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Species choice and spatial arrangement in soybean-based intercropping: levers that drive the delivery of multiple services.

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Highlights

- The species intercropped with soybean affected soybean production and weed control
- The higher the soybean production was, the more weeds developed
- The spatial arrangement only affected soybean production, not weed control
- The spatial arrangement altered the trade-off between these services for some species

Abstract

The introduction of new crops into cropping systems is confronted with many barriers. For soybean, the main barriers are weed infestations and yield variability. With the proposition of using intercropping to overcome these barriers in soybean, this study explored the effects of combinations of different second-crop species and spatial arrangements on the delivery of multiple services.

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 services.

The results showed that the highest soybean production 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 the weed control service, revealing a trade-off between the soybean production and weed control services. Nonetheless, alternate-row intercropping helped to increase soybean production without compromising weed control for some species.

Thus, combining these two intercropping management options is a promising way to achieve multiple service delivery from intercropping and to ease the introduction of soybean into cropping systems.

Key words:

Intercropping
Cropping systems diversification
Multiple services
Soybean
Spatial pattern

Introduction

The diversification of cropping systems is presented as one solution for reducing the environmental impacts of crop production, handling the withdrawal of chemical control solutions from the market, and stabilizing crop production through the prevention of yield decline (Bennett et al., 2012; Isbell et al., 2017; Kremen and Miles, 2012). Nonetheless, the diversification of cropping systems may be complicated by the many lock-ins in agrifood systems (Magrini et al., 2016). At the farm scale, farmers might not be inclined to try “diversification crops” due to the risks of failure, yield variability over the years, or the lack of technical advice and/or chemical solutions for weed, pest and disease control (Meynard et al., 2018).

Legumes are well known for their potential positive impact on crop rotations and their improvement of cropping system sustainability (Nemecek et al., 2008). Soybean, producing protein-rich grain, is still rarely cultivated in France (about 154 000 ha in 2018; Agreste, 2020). However, 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, weed competition is the main biotic source of soybean yield losses at the global scale, before pathogens, animal pests and viruses (Oerke, 2006). Carkner and Entz (2017) attributed part of the high yield variability of soybean to the variable weed density in organic soybean cultivation. As a consequence, solutions to reduce yield variability, weed pressure and other risks linked to the introduction of soybean into cropping systems should be investigated.

We propose to use intercropping (IC) - the growing of two or more crops in the same field for a significant part of their life cycles (Willey, 1979) - as a facilitator of cropping system diversification. Indeed, the reduction of pest, weed and disease pressures through IC (Boudreau, 2013; Liebman and Dyck, 1993; Trenbath, 1993) could compensate for the low competitive ability or low tolerance of a diversification crop and address the lack of technical or chemical solutions. Moreover, the higher resilience of IC to biotic and abiotic stresses (Lithourgidis et al., 2011; Malézieux et al., 2009) and the higher yield stability (Raseduzzaman and Jensen, 2017) could mitigate the risk of crop failure. In our study, soybean was the diversification crop used to produce grains with high protein content. The “facilitator crop”, to be intercropped with soybean, was expected to help with weed control and was also harvested to increase productivity and provide harvest insurance.

The choice of the facilitator crop is expected to influence the level of competition between species – crop-crop and crop-weeds – and, as a consequence, change the service outcome. Few studies have studied soybean intercropped with several species (e.g.: Echarte et al., 2011; Pal et al., 1993), and none of the studies was located in Europe. In addition to the choice of intercropped species, different management options can influence the competition between component crops and affect the outcome of the intercropping. Some of these options have been extensively studied, including through meta-analysis for cereal-legume intercropping and, in a few cases, for soybean-based intercropping: relative density and relative sowing time (Echarte et al., 2011; Yang et al., 2017; Yu et al., 2015) and fertilization (Gomez and Gurevitch, 1998; Pelzer et al., 2014). However, few studies have explored the effect of spatial arrangement, and no consensus can be drawn from the available literature concerning the effects on productivity. Kermah et al. (2017) found that both maize and legume grain yields were generally higher in within-row intercropping than in alternate-row intercropping. In a faba bean-barley mixture, barley yield was not affected by the spatial arrangement (SA), while the faba bean yield was higher in alternate-row than in within-row intercropping, resulting in a productive advantage for alternate-row (Martin and Snaydon, 1982). Finally, in pea-barley intercropping, no spatial arrangement effect was detected in the yield of either crop (Chapagain and Riseman, 2014). However, given the diversity of crops used in these studies and the lack of a general effect of spatial arrangement, we argue that there could be an interaction effect from spatial arrangement and species on both production and weed suppression.

The study of the relationships among several services and the effects of different management options should provide more insight into combining several agronomic practices to improve the delivery of multiple services.

The objective of this work was to explore the delivery of services (production and weed control) expected 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.

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.

Table 1: Air temperature, cumulative rainfall and irrigation for the 2018 and 2019 cropping seasons and 10-year averages recorded in Brain-sur-l’Authion, France (47°28'N, 0°23'W).

