Species choice and spatial arrangement in soybean-based intercropping: Levers that drive yield and weed control

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USC 1432 LEVA, École Supérieure d'Agriculture (ESA), INRAE, SFR 4207 QUASAV, 55 rue Rabelais, F-49007 Angers, France

Corresponding author: g.hellou@groupe-esa.com

Highlights

- The species intercropped with soybean affected soybean production and weed control
- Soybean yield and weed control are related to the associated crop biomass and height
- The higher the soybean production was, the larger the weed biomass was
- The spatial arrangement only affected soybean production, not weed control
- Alternate-row limit the trade-off in sorghum and buckwheat intercrops

Abstract

Soybean is prone to weed infestations and yield variability. With the proposition of using intercropping to overcome these problems, this study explored the effects of combinations of different associated crop species and spatial arrangements on grain production and weed control.

In a two-year field experiment in western France, soybean was intercropped with buckwheat, lentil, sorghum and sunflower in two spatial arrangements: within-row intercropping and alternate-row intercropping, to investigate their effects on weed control and soybean production.

The results showed that the highest soybean yield occurred in the intercropping with lentil, followed by sorghum and sunflower, and finally buckwheat, but this effect varied by year. The opposite species order was obtained for weed control, revealing a trade-off between soybean production and weed control. We also demonstrated that associated species height was related to soybean yield and weed control. Alternate-row intercropping helped to increase soybean production without compromising weed control for sorghum and buckwheat, which have small height difference with soybean.

Finally, our paper showed that combining associated species choice and spatial arrangement allows farmers to manage the trade-off between soybean yield and weed control.

Key words:

Intercropping

Cropping systems diversification

Soybean

Spatial pattern

1. Introduction

Intercropping - the growing of two or more crops in the same field for a significant part of their life cycles (Willey, 1979) - is gaining an increasing interest in Europe. Several studies have demonstrated the multiple benefits of intercropping such as a better weed control and improvement of productivity and yield stability compared to sole crops, especially in low input systems (Lithourgidis et al., 2011; Raseduzzaman and Jensen, 2017). Thus, intercropping could be proposed as a tool to facilitate the introduction of a crop known for its yield variability and low competitive ability against weeds notably when there are few mechanical or chemical solutions available. Legumes are well known for their potential positive impact on crop rotations and their improvement of cropping system sustainability (Nemecek et al., 2008) but are also known for their low competitiveness toward weeds and their high yield variability. Soybean (*Glycine max* (L.) Merr.), producing protein-rich grain, is still rarely cultivated in France (about 154 000 ha in 2018; Agreste, 2020). The development of early cultivars, the global increase in temperatures (Moriondo et al., 2010) and a favourable market for locally produced protein crops (Martin, 2015) are opportunities to increase its production area, even in regions where it has not been cultivated in the past. However, soybean has been shown to have the second most variable yield among the major legume crops of Western Europe (Cernay et al., 2015). In addition, Oerke, (2006) demonstrated that weed competition was the main biotic source of soybean yield losses, before pathogens, animal pests and viruses.

While pea- and faba bean-cereal intercropping have been the subjects of numerous studies, intercropping soybean with another species is an innovative practice that has received little attention in Europe. Moreover, previous studies dealing with cereal-grain legume intercrops often focused on one particular species combination and tried to optimize it (Carton, 2017; Yu et al., 2016, 2015). The originality of our approach is to explore a wide range of associated species, with different competitive abilities, imposing different levels of competition to soybean and weeds. This approach should help better understand how grain yield and weed control can be altered in intercrops depending on the competitive ability of the associated crop. The level of crop biomass and crop height are expected to influence the level of inter-species competition – crop-crop and crop-weeds – and, as a consequence, change soybean yield and weed control obtained. In previous studies on cereal-grain legumes intercrops, the difference in plant height between the two species was usually low and there is a lack of references for intercropped species having very contrasted heights in temperate agricultural conditions.

In addition to the choice of the associated species, other technical levers can influence the level of competition and therefore the expected soybean production and weed control. Some options have been extensively studied, including through meta-analysis for cereal-grain legume intercropping: relative density and relative sowing time (Echarte et al., 2011; Yang et al., 2017; Yu et al., 2015) and fertilisation (Gomez and Gurevitch, 1998; Pelzer et al., 2014). Amongst the different spatial arrangements - the way crops are mixed together in intercropping (Andrews and Kassam, 1976) – row intercropping is particularly relevant for mechanised agriculture where farmers may be constrained by available farm machinery for their intercrop management choices. Combining crops within the same row or sowing them one row out of two may affect the competition between crops and has been rarely compared. In addition, no consensus can be drawn from the available literature concerning the effects of within-row and alternate-row intercropping on productivity and weed control (Chapagain and Riseman, 2014; Kermah et al., 2017; Martin and Snaydon, 1982). Given the diversity of species used in these studies, we argue that there might be an interaction between species and spatial arrangement. Hence, using a diversity of crops in both spatial arrangements should clarify the effect of spatial arrangement on intercrops performances when varying the level of competition.

The objective of this work was to study soybean grain production, associated crop yield and weed control obtained from soybean-based intercropping as affected by species choice, spatial arrangement and their combination through field experiments carried out in western France in 2018 and 2019.

2. Materials & Methods

2.1 Site and soil

The experiments were carried out in 2018 and 2019 in Brain-sur-l'Authion, France (47°28'N, 0°23'W). Over ten years (2008 to 2017), the mean annual rainfall was 660 mm on the experimental site, and the mean annual air temperature was 12°C. The air temperature, rainfall and irrigation recorded during the time of the experiments are shown in Figure 1. In 2018, the second half of May and June were particularly humid and warm compared to the normal. In 2019, late May and early June were cooler than in 2018, and early June temperatures were below normal. We thus have experienced contrasted early growth conditions. In both years, July was warmer than the 10-year average.

Two different fields were used for the experiments, one per year. In both fields, the soil was at least 90 cm deep. The topsoil (0-30 cm) of the field used in 2018 was a sandy loam with 7.7% clay, 18.3% silt, 24.9% fine sand and 49.1% coarse sand. The organic matter content was 1.2%, and the pH of the soil in water was 7.3. In 2019, the soil texture was also sandy loam, with 16.9% clay, 21.5% silt, 24% fine sand and 37.6% coarse sand. There was 1.9% organic matter, and the pH of the soil in water was 7.9. Soil mineral nitrogen content in the 0-90 cm soil layer before sowing was 84 kg ha^{-1} in 2018 and 94 kg ha^{-1} in 2019. In both years, P, K and Mg were present in the soil with values above the locally recommended thresholds of fertilisation for these elements. The preceding crop was a spring barley

