilization was found in this study, this
418 topic appeared as an interesting avenue to explore in future research.

419 The cover crop's late destruction or disappearance date also negatively impacted sugarcane yield,
420 suggesting that legumes exert a competitive pressure even at the end of sugarcane's growth. Conversely,
421 early destruction of the cover crop may have facilitated sugarcane growth through an additional supply
422 of N from the mineralization of legume residues. To our knowledge, the effect of destruction date has
423 not been addressed in intercropping systems. However, the destruction date is a major issue in relay-
424 intercropping system, influencing cover crops' beneficial or detrimental effect on the following cash
425 crop (Keene et al., 2017; Mirsky et al., 2013). Alonso-Ayuso et al. (2014) showed that the destruction
426 date must be adapted according to the dynamic of mineralization (linked to the residues quality and
427 climate and soil conditions) to ensure synchronization between N release from cover crops and the cash
428 crop N requirement. These principles can be transposed to sugarcane-legume intercropping systems.
429 The destruction date must be considered in future work to maximize the potential benefits of legumes
430 as green manures. Destroying the legume during the sugarcane cycle involves additional costs and labor
431 time and can be technically complex when the sugarcane is well developed. A solution could be to use
432 legumes varieties with short growth cycles.

433 The expected benefits of intercropping with legumes are a gradual enrichment of soil N due to biological
434 nitrogen fixation (Cong et al., 2015), interspecific facilitation through N transfers during senescence and
435 decomposition of the different components of legumes (aerial biomass, roots and nodules) and from
436 root exudates to the non-legume species (Thilakarathna et al., 2016), and increased resource availability
437 (Latati et al., 2014). However, the amount of N fixed by the legume will depend on agro-environmental
438 conditions and the crop's growth. A late sowing date should benefit the sugarcane competitiveness and
439 productivity but at the expense of the legume's growth. One of the studies selected for this meta-analysis

observed that biomass and N uptake by legumes was three-fold higher for early sowing compared to late sowing (Prellwitz and Coelho 2011). In addition, an early sowing dates can facilitate legume establishment and enhance weed control (Mansuy et al., 2016). The destruction date must also allow sufficient N accumulation to maximize expected legume benefits.

The timing of sowing and destruction of cover crops plays a crucial role in the performance of these intercropping systems. Further work is therefore needed to optimize legume sowing and destruction dates to find a trade-off between expected services (N enrichment and weed control) and disservices (yield loss, costs, and labor time).

4.4. Sustainability of sugarcane-legume intercropping

We hypothesized that sugarcane yield might increase over time related to an increase in soil N fertility thanks to legume-N fixation. However, our study showed that the IC-to-CT yield ratio decreased over time. These results are in opposition to those reported by Li et al. (2021) in long-term maize-wheat and maize-legume experiments. The authors attributed the increasing yield benefits of intercropping over time to an increase in soil fertility in intercropping treatments. Nevertheless, very few studies have investigated the effect of legumes on soil properties in sugarcane-legume intercropping systems. Higher available NPK and microbial activity have been observed in short-term sugarcane experiments (Lian et al., 2019; Solanki et al., 2019; Yadav and Yaduvanshi 2001). However, an increase of soil organic carbon content has not been observed in a seven-year sugarcane intercropping experiment (e.g., in China, Wang et al., 2020), while in other crops, many studies have shown that multi-species systems can enhance the soil organic C and N content (Cong et al., 2015; Dybzinski et al., 2008). A few studies selected for this meta-analysis measured the amount of N supplied via biological N-fixation, ranging from 13 to 60 kg N ha⁻¹ (de Resende et al., 2003; Tian et al., 2020). Therefore, the fate of C and N of legumes in the soil-plant system needs to be investigated in the short- and long-term.

To explain the decrease in IC-to-CT yield ratio over the years, a first hypothesis is that the negative impact of legumes one year could be passed on onwards. Indeed, a negative effect on sugarcane growth can reduce the belowground reserves at harvest and thus slow down the growth of the following cycle. This hypothesis must be nuanced because many trials (mainly in Asia) in the literature replant

sugarcane yearly. However, we observed the same trend when restricting the data set to only the trials that did not replant each year (Fig. B8). Additionally, weed control by cover crops is limited in intercropping compared to chemical treatment (Verret et al., 2017). Therefore, a second hypothesis could be an increase in weed pressure over time compared to conventional systems (observed in one long-term trial in Reunion Island, Trial 2). Our analysis showed that the IC-to-CT yield ratio decreased with the global mean ground cover (legumes and weeds). However, we also showed that weeds were more damaging than legumes to sugarcane yield. This result can be attributed to lower competition for N of the legume, due to their ability to fix N from the atmosphere. In addition, multi-species communities like weeds have a higher potential competitiveness because species have a range of resource acquisition strategies. Consequently, the sugarcane–legume–weeds interaction must be further investigated to optimize the long-term sustainability of sugarcane-legume intercropping.

5. Conclusion

Despite an average 3.34% decrease in yield in the sugarcane-legume intercropping system compared to monocropping, this meta-analysis supports the assumption that legumes are less damaging than weeds for sugarcane, consolidating sugarcane-legume intercropping as a promising practice to reduce herbicide use. The effect of legumes intercrops on sugarcane yield was significantly influenced by environmental conditions (e.g., annual temperature, soil organic carbon content) and management practices (e.g., sowing and destruction dates), allowing to suggest some management options to limit the negative impact of legumes on sugarcane yield. However, there were currently insufficient elements to reason the management practices regarding different environmental conditions. There is a need for additional studies across various environments and situations to unlock the potential of sugarcane-legume intercropping and to encourage the spread of this technique among farmers. Finally, very few studies have quantified the amount of N provided by legume fixation. Further research should investigate the long-term benefits on soil fertility of legumes in sugarcane systems.

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Author contributions

P. Viaud: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft. B. Heuclin & P. Letourmy: Methodology, Formal analysis, Visualization. M. Christina, A. Versini & K. Naudin: Conceptualization, Methodology, Validation. A. Mansuy & J. Chetty: Conceptualization, Investigation. All authors: Writing - Review & Editing.

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