	Average temperature (°C)			Cumulative rainfall (mm)			Irrigation (mm)	
	2008-2017	2018	2019	2008-2017	2018	2019	2018	2019
May 16th - May 31st	15.2	17.7	15.3	37.2	63.0	7.0		30
June 1st - June 15th	17.2	18.5	15.6	26.4	86.6	57.4		
June 16th - June 30th	18.7	20.4	22.5	22.2	1.0	2.8	20	
July 1st - July 15th	19.5	22.1	22.0	18.3	79.2	0,0	26	30
July 16th - July 31st	19.9	22.0	22.2	24.6	10.4	18.2	55	30
August 1st - August 15th	19.1	21.8	19.8	23.4	23.6	13.2	20	
August 16th - August 31st	19.2	19.3	20.0	28.4	23.0	23.8		24
September 1st - September 15th	17.1	18.1	16.5	24.0	0.4	11.0		
September 16th - September 30th	15.1	16.1	17.3	18.4	5.4	31.8		

The air temperature, rainfall and irrigation recorded during the time of the experiments are shown in Table 1, averaged over 15-day periods. 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 the early June average temperature was below normal. In both years, July was warmer than the 10-year average.

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. In both years, P, K and Mg were present in sufficient quantities in the soil. The preceding crop was a winter cereal-legume intercrop in 2018 and wheat in 2019. In both fields, a mustard-fava 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 setup

Soybean (*Glycine max* (L.) Merr.) cv. Sirelia, from maturity group 000 with an indeterminate growth habit, was chosen to be intercropped with four crops. The four crops were selected from different families for their differences in morphology and growth habit 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), 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 "second-crops".

All five crops were grown as sole crops (SC), and soybean was intercropped with each of the four second-crops in two spatial arrangements: mixed within-row (WR), with both crops mixed within the same row, and in alternate-row (AR), 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 second-crop density.

The seeding rates for the sole crops were based on the densities recommended to farmers locally. The sole crop seeding densities were 68, 168, 350, 42 and 7.2 seeds per square metre for soybean, buckwheat, lentil, sorghum and sunflower, respectively. The soybean seeds were inoculated with *Bradyrhizobium japonicum* (strain G49; Force 48, Euralis Semences), while the lentil seeds were not inoculated because their inoculant was present in the soil. A bare-soil treatment was also performed to evaluate weed potential. The 14 treatments were sown on May 16th in 2018 and May 15th in 2019 in a randomized complete block design with 4 replicates in each year. The plots were 18.0 m long by 1.44 m, with four rows sown 36 cm apart. A north-south row orientation was maintained for both years. The crops were managed without fertilizers, pesticides or fungicides, except for the pesticides present on sunflower and sorghum seeds. Weeds were left to grow from the beginning of the experiment without any chemical or mechanical control. Irrigation was provided as needed (Table 1).

2.3 Sampling and analysis

Crop and weed 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 metre 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 occurred on September 25th. All samples were dried at 70°C for 48 hours before weighing. Crop samples from sampling at soybean maturity 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.

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).

To compare the services obtained from intercropping to those obtained from the sole soybean crop, two ratios were calculated: the soybean yield in a given intercrop divided by the yield of soybean in the sole crop and the weed biomass at harvest in a given intercrop divided by the weed biomass at harvest in the soybean sole crop. The productivity of the second-crop in the intercrop was assessed through the ratio of its yield in a given intercrop to its yield in the corresponding sole crop. These indices were calculated from the estimates obtained after fitting the appropriate linear mixed model as suggested by Jensen et al. (2020).

Statistical analysis was performed separately for each year using linear mixed models with the lme4 package in R software (Bates et al., 2015; R Core Team, 2019). The models had the form Y ~ Species * Spatial Arrangement + (1|Block) (lme4 syntax), with Y as the response variable, "Species" and "Spatial arrangement", the explanatory variables, as fixed factors and "Block" as the random factor. ANOVA was performed on the fixed part of the model to determine the significance of each factor and their interactions. When not significant ($\alpha = 0.05$) or nearly significant ($\alpha = 0.1$), the interaction was withdrawn from the model, and the model was refitted accordingly. 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 ($\alpha = 0.05$) and for homoscedasticity through the Bartlett test ($\alpha = 0.05$). When the assumptions were not met, transformation using the Box-Cox procedure was performed (Box and Cox, 1964). Post hoc analysis was performed with Tukey's HSD.

Linear mixed models were used to assess the relationships between biomass variables. They had the form Y ~ X + (1|Block) (lme4 syntax), and the relation was tested for Y and log(Y). They were calculated using the individual values of all treatments considered (i.e., not using the averaged values) and within each year. For each regression, only the data from intercropping treatments were considered, except for the relationship between the final weed biomass and the crop biomass, for which the soybean sole crop was included. 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 R² was selected.