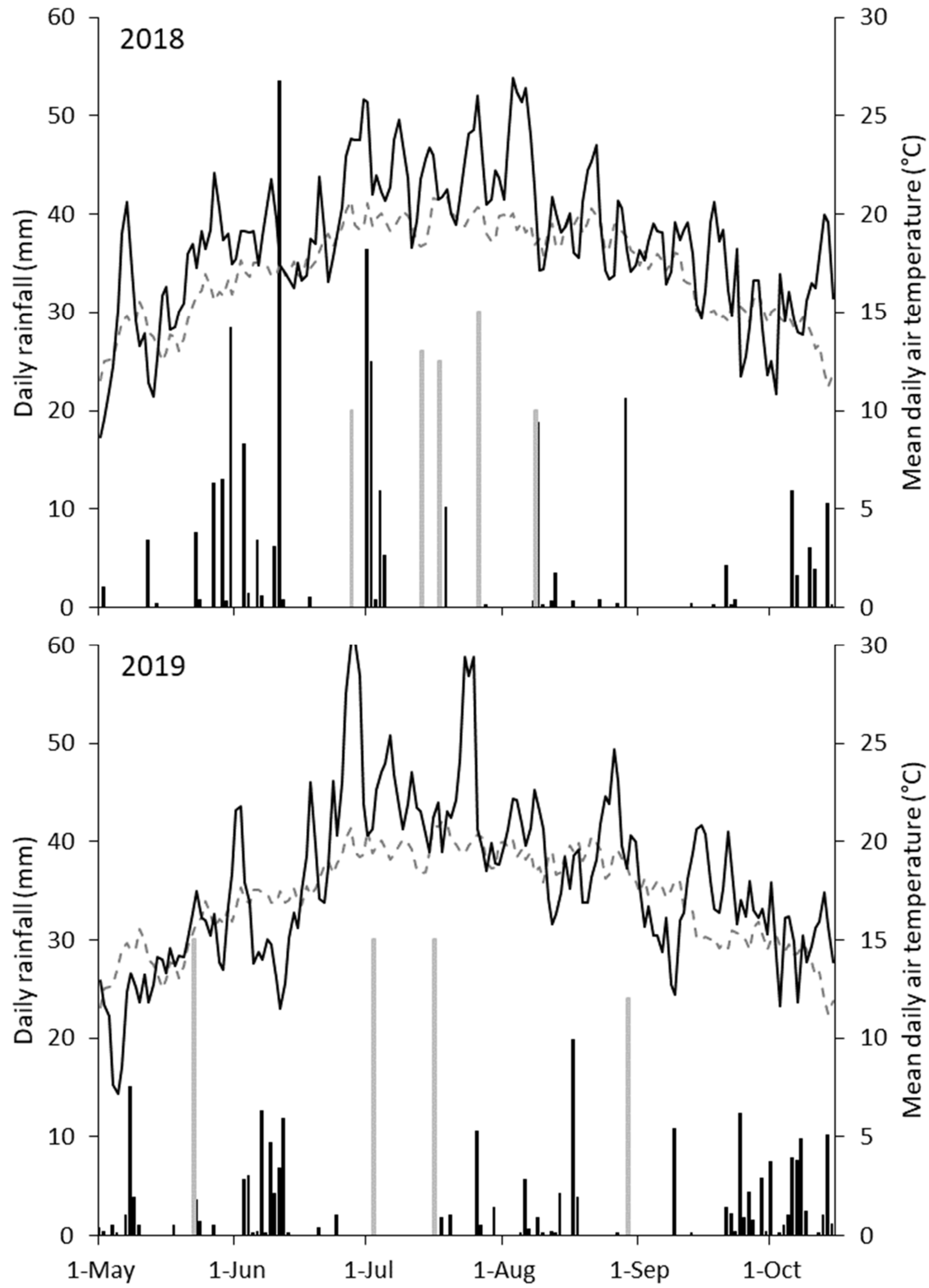

Figure 1: Mean daily air temperature and daily rainfall recorded in 2018 and 2019 in Brain-sur-l'Authion, France (47°28'N, 0°23'W). Black bars in histogram correspond to rainfall while grey ones correspond to irrigation. Black continuous line represents the mean daily temperature for the cropping season and the grey dashed line, the mean daily air temperature over a ten-years period, from 2008 to 2017.

in 2018 and winter wheat in 2019. In both fields, a mustard-faba bean cover crop was sown in July after the harvest of the preceding crop and mechanically destroyed in March before soil preparation.

2.2 Experimental design

Soybean cv. Sirelia, a very early maturing cultivar (maturity group 000; recommended for the local pedoclimatic conditions) with an indeterminate growth habit, was chosen to be intercropped with four crops. The four intercrop species were selected from different families for their differences in morphology and competitive ability (amount of biomass produced, height, growth habit) and nitrogen fixation capacity, in order to obtain different levels of competition. The ability to complete their cropping cycle at the same time as soybean was also a major criterion for cultivar choice. These crops were buckwheat (*Fagopyrum esculentum* Moench cv. Harpe), lentil (*Lens culinaris* Medik. cv. Rosana), grain sorghum (*Sorghum bicolor* (L.) Moench cv. RGT Iggloo) and sunflower (*Helianthus annuus* L. cv. SY Valeo). These four crops will hereafter be referred to as “associated crops”.

All five crops were grown as sole crops, and soybean was intercropped with each of the four associated crops in two spatial arrangements: mixed within-row, where both crops were randomly sown within the same row (i.e.: there was no specific pattern between plants within the rows), and in alternate-row, with each crop being sown in every other row. The intercropping systems were designed following the replacement principle, with 50% of the sole soybean crop density replaced with 50% of the sole associated crop density.

The seeding rates for the sole crops were based on the densities recommended by local agricultural institutes to farmers. The sole crop seeding densities were 68, 168, 350, 42 and 7.2 seeds m^{-2} for soybean, buckwheat, lentil, sorghum and sunflower, respectively. The soybean seeds were inoculated with *Bradyrhizobium japonicum* (strain G49; Force 48 Inoculum Soja NPPL®, Euralis Semences). Due to the regular presence of leguminous crops in the fields used for the study, decision was made not to inoculate lentil. Later on, nodule presence was confirmed for soybean and lentil.

Before sowing, the soil of the experimental fields was tilled to completely destroy the cover crop and get rid of any weed present in the field. On May 16th 2018 and May 15th 2019, the five sole crops, the eight intercrops and a bare soil treatment were sown in a randomized complete block design with 4 replicates in each year. The bare soil treatment received exactly the same mechanical treatment as the other ones; the seed-drill went through “bare soil” plots, without seeds. The plots were 18.0 m long by 1.44 m wide, with four rows sown 36 cm apart. A north-south row orientation was maintained for both years. The crops were managed without fertilizers, fungicides, insecticides nor chemical or mechanical weed control, except for the seed treatments present on sunflower and sorghum seeds. Irrigation was provided for all treatments at once when needed, based on visual observation of the state of the crops, mainly soybean, and soil (Figure 1).

2.3 Measurements and analysis

Soybean, associated crop and weed above-ground biomass samples were taken in every plot at soybean flowering (R1; Fehr and Caviness, 1977) and soybean maturity (R8) from the two central rows and from inter-rows over one meter long (1 m x 0.72 m). In 2018, R1 occurred on July 4th and R8 occurred on September 19th. In 2019, R1 occurred on July 8th and R8 on September 25th. All samples were dried at 70°C for 48 hours before weighing. At soybean maturity, crop samples were threshed using a stationary thresher (Type 350C-S.R.C. sas, Mayet, France) before drying. The soybean grain samples were ground down to 120 µm (universal cutting mill "Pulverisette 19"; variable-speed rotor mill "Pulverisette 14"–Fritsch, Idar-Oberstein, Germany) and then analysed through isotope ratio mass spectrometry for their total N content.

At soybean flowering, the names of the main weeds present in the field were recorded, based on a rapid visual assessment of plant number and size. Also, crop height was recorded for five randomly chosen plants of each crop species per plot. Height was measured as the longest distance from the soil to the highest standing part of the plant, meaning that prostrated plants would not be straightened up before measurement.

2.4 Calculations and statistical analysis

The soybean seed protein content was calculated by multiplying the soybean grain nitrogen content by 5.5, a conversion factor suggested by Mariotti et al. (2008).

Statistical analysis were conducted on crop yields, crop biomasses at flowering and weed biomasses at flowering and harvest using linear mixed models with the lme4 package in R software (Bates et al., 2015; R Core Team, 2019). For each year separately, we used the following linear mixed model:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + B_k + \epsilon_{ijk}$$

where μ is the intercept, α_i, the main effect of the i^{th} associated crop species and β_j, the main effect of the j^{th} spatial arrangement and $\alpha\beta_{ij}$, the associated crop species by spatial arrangement interaction, which are all fixed factors. B_k correspond to the k^{th} block, the random factor and ε_{ijk} is the residual error of y_{ijk}. ε_{ijk} and B_k are assumed to be independent from each other and normally distributed around 0 with unknown variance parameters.

ANOVA was performed on the fixed part of the model to determine the significance of each factor and their interaction. To deal with the few missing data points, Type II sum of squares was used for the ANOVA (Langsrud, 2003).

To check the model assumptions, the residuals were tested for normality with the Shapiro test and for homoscedasticity through the Bartlett test. When the assumptions were not met, transformation using the Box-Cox procedure was performed (Box and Cox, 1964). In the situations were homoscedasticity and normality of the residuals were not met after the Box & Cox transformation, Kruskal-Wallis test was used. Post hoc comparison of the different factors was performed with Tukey's HSD.

To go beyond species and spatial arrangement effects and to investigate mechanisms responsible for the grain production and weed control variations, relationships between soybean yield and weed biomass as response variable and crop characteristics (crop above-ground biomass, associated crop proportion in the mixture) as explanatory variables were tested using a simple linear mixed model. For all models, the explanatory variable was the fixed part of the model and Block was the random part. Relationships were investigated within experimental years considering all measured intercropping treatments and repetitions. The response variables were tested without transformation and log transformed. The residuals were inspected to assess the normality and heteroscedasticity of their distribution. The marginal R^2 of the model, representing the variance explained by the fixed part of the model, was calculated using the r.squaredGLMM function based on Nakagawa et al. (2017). The model with the highest marginal R^2 was selected.

To compare the grain production and weed control obtained from intercropping to those obtained from the sole soybean crop, three indices were calculated: the soybean production, the weed control and the associated crop production indices. Following the recommendations of Jensen et al. (2020), all indices were calculated, for a given year, from the average of the values obtained from the four blocks. Thus, soybean production index was obtained by dividing the averaged soybean yield in a given intercrop by the average yield of soybean in the sole crop. Similarly, weed control index was calculated as 1 minus the averaged above-ground weed biomass at harvest in a given intercrop divided by the averaged weed biomass at harvest in the soybean sole crop. The associated crop production index was, for a given associated crop, the ratio of its averaged yield in a given intercrop to its averaged yield in the corresponding sole crop. Thus, whether it is for crop yields or weed control, the higher the indices, the better the situation.

3. Results

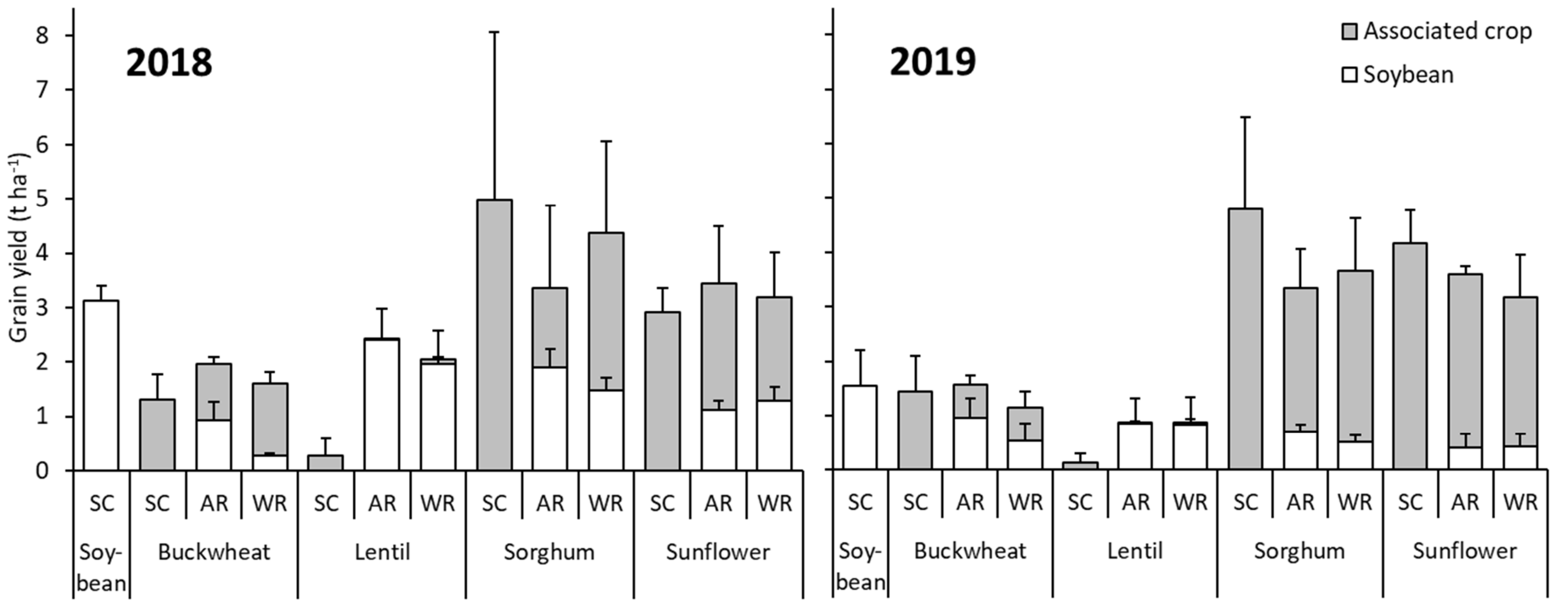

Figure 2: Grain yields of soybean, buckwheat, lentil, sorghum and sunflower in sole crops (SC) and intercropping in two spatial arrangements: alternate-row intercropping (AR) and within-row intercropping (WR). In the cumulated histograms, error bars represent the standard deviation.

3.1 Soybean productivity

The soybean sole crop yielded 3.12 t ha^{-1} in 2018 and 1.56 t ha^{-1} in 2019 (Figure 2). In the intercropping treatments, the soybean yield ranged from 0.26 to 2.40 t ha^{-1} in 2018 and from 0.40 to

0.95 t ha^{-1} in 2019. The choice of the associated crop species significantly affected soybean yield in both years (Table 1). Soybean yield was the highest with lentil in both years and the lowest with buckwheat in 2018 and sunflower in 2019. Spatial arrangement also had an effect on soybean yield, but this effect was significant only in 2018 (Table 1). Alternate-row intercropping increased soybean yield by 31% compared to that in within-row intercropping in 2018.