Results

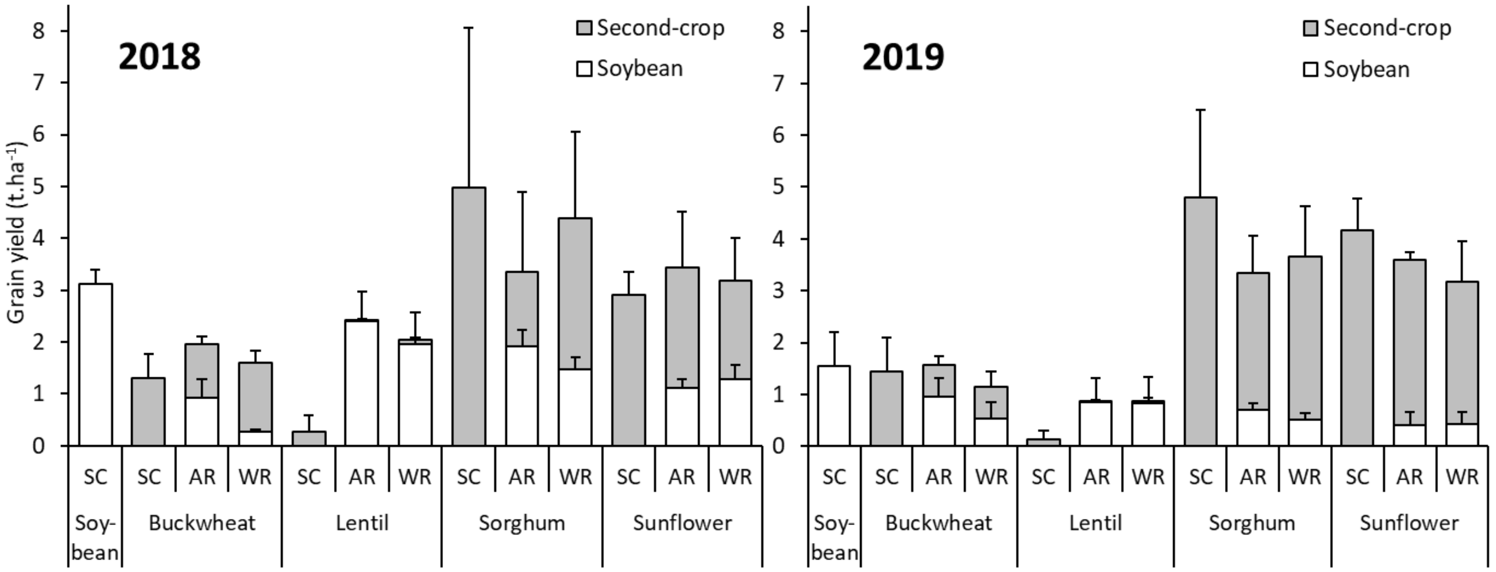

Figure 1: Grain yields of soybean, buckwheat, lentil, sorghum and sunflower in sole crops (SC) and intercropping in two spatial arrangements: alternate-row intercropping (AR) and within-row intercropping (WR). Error bars represent the standard deviation.

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 1). 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 second-crop species significantly affected soybean yield in both years (Table 2). Soybean yield was the highest with lentils 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 2). Alternate-row intercropping increased soybean yield on average by 31% compared to that in within-row intercropping in 2018.

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: Species and spatial arrangement effects on soybean yield and weed dry matter at crop maturity within intercropping treatments. When interaction was non-significant (N.S.; p-value > 0.1), models were refitted to a simpler additive model and results displayed. Significance levels are: . p-value <0.1, * <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)		Weed dry matter (t.ha-1)	
	2018	2019	2018	2019
Species significance	<0,001 ***	0,026 *	<0,001 ***	<0,001 ***
Lentil-soybean	2,18 a	0,84 a	3,55 a	4,18 a
Sorghum-soybean	1,69 ab	0,61 ab	1,30 b	2,11 b
Sunflower-soybean	1,22 b	0,42 b	1,66 b	1,60 b
Buckwheat-soybean	0,60 c	0,74 ab	0,34 c	2,52 b
Spatial arrangement significance	0,011 *	0,128	0,419	0,500
Alternate-row	1,62 a	0,73	1,68	2,47
Within-row	1,24 b	0,58	1,75	2,73
Interaction significance	N.S.	N.S.	0.080 .	N.S.

Soybean yield decreased with the increase in second-crop dry matter measured at soybean flowering (Figure 2). Lentil had the lowest crop biomass in both years and was associated with the lowest yield reduction. Sorghum had a relatively stable biomass in both years, whereas buckwheat and sunflower had contrasting biomass in 2018 and 2019, which influenced the level of yield reduction. The relationship linking soybean yield to the second-crop biomass at soybean flowering was stronger in 2018 than in 2019 (Figure 2).