Soybean yield decreased with the increase in associated crop above-ground dry matter measured at soybean flowering (Figure 3). The relationship linking soybean yield to the associated crop biomass explained more variance in 2018 than in 2019 (Figure 3). Buckwheat in 2018 and sunflower in 2019 had the highest crop biomass (Table 2) and entailed the higher yield reduction. As early as flowering, soybean biomass was affected by buckwheat growth in within-row intercropping in 2018 (Table 2). In both years, lentil produced the smallest amount of biomass at soybean flowering and displayed the highest soybean yield.

Table 1: Species and spatial arrangement effects on soybean yield within intercropping treatments. Significance levels are: * <0.05, ** <0.01 and *** <0.001. Different letters amongst species or spatial arrangements indicate significant differences with Tukey-HSD (p< 0.05).

	Soybean yield (t ha^{-1})	
	2018	2019
Species significance	<0.001 ***	0.028 *
Lentil-soybean	2.18 a	0.84 a
Sorghum-soybean	1.69 ab	0.61 ab
Sunflower-soybean	1.22 b	0.42 b
Buckwheat-soybean	0.6 c	0.74 ab
Spatial arrangement significance	0.010 *	0.128
Alternate-row	1.62 a	0.73
Within-row	1.24 b	0.58
Interaction significance	0.211	0.378

The protein content of soybean seeds was high and rather stable, on average 40.9 (±2.3) % in 2018 and 34.6 (±3.4) % in 2019. Neither the intercropped species nor the spatial arrangement had a significant impact on soybean protein content. As a consequence, the total protein production was closely related to the soybean yield.

Table 2: Soybean, associated crop and weed biomasses at soybean flowering. Mean and standard deviation (in brackets) values are presented. SC stands for sole crop, AR for alternate-row and WR for within-row. Significance levels are shown for each factor and their interaction: N.S. stands for non-significant (α > 0.05). Small bald letters distinguish treatments which are significantly different according to Tukey's HSD and capital bald letters identify species with significant differences according to Tukey's HSD. † Non-significant according to Kruskal-Wallis test.

		2018							
		Soybean (t ha^{-1})			Associated crop (t ha^{-1})			Weeds (t ha^{-1})	
Soybean	SC	2.497	(0.42)					0.597	(0.33)
Buckwheat-soybean	AR	1.039	(0.17)	**ab**	2.850	(0.63)	**A**	0.307	(0.07)
	WR	0.417	(0.21)	**b**	3.154	(0.99)		0.330	(0.24)
Lentil-soybean	AR	1.452	(0.19)	**a**	0.765	(0.18)	**C**	0.687	(0.21)
	WR	1.395	(0.35)	**a**	0.540	(0.14)		0.561	(0.28)
Sorghum-soybean	AR	1.153	(0.39)	**a**	1.625	(0.65)	**B**	0.525	(0.21)
	WR	1.441	(0.42)	**a**	1.812	(0.46)		0.417	(0.10)
Sunflower-soybean	AR	1.142	(0.27)	**ab**	1.647	(0.95)	**BC**	0.595	(0.54)
	WR	1.560	(0.32)	**a**	1.333	(0.28)		0.545	(0.27)
	Species	< 0.001			< 0.001			N.S.	
	Spatial arrangement	N.S.			N.S.			N.S.	
	Interaction	0.013			N.S.			N.S.	
		2019							
Soybean	SC	0.995	(0.20)					2.241	(0.99)
Buckwheat-soybean	AR	0.738	(0.16)		1.876	(0.47)	**BC**	0.740	(0.51)
	WR	0.419	(0.10)		1.861	(0.99)		0.929	(0.94)
Lentil-soybean	AR	0.690	(0.25)		1.100	(0.16)	**C**	1.067	(0.42)
	WR	0.582	(0.18)		1.509	(0.83)		0.905	(0.25)
Sorghum-soybean	AR	0.612	(0.10)		2.36	(0.43)	**B**	0.898	(0.36)
	WR	0.678	(0.03)		2.328	(0.53)		1.026	(0.34)
Sunflower-soybean	AR	0.508	(0.17)		4.767	(0.56)	**A**	0.510	(0.15)
	WR	0.506	(0.11)		3.503	(0.86)		0.832	(0.32)
	Species	N.S.			< 0.001			-	
	Spatial arrangement	N.S.			N.S.			-	
	Interaction	N.S.			N.S.			N.S.†	

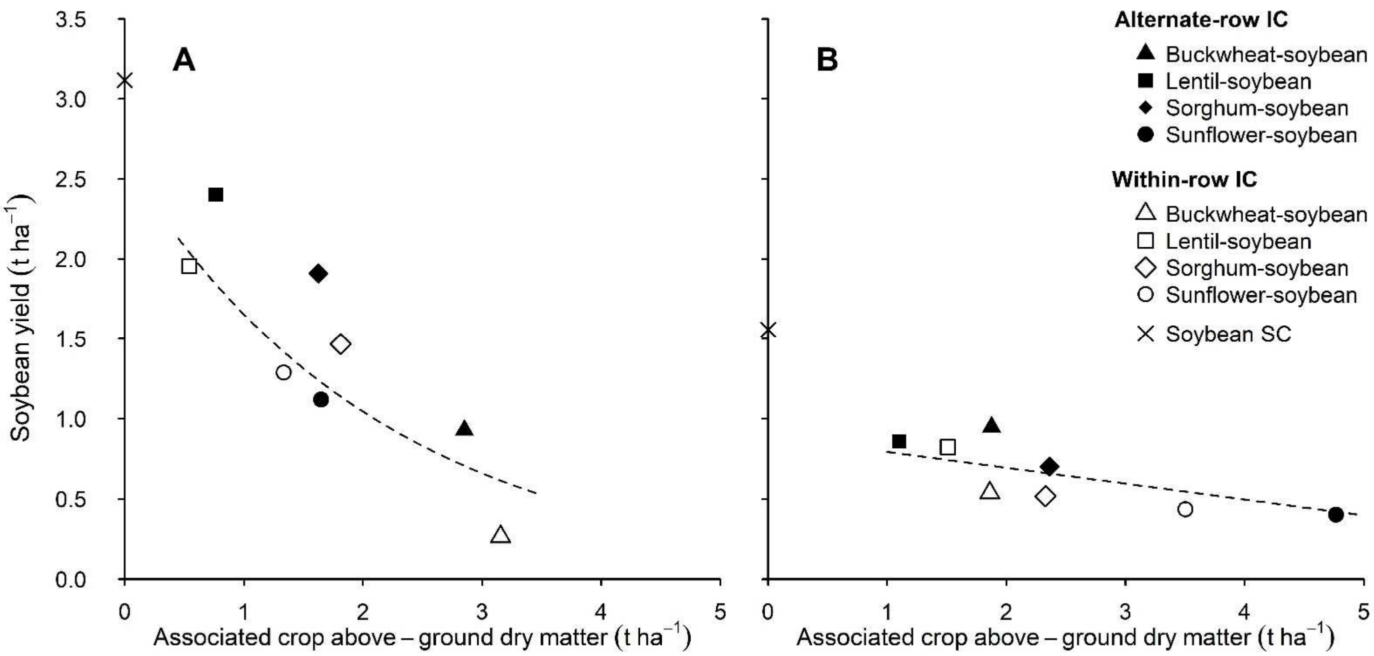

Figure 3: Soybean yield as a response to associated crop dry matter at soybean flowering. IC stands for intercropping, and SC stands for sole crop. **A** corresponds to 2018 and **B** to 2019. Each symbol corresponds to the averaged values of each treatment. The dashed lines represent the regressions fitted with all intercropping measurements. The soybean sole crop was not included in the regression calculation. In 2018, $\log(Y) = -0.459 * X + 0.962$ ($R^2 = 0.443$; p-value < 0.001); in 2019, $Y = -0.099 * X + 0.892$ ($R^2 = 0.122$; p-value = 0.023).

3.2 Weed biomass

At crop maturity, the weed potential measured on bare soil was similar in both years, with values of 6.32 and 6.68 t ha^{-1} in 2018 and 2019, respectively. The main weed species occurring in both years were lamb's quarters (*Chenopodium album* L.) and lady's thumb (*Polygonum persicaria* L.). The weed biomass in the soybean sole crop reached 2.29 t ha^{-1} in 2018 and 3.94 t ha^{-1} in 2019. In the intercropping treatments, weed biomass varied greatly by treatment from 0.32 to 3.90 t ha^{-1} in 2018 and from 1.37 to 4.29 t ha^{-1} in 2019.

The choice of the species intercropped with soybean had an effect on weed biomass measured at crop harvest in the intercropping treatments which was significant both years (Table 3). The lentil-soybean intercrop had a significantly higher weed biomass in both years than the other intercropping treatments. Sorghum and sunflower intercropped with soybean had comparable weed control abilities, while buckwheat significantly lowered weed biomass in 2018 compared to the other crops, but this was not the case in 2019. Spatial arrangement had no significant effect on weed biomass at harvest (Table 3).

At soybean flowering, no significant effects of species, spatial arrangement, nor their interactions were found on the weed biomass (Table 2). The effect of associated species occurred after flowering.

Table 3: Species and spatial arrangement effects on weed dry matter at crop maturity within intercropping treatments. Significance levels are: * <0.05, ** <0.01 and *** <0.001. Different letters amongst species or spatial arrangements indicate significant differences with Tukey-HSD (p< 0.05).

	Weed dry matter (t ha^{-1})	
	2018	2019
Species significance	<0.001 ***	<0.001 ***
Lentil-soybean	3.55 a	4.18 a
Sorghum-soybean	1.3 b	2.11 b
Sunflower-soybean	1.66 b	1.6 b
Buckwheat-soybean	0.34 c	2.52 b
Spatial arrangement significance	0.419	0.516
Alternate-row	1.68	2.47
Within-row	1.75	2.73
Interaction significance	0.080	0.705

Overall, weed dry matter decreased with the increasing accumulation of dry matter by crops measured at soybean flowering (Figure 4). Low crop biomass (about 2 t ha^{-1}) was associated with a

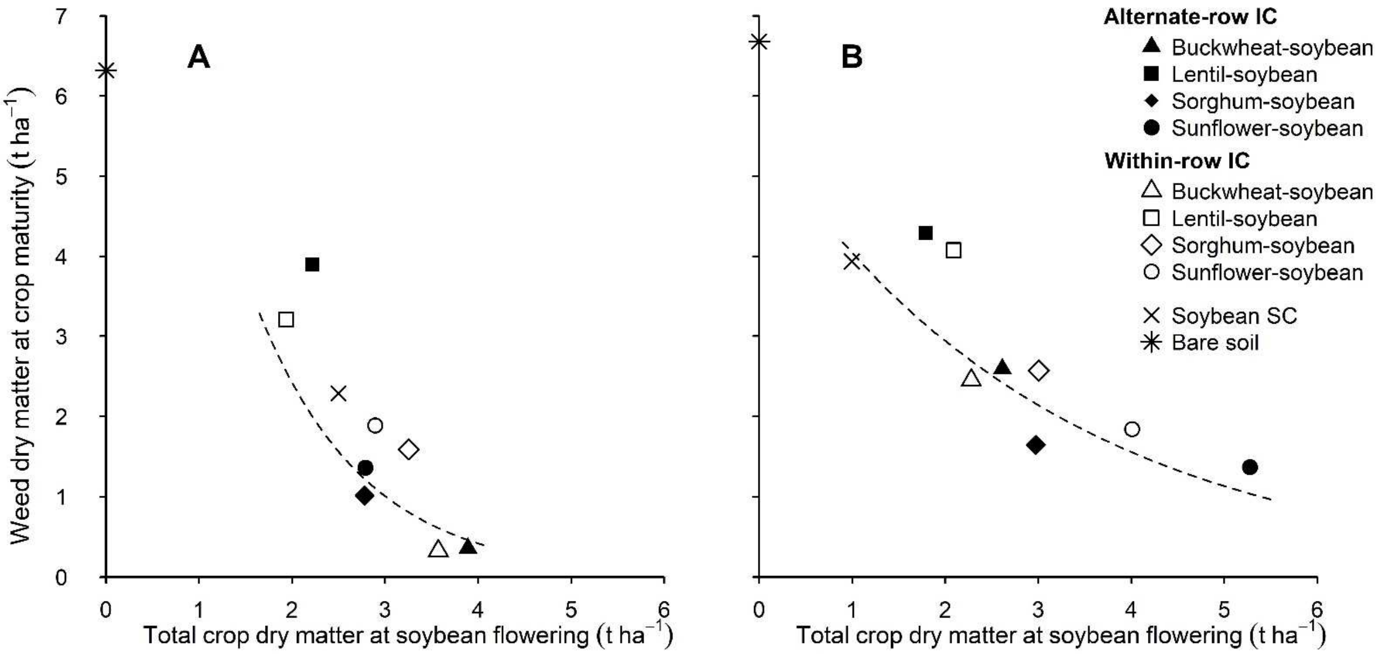

Figure 4: Weed dry matter at crop maturity as a response to total crop dry matter at soybean flowering. Total crop dry matter corresponds to above-ground dry matter of soybean summed with the associated crop above-ground dry matter in intercropping treatments or to soybean above-ground dry matter for sole soybean crop. IC stands for intercropping and SC for sole crop. **A** corresponds to 2018 and **B** to 2019. Each symbol corresponds to the averaged values of each treatment. The dashed lines represent the regressions fitted with all intercropping measurements. Soybean sole crop was included for the regression calculation but not bare soil. In 2018, $\log(Y) = -0.877 * X + 2.637$ ($R^2 = 0.411$; p-value < 0.001) and in 2019, $\log(Y) = -0.318 * X + 1.716$ ($R^2 = 0.359$; p-value < 0.001).

low competitive ability of lentil-soybean intercropping in both years. The other intercropping combinations had higher weed control ability due to their higher crop biomass. The buckwheat-soybean intercrops produced less total biomass in 2019 than in 2018, 4.89 and 3.73 t ha^{-1} respectively, while the sunflower-soybean intercrops showed the opposite trend with an average of 2.84 t ha^{-1} in 2018 and 4.64 t ha^{-1} in 2019. Thus, the level of weed control for a given intercropping treatment differed between years based on the level of crop biomass. In addition, the weed biomass decreased as the associated crop dry matter proportion in the total crop biomass at soybean flowering increased (Figure 5). In 2018, the associated crop dry matter proportion varied from 28% to 88% in lentil-soybean within-row and buckwheat-soybean within-row, respectively. In 2019, the range was smaller, from 62% in lentil-soybean alternate-row intercrop to 90% in sunflower-soybean alternate-row intercrop.