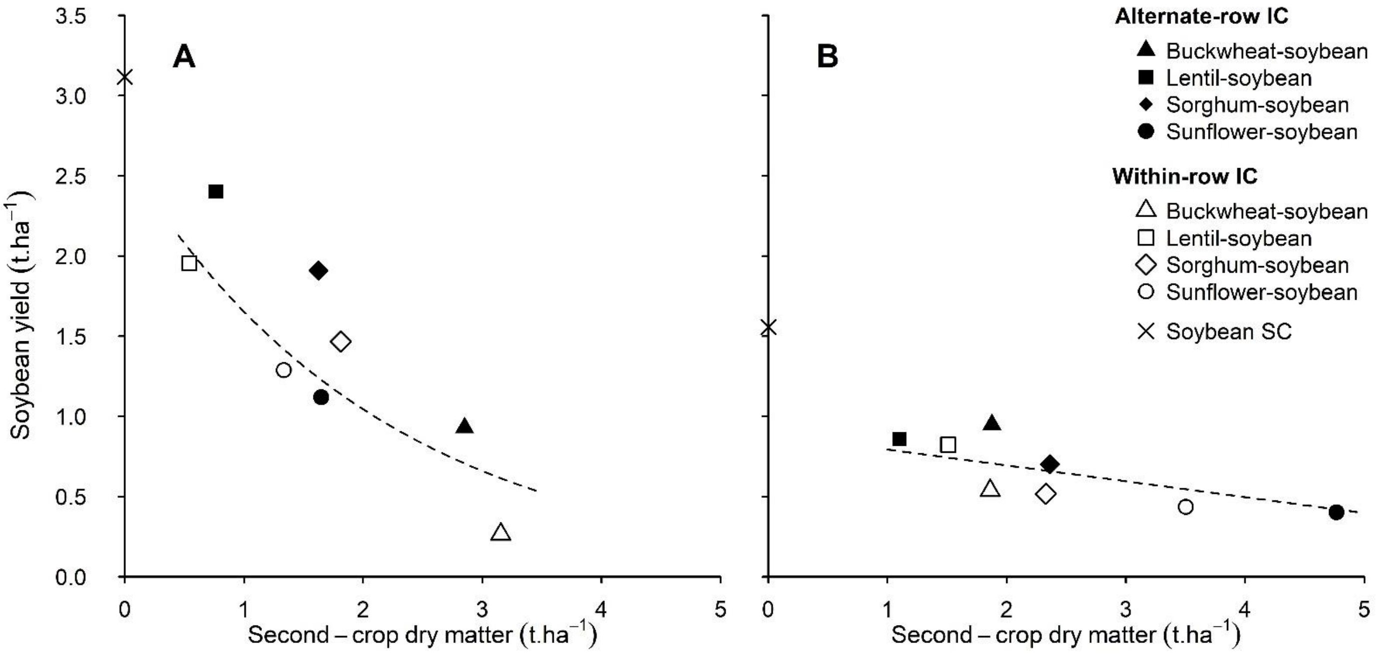

Figure 2: Soybean yield as a response to second-crop dry matter at soybean flowering. IC stands for intercropping, and SC stands for sole crop. **A** corresponds to 2018 and **B** to 2019. Each symbol corresponds to the averaged values of each treatment. The dashed lines represent the regressions fitted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

3.2 Weed biomass

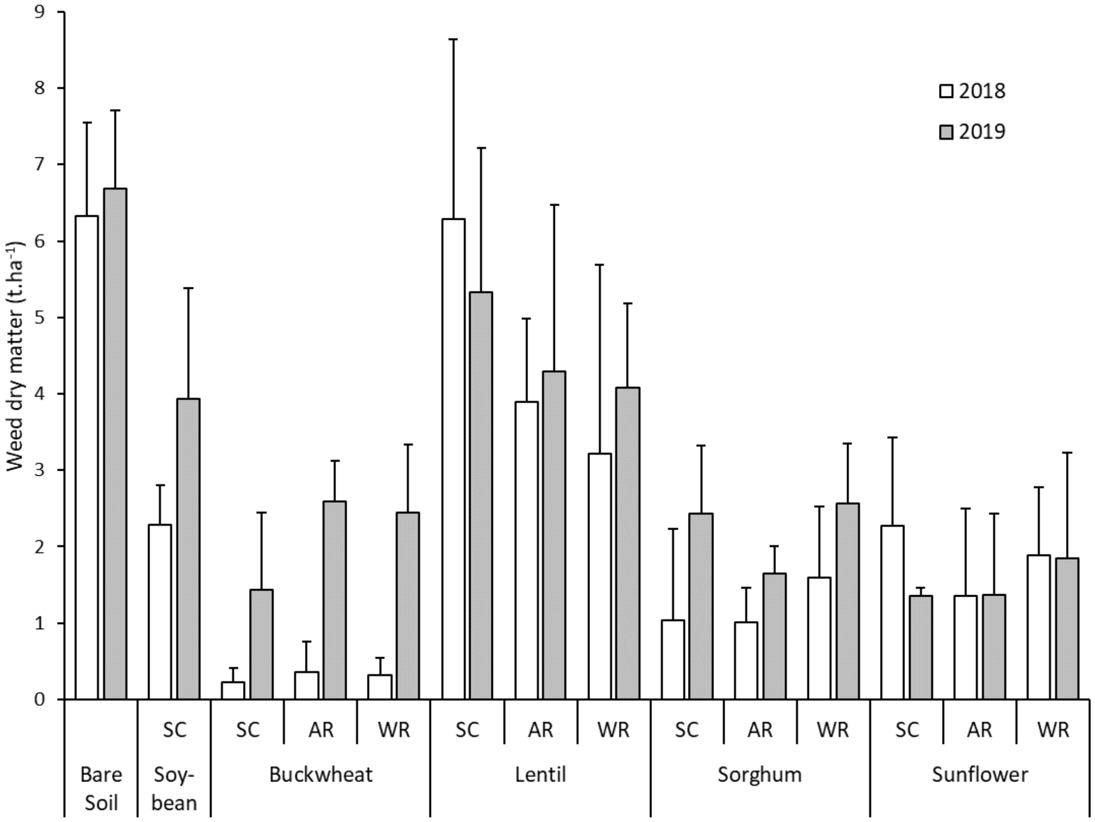

Figure 3: Weed dry matter at crop harvest for all treatments. SC stands for sole crop, AR for alternate-row intercropping with soybean and WR for within-row intercropping with soybean. Error bars represent the standard deviation.

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 (Figure 3). The lentil sole crop had the highest average weed biomass, with more than 5 t.ha^{-1} in both years. At 0.22 t.ha^{-1}, buckwheat had the lowest average weed biomass value in 2018, while in 2019, it was sunflower, with 1.35 t.ha^{-1}. 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 species effect on weed biomass in the intercropping treatments was significant in both years (Table 2). The lentil-soybean IC 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 2).

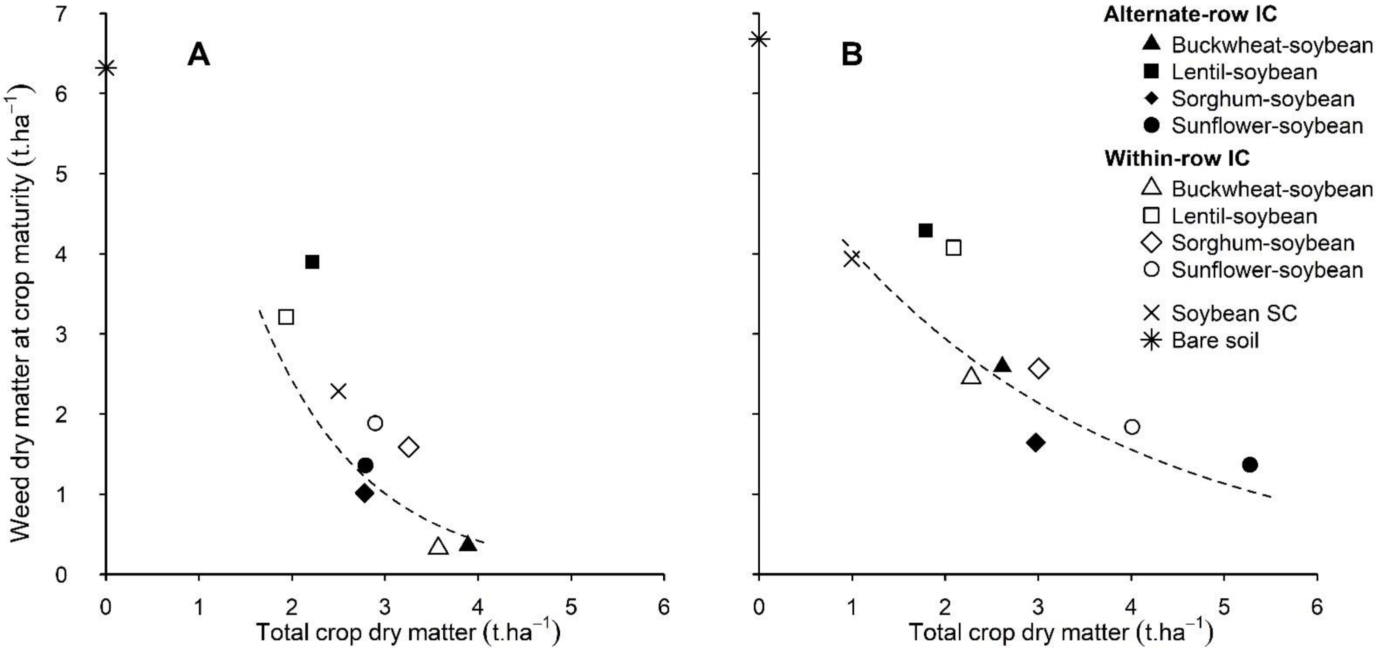

Figure 4: Weed dry matter at harvest as a response to total crop dry matter at soybean flowering. IC stands for intercropping and SC for sole crop. **A** corresponds to 2018 and **B** to 2019. Each symbol corresponds to the averaged values of each treatment. The dashed lines represent the regressions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

Overall, weed dry matter decreased with the increasing accumulation of dry matter by crops measured at soybean flowering (Figure 4). The low competitive ability of lentil-soybean intercropping was associated with a low crop biomass in both years. The other IC combinations had higher weed control ability due to their higher crop biomass. The buckwheat-soybean IC produced less total biomass in 2019 than in 2018, while the sunflower-soybean IC showed the opposite trend. Thus, the level of weed control in a given intercropping treatment differed between years based on the level of crop biomass. In addition, the weed biomass decreased as the second-crop dry matter proportion in the total crop biomass at soybean flowering increased (Figure 5). In 2018, the second-crop dry matter proportion varied from 28% to 88% in lentil-soybean WR and buckwheat-soybean WR, respectively. In 2019, the range was smaller, from 62% in lentil-soybean AR to 90% in sunflower-soybean AR.