3.3 Trade-off between soybean production and weed control

When considering within-row intercropping, soybean production appeared to be related to weed control (Figure 6A). Specifically, the higher the level of weed control, the stronger the reduction of

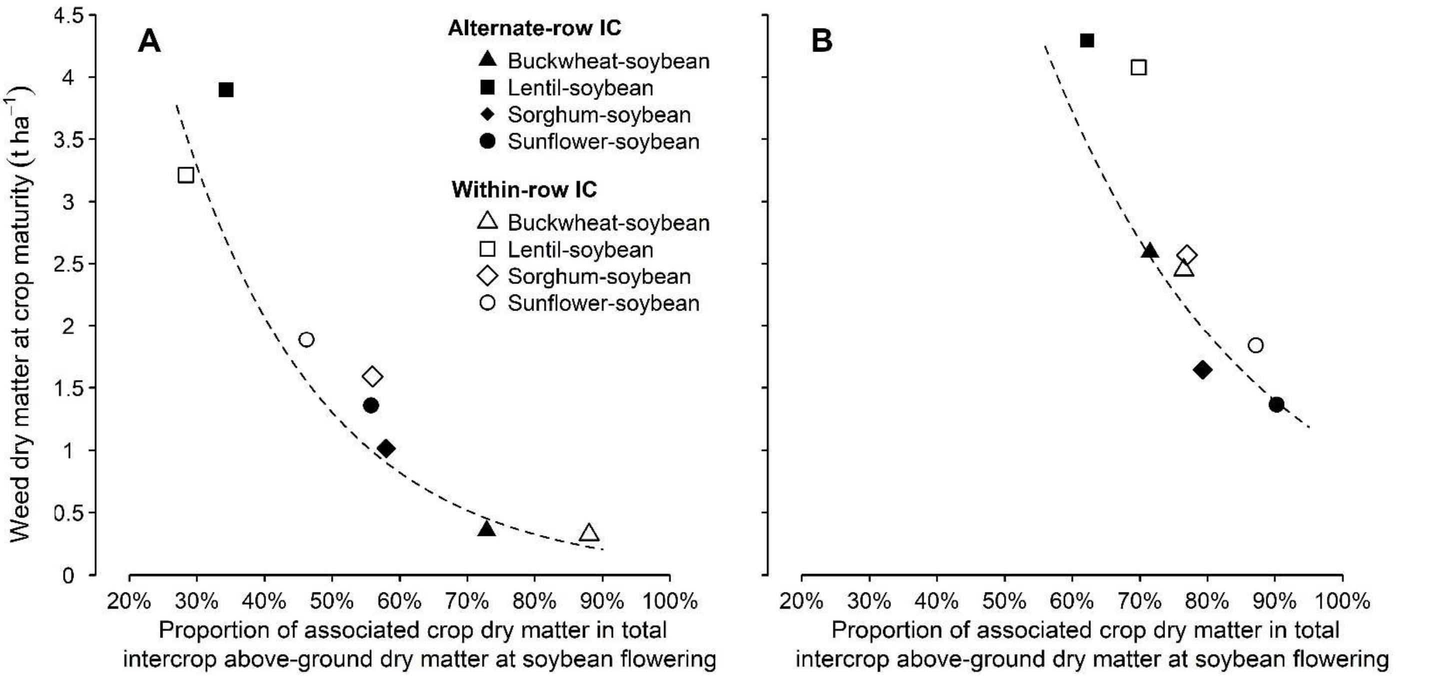

Figure 5: Response of weed dry matter at crop maturity to associated crop dry matter proportion of the total intercropped dry matter at soybean flowering. IC stands for intercropping. **A** corresponds to 2018 and **B** to 2019. Each symbol corresponds to the averaged values of each treatment. The dashed lines represent the regressions fitted for all intercropping measurements. In 2018, $\log(Y) = -4.619 * X + 2.574$ ($R^2 = 0.591$; p-value < 0.001); in 2019, $\log(Y) = -3.270 * X + 3.276$ ($R^2 = 0.254$; p-value = 0.003).

soybean grain yield. However, in the case of alternate-row intercropping, two situations were observed. On the one hand, sunflower-soybean alternate-row and lentil-soybean alternate-row followed approximately the same trend as within-row intercropping. On the other hand, alternate-row sorghum-soybean and alternate-row buckwheat-soybean had higher soybean production indices than their respective within-row intercropping treatments, with similar weed control indices (Figure 6A).

As shown in figure 2, associated crops production was different between species. In intercrops, the associated crop yielded, on average, 0.04 t ha^{-1} for lentil, 0.90 t ha^{-1} for buckwheat, 2.54 t ha^{-1} for sorghum and 2.56 t ha^{-1} for sunflower. Statistical comparison of associated crop yields did not reveal interaction between spatial arrangement and species both years. Spatial arrangement had a significant effect in 2018 only, with the associated crops producing in within-row intercropping an average of 38% more than in alternate-row intercropping.

Associated crop production index ranged from 0.08 to 1.07 in 2018 and from 0.19 to 0.77 in 2018 (Figure 6B). The treatments with a high reduction in the soybean grain production index had high