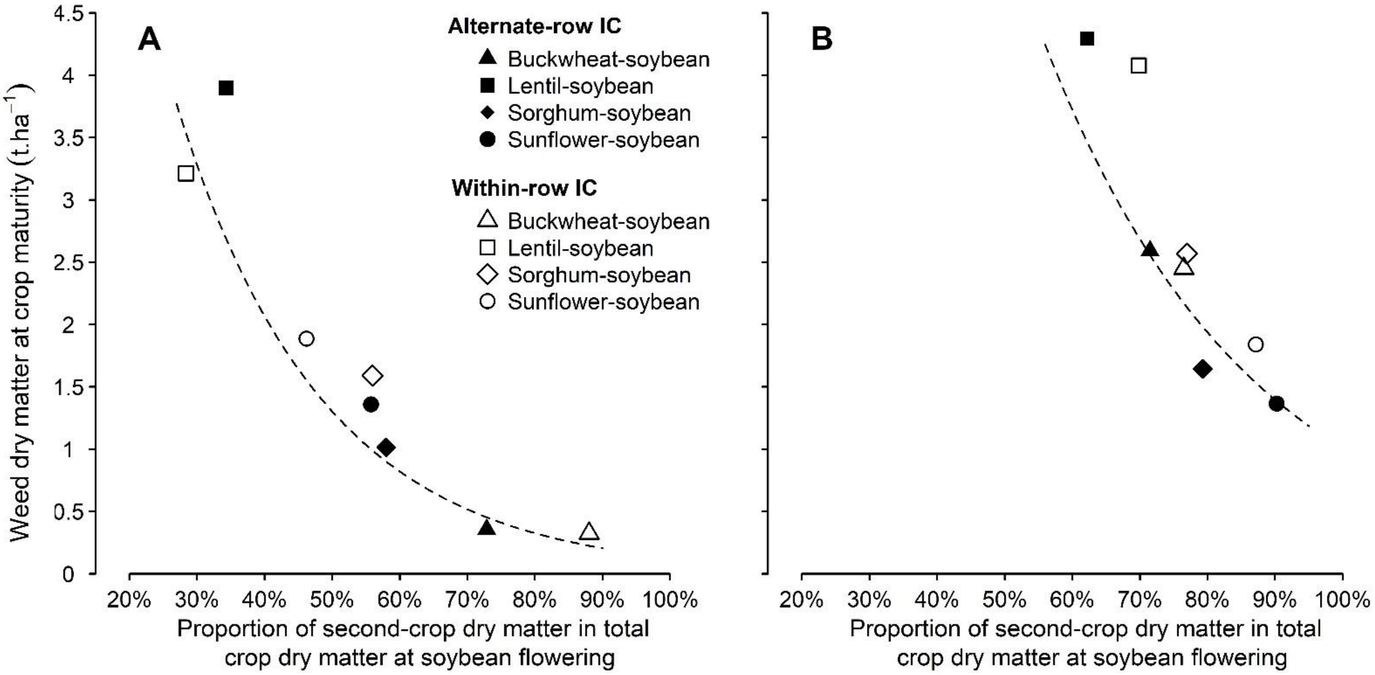

Figure 5: Response of weed dry matter at crop maturity to second-crop dry matter proportion of the total intercropped dry matter at soybean flowering. IC stands for intercropping. **A** corresponds to 2018 and **B** to 2019. Each symbol corresponds to the averaged values of each treatment. The dashed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

3.3 Trade-off between soybean production and weed control services

When considering within-row intercropping, the soybean production service, expressed as the soybean yield ratio, appeared to be related to the weed control service, expressed as the ratio of weed biomass present in the intercropping treatments to that in the soybean sole crop (Figure 6A).

Specifically, the higher the level of the weed control service, the stronger the disservice to soybean grain yield. However, in the case of alternate-row intercropping, two situations were observed. On the one hand, sunflower-soybean AR and lentil-soybean AR followed approximately the same trend as WR intercropping. On the other hand, sorghum-soybean AR and buckwheat-soybean AR had higher soybean yield ratios than their respective within-row intercropping treatments, with similar weed ratios.

Second-crop relative productivity 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 service had high second-crop relative productivity. Thus, as weed control increased in the intercropping treatments, soybean grain production decreased, but the second-crop yield ratio increased.

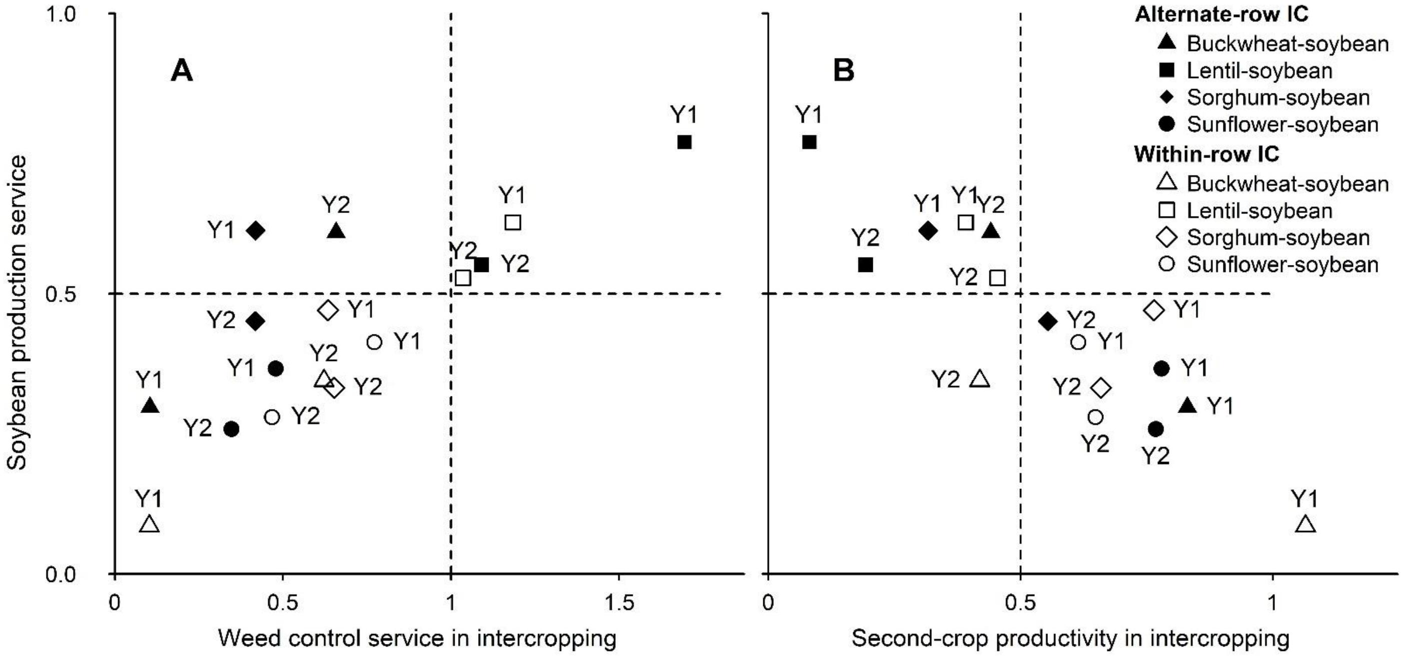

Figure 6: Soybean production service of intercropping treatments in relation to their weed control service (A) and to the second-crop relative productivity (B). The soybean production service value was obtained as the ratio of the soybean yield in a given intercropping treatment to the soybean yield in the sole crop. The weed control service value was obtained with the same ratio but using the final weed biomass. Second-crop relative productivity corresponds to the yield of the second crop in a given intercropping divided by the yield of the corresponding sole crop. 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.

Discussion

Our study highlighted that the delivery of services such as soybean yield or weed suppression depended on management options. The choice of the intercropped species and the spatial arrangement are key levers for influencing the delivery of these services. Thanks to the range of contrasting species studied, we observed a strong negative correlation between soybean yield and weed suppression. A key result is that the trade-off between the two types of service can be managed through spatial arrangement in some situations.

4.1 Weed control

The weed competition potential was high in our study. Furthermore, no mechanical or chemical control was applied. We demonstrate that intercropping soybean with another species seems to be a relevant practice for improving weed control, but it depends greatly on the choice of the second crop. Lentil intercropped with soybean was not able to improve weed control, whereas intercropping with the other species (buckwheat, sorghum and sunflower) reduced weed biomass by 23 to 90% compared to that in the soybean sole crop (Figure 6). The overall intercrop biomass production was important for competitiveness against weeds. Indeed, our results showed that an increase in the total intercropped biomass was associated with a reduced final weed biomass (Figure 4), which is in agreement with previous studies on intercropping (e.g.: Corre-Hellou et al., 2011; Gomez and Gurevitch, 1998) and on cover crops (e.g.: Finney et al., 2016; MacLaren et al., 2019). Additionally, an increase in the proportion of the second crop dry matter in the total intercropping dry matter was associated with weed biomass suppression (Figure 5). This is in accordance with the findings of cover crop studies where the augmentation of the proportion of non-legume biomass in mixtures was linked to higher weed biomass reduction (Hayden et al., 2014; MacLaren et al., 2019). Several mechanisms are involved in weed-crop competition, such as early N, light and moisture capture (Corre-Hellou et al., 2011; MacLaren et al., 2019). Early aboveground growth and relative crop height compared to weed height are important factors in weed-crop competition for light (Hock et al., 2006; Violle et al., 2009). Crop competition with weeds also depends on the nitrogen uptake capacity of the crop. Crops that are able to obtain a large amount of N from sources other than the soil N pool (seed N and atmospheric N_2) leave more soil resources available for weed development (Corre-Hellou et al., 2011). The highly diverse crops chosen for this study were characterised by their different resource acquisition strategies and different levels of biomass production potential, which undoubtedly affected weed control. Lentil, which was the least competitive against weeds, is known for its low biomass production, short canopy, and ability to fix a great part of its own nitrogen requirements, contributing to its low weed competitiveness ability (Erskine et al., 2011). In contrast, buckwheat was the most competitive species in our study and is known for its early thick canopy development, production of allelopathic compounds and competitiveness for soil resources (Falquet et al., 2015).