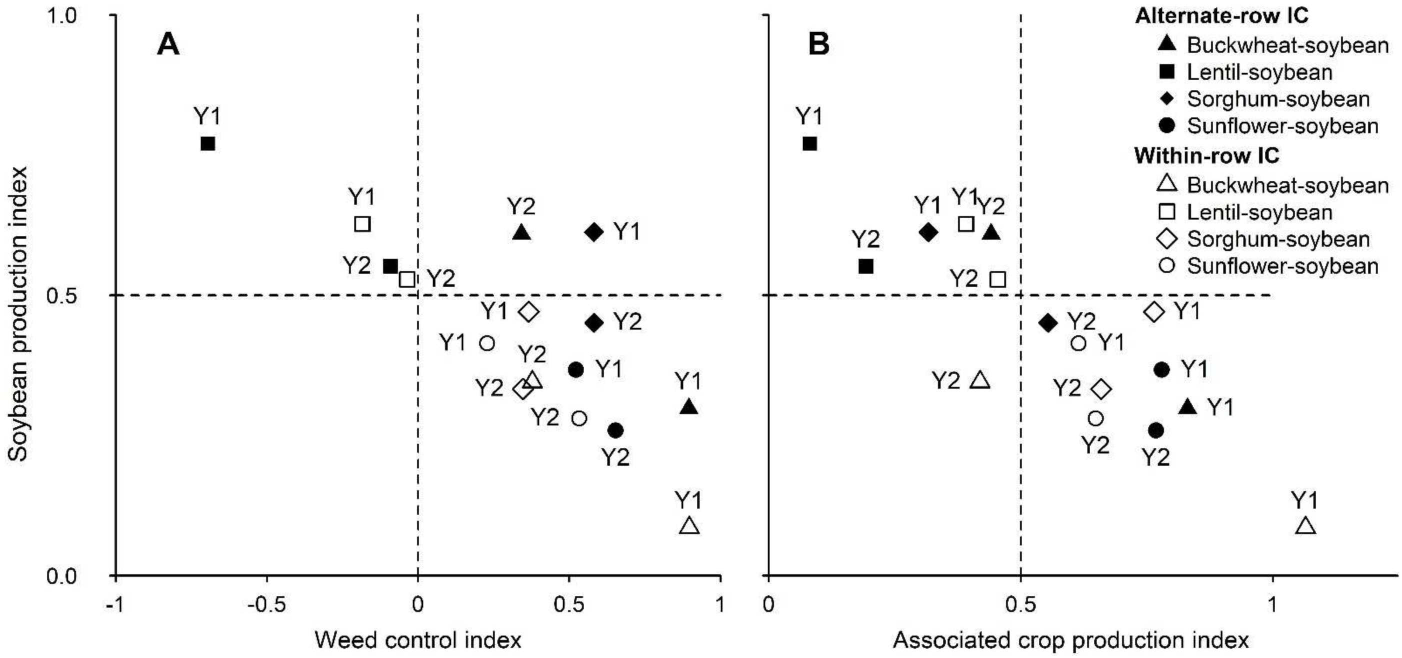

Figure 6: Soybean production of intercropping treatments in relation to weed control (A) and to the associated crop productivity (B). The soybean production index value was obtained as the ratio of the soybean yield in a given intercropping treatment to the soybean yield in the sole crop. The weed control index value is 1 minus the ratio of final weed biomass within a given intercropping treatment divided by that in soybean sole crop. Associated crop production index corresponds to the yield of the associated crop in a given intercropping divided by the yield of the corresponding sole crop. Each symbol corresponds to the averaged values of each treatment. IC stands for intercropping, AR for alternate-row intercropping and WR for within-row intercropping. Points labelled Y1 correspond to 2018 and Y2 to 2019.

associated crop production index. Thus, as weed control increased in the intercropping treatments, soybean grain production decreased, but the associated crop production index increased.

3.4 Crop height in relation to soybean productivity and weed control

Crop heights at soybean flowering averaged over all treatments were 55 (±5) and 43 (±7) cm for soybean, 117 (±10) and 85 (±11) cm for buckwheat, 31 (±3) and 28 (±3) cm for lentil, 83 (±5) and 80 (±4) cm for sorghum and 119 (±7) and 106 (±7) cm for sunflower in 2018 and 2019, respectively. As shown in Figure 7A, lentil was thus the only crop smaller than soybean, the other ones were on the contrary taller, up to 67 cm for sunflower. We found significant (p-value < 0.001 in 2018 and p-value < 0.01 in 2019) negative correlation between soybean production index and the height difference between the associated crop (Figure 7A) while weed control index increased as maximum canopy height increased (Figure 7B).

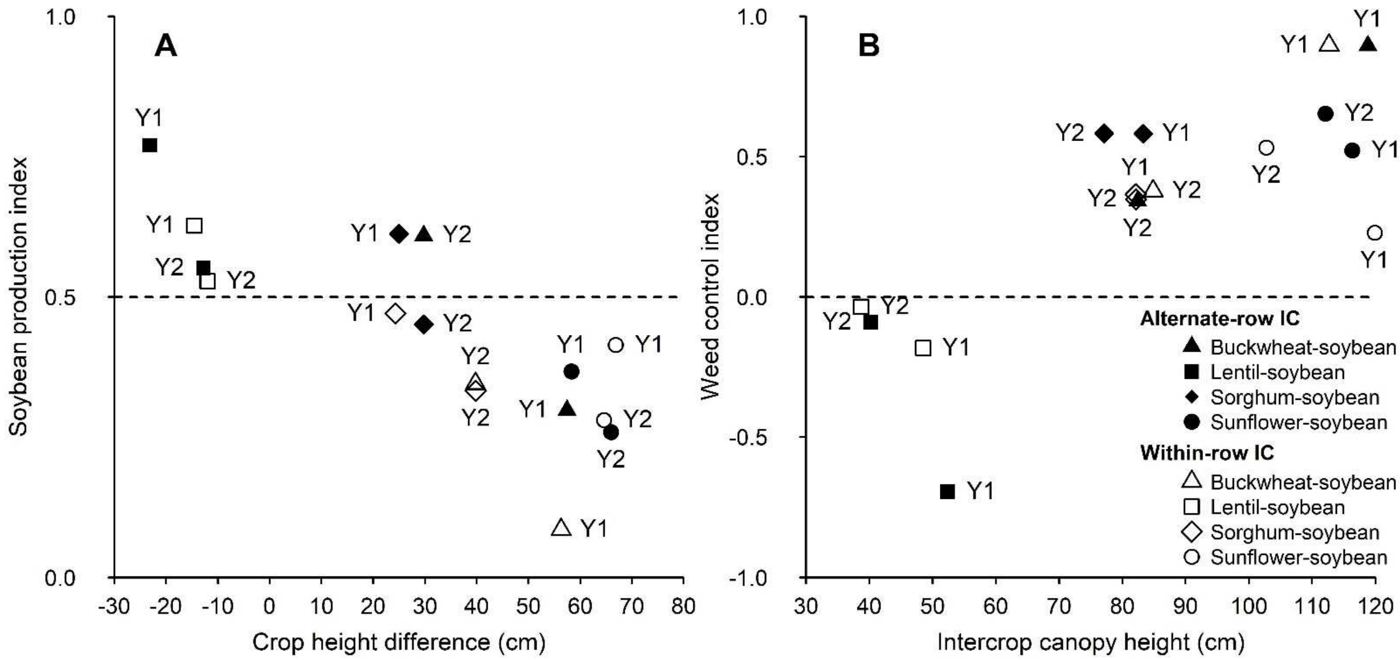

Figure 7: Soybean production in relation to crop height difference within intercrops (A) and weed control in relation to intercrop canopy height (B). The soybean production index value was obtained as the ratio of the soybean yield in a given intercropping treatment to the soybean yield in the sole crop. The weed control index value is 1 minus the ratio of final weed biomass within a given intercropping treatment divided by that in soybean sole crop. Height difference was calculated the following way: Associated crop height – Soybean height. Each symbol corresponds to the averaged values of each treatment. IC stands for intercropping, AR for alternate-row intercropping and WR for within-row intercropping. Points labelled Y1 correspond to 2018 and Y2 to 2019.

4. Discussion

Our study highlighted that soybean yield and weed suppression depended on management options. The choice of the intercropped species and the spatial arrangement are key levers for influencing the level of competition between species and, consequently, grain production and weed control. Thanks to the range of contrasted species studied, we observed a strong negative correlation between soybean yield and weed suppression. A key result is that the trade-off between soybean production and weed control can be, in some situations, managed through spatial arrangement. Also, it appears that the level of biomass and height of the associated species influenced soybean production and weed control.