No effect of spatial arrangement was found on the weed control service (Table 2). Due to the differences in the aboveground architecture of the plants chosen for intercropping, within-row mixtures could have been expected to provide more regular soil shading than alternate rows of crops, especially for crops with low sowing densities. However, both spatial arrangements were established in rows separated by the same distance, with no weed control of any kind. Hence, weeds had the same opportunity to develop between rows before canopy closure, and their biomass accumulation was probably more related to the ability of certain species to close the canopy quickly than to an allegedly more homogeneous canopy structure.

4.2 Soybean production

We demonstrated that weed growth was affected by the second-crop, and the same was true for soybean. Soybean production was affected by the level of competition from the second-crop (Figure 2). Even though the year effect was strong, with lower soybean yield in 2019, lentil, sorghum and sunflower had a consistent effect on soybean yield. The buckwheat effect changed between the first and second years mainly due to its weaker and slower establishment in 2019 (author observations). Soybean, known to have low early growth at the beginning of its cropping cycle, can easily be outcompeted by an early fast-growing crop such as buckwheat (Hock et al., 2006; Jannink et al., 2000). This certainly occurred in 2018 and to a lesser extent in 2019. The early competitiveness of sorghum, lentil and sunflower, considered rather poor, may not have been the most decisive factor in their competition against soybean. Thus, a second crop with relatively slow early growth will probably be better tolerated by soybean than one with early vigour. Geier et al. (1996) concluded that, in the case of sunflower-soybean interaction, light interception by sunflower above the soybean canopy was an important component explaining sunflower interference in soybean growth. Looking at crop characteristics, sunflower was the tallest; buckwheat, sorghum and soybean were more or less the same height; and lentil was the shortest (data not shown). Thus, as suggested by the ranking of the second crops in terms of competitiveness, the relative heights of the species might explain the differences in soybean productivity among intercropping treatments, as light extinction for a given plant is related to neighbour height (Violle et al., 2009).

Unlike weed control, soybean production was affected by the spatial arrangement (Table 2). Globally, soybean was more productive in alternate-row. Thus, resource acquisition by soybean could be improved by the spatial separation of soybean from the second crop. In contrast, the second-crop yield tended to be higher in within-row intercropping, suggesting that soybean was generally less competitive than the second 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, therefore delaying interactions (positive or negative) until one species was able to reach the resource pool of the other. By extension, in the alternate-row design, row spacing is expected to influence the timing of interactions between crops and the resulting services.

4.3 Interactions between services

As explained above, the same crop characteristics and mechanisms may be involved in competition against both weeds and soybeans, thus contributing to weed control and impeding soybean production. This is in line with the trade-off we highlighted (Figure 6) and with the findings of den Hollander et al. (2007), who 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 and concluded that competition for light was the most important component between the cover crop and the main crop. They also identified clover species height and soil cover as two important traits involved in weed control. Lorin (2015) highlighted the importance of the same indicator, the living mulch biomass growth rate, in competition against both weeds and winter oilseed rape. This indicator was also related to traits such as vertical growth rate and leaf area. Hence, if similar traits are involved in both weed control and competition against the main crop, one might expect that a crop that is more competitive than the main crop against weeds as a sole crop will also be competitive against the main crop. Consequently, a ranking of sole crops on their ability to control weed development might be helpful in anticipating competition between crops. Additionally, trait-based approaches could be used to better anticipate service delivery and trade-offs (Damour et al., 2014; Gaba et al., 2015; Malézieux et al., 2009).

The trade-off between the weed control and soybean production services seems inevitable and difficult to manage. Nevertheless, we demonstrated that, through appropriate management options, it is possible to reduce the opposition between these services. For the same level of weed control, the spatial arrangement (alternate-row) limited the reduction in soybean yield, but the response to this arrangement differed among species (Figure 6).

There was also an antagonistic relationship between soybean production and second-crop production, as shown by the yield ratio values (Figure 6). However, this can be seen as positive for farmers because the second crop can improve the total yield at the field level and provide an additional service – production insurance – in the case of a low yield from the main crop.

Conclusion

Intercropping seems to be a promising tool for facilitating cropping system diversification and thereby providing multiple services. Nevertheless, due to the potential antagonistic relationships between these services, it is necessary to clearly define and rank the expectations for intercropping systems according to their relative importance to farmers; this should help in species choice. Moreover, relevant combinations of different management options can be designed to moderate these antagonistic relationships and achieve multiple services. 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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