4.1 Weed control

Weed control by intercropping depends on the total biomass of the mixture. Our results showed that a high total intercrop biomass in the first part of the crop cycle (up to soybean flowering) was associated with a low final weed biomass. A fast growth in early stages is often considered as a strong advantage in weed-crop competition but such correlations have been mainly investigated in sole crops (e.g. Pérez et al., 2006), in intercrops with companion crops (Hiltbrunner et al., 2007; Lorin et al., 2015) or in studies dealing with cover crops (Finney et al., 2016; MacLaren et al., 2019). The use of highly contrasted species allowed us to cover a wide range of crop biomass and demonstrate its effect on weed control. Another result is that the level of biomass accumulation by the associated species appears crucial; indeed, weed biomass was negatively strongly correlated to the percentage of the associated crop in total intercrop biomass, which is in line with previous studies including cover crops (MacLaren et al., 2019).

Among the studied species, buckwheat was the most competitive species in relation to a fast early growth ; this species is known for its high ability to compete early for growth resources (Falquet et al., 2015). Lentil, the least competitive against weeds, had a low biomass production and a short canopy. Moreover, due to its ability to fix a great part of its own nitrogen requirements by N_2 fixation, a large amount of soil N was probably available for weeds. Previous studies have demonstrated that the low competitive ability of legumes for soil N contribute to their low competitive ability against weeds (Corre-Hellou et al., 2011).

Canopy height has been shown to be an important factor in plant competition for light (Violle et al., 2009). This crop trait is especially determinant in weed-crop competition when weed community is dominated by tall weed species. Sunflower canopy height, being superior to the two dominant weed species maximum height (Kleyer et al., 2008), gave it a competitive advantage over both C*henopodium album and Polygonum persicaria* while sorghum and buckwheat had this advantage on *Polygonum persicaria* only. Lentil, being shorter than the two dominant weed species could not compete for light with them.

Despite our hypothesis that within-row mixtures would provide a more regular soil shading than alternate-rows of crops, especially for crops with low sowing densities, no effect of spatial arrangement was found on weed control. In fact, regardless of the species, intercrops biomass was not affected by spatial arrangement at soybean flowering, which in turn did not influence weed growth. Hence, weed biomass accumulation was probably more related to the ability of associated species to produce biomass and capture resources all along the cropping cycle than an early change in canopy structure.

4.2 Soybean production

We demonstrated that weed growth was affected by the associated crop, and the same was true for soybean. A level of biomass higher than 1.5 t ha^{-1} for the associated crop at soybean flowering entailed soybean yields in intercrops below 50% of soybean sole crop yield. Thus, soybean, known to have slow early growth at the beginning of its cropping cycle (Hock et al., 2006; Jannink et al., 2000), was easily outcompeted by an early fast-growing crop such as buckwheat in 2018 and to a lesser extent in 2019, especially in within-row intercropping (Table 2). An associated crop with relatively slow early growth will probably be better tolerated by soybean than one with early vigour. Our result showed also that the crops with the largest difference in height with soybean at flowering did impact the most soybean production. Very high differences in heights were obtained in soybean-sunflower intercrop. A large part of light is certainly intercepted by such a dominant species (Geier et al., 1996). Unlike weed control, soybean production was affected by the spatial arrangement. Globally, soybean was more productive in alternate-row. Thus, resource acquisition by soybean might be improved by the spatial separation of soybean from the associated crop. In contrast, the associated crop yield tended to be higher in within-row intercropping, suggesting that soybean was generally less competitive than the associated crop. Like Martin and Snaydon (1982), we argue that the spatial separation of crops reduced the competitive advantage of the most competitive crop in the intercropping system by allocating a given space with corresponding resources to each species, thereby delaying interactions (positive or negative) until one species was able to reach the resource pool of the other.

4.3 Interactions between grain productions and weed control

As detailed above, associated crop biomass and height are involved in competition against both weeds and soybeans, thus contributing to weed control but impeding soybean production. This is in line with the trade-off between soybean production and weed control we highlighted. Such trade-offs have not yet been demonstrated through a range of species in intercropping systems except in systems integrating cover crops (Finney et al., 2017). den Hollander et al. (2007) highlighted a trade-off between weed control and leek production in leek intercropped with different clover species. In their study, they linked the reduction in leek biomass to clover species height which was also involved in weed control. In winter oilseed rape-living mulch intercrops, Lorin (2015) also highlighted the importance of the living mulch crop biomass growth rate as a key indicator for the delivery of weed control and grain production.

Nonetheless, our results also revealed that the soybean production could be improved by spatial separation of crops without compromising weed control, for soybean intercropped with sorghum and buckwheat. Thus, spatial arrangement can be a lever to modulate the level of antagonisms between soybean production and weed control. However, we argue that crop characteristics may play an important part in the success of spatial arrangement implementation. Indeed, for soybean-sorghum and sorghum-buckwheat intercrops, the differences in height were moderate. By contrast, in soybean-sunflower intercrop, the sunflower was much taller than soybean and exhibited a strong and similar competition on soybean whatever the spatial arrangement. These results suggest that response to spatial arrangement is dependent on the level of differences in crop height between species and crop early competitiveness. The analysis of the distance between values of different traits between species and the plasticity of traits in response to crop management options could help to understand performances and trade-offs occurring in intercrops (Damour et al., 2014; Gaba et al., 2015; Malézieux et al., 2009).

There was also an antagonistic relationship between soybean production and associated crop production, as shown by the values of the production indices (Figure 6). However, this can be seen as positive for farmers because the associated crop can improve the total yield and potentially the income at the field level and provide some sort of production insurance in the case of a low yield from the main crop.

4.4 Soybean intercropping management for grain production and weed control

From our results, some recommendations can be made as regard to intercrops design. For weed control, overall intercrop biomass should be maximized and canopy height should be as high as possible. Hence, an additive design should be favoured (e.g. Gomez and Gurevitch, 1998). Soybean, should be favoured by being separated in space (alternate-row) from a more competitive associated crop, ideally being the tallest crop of the mix and could be fostered by increasing the soybean density proportion in the mixture. The associated crop should be added in sufficient density if a grain harvest is expected, but less in proportion than soybean to avoid strong competition with it (Bedoussac et al., 2015; Yu et al., 2016). Also, it should be producing as much biomass as possible, with a height inferior or equal to that of soybean. Other levers can be used: inter-row width is expected to delay or increase crop interactions (Elmore and Jackobs, 1984) and sowing soybean first can give a head start to soybean, for higher tolerance to the associated crop competitivity (Yu et al., 2016). Cultivar choice can also play a role in associated crop tolerance (Hauggaard-Nielsen and Jensen, 2001).

Despite the potential benefits on yield, the intercropping of soybean with another legume crop is not recommended unless chemical weed control can be applied. Further research on intercrops composed of two grain legumes crops should be conducted to use the existing variability among legumes for early growth (Dayoub et al., 2017; Hiltbrunner et al., 2007).

Given that many legumes crops present the same problems than soybean, the results obtained in this study should be rather easily transferred to other crops. However, the difficulties encountered with other intercrops also have to be addressed such as machinery issues for sowing, harvesting and grain sorting.

5. Conclusion

Soybean production and weed control are both driven by the associated crop biomass production and as a consequence are antagonists. Nonetheless, relevant combinations of different management options, amongst which spatial separation of crops in alternate rows and the choice of an associated specie with comparable height, can help modulate these antagonistic relationships and obtain higher soybean yield while maintaining weed control. The identification of these management options requires further investigation of the competition between different cropping system components in terms of their respective crop traits.

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