

Is sunflower-soybean intercropping an efficient solution for increasing natural resources use efficiency and yield production?

Hélène TRIBOUILLOIS¹, Philippe CRISTANTE², André ESTRAGNAT², David CHAMPLOU¹, Grégory VERICEL¹, Nathalie LANDE², Laurent BEDOUSSAC^{1,3} and Eric JUSTES¹

¹INRA, UMR AGIR, 31326 CASTANET TOLOSAN, France, Eric.Justes@toulouse.inra.fr

²CETIOM, Avenue Lucien Bretignières, 78850 THIVERVAL GRIGNON, France, lande@cetiom.fr

³ENFA, UMR AGIR, 31326 CASTANET TOLOSAN, France, Laurent.Bedoussac@toulouse.inra.fr

ABSTRACT

- Intercropping (IC) is the simultaneous growing of two or more species in the same field for a significant period. Intercropping could be considered as a way of ecological intensification allowing the increase of natural resources use efficiency by positive interspecific interactions. Previous studies on grain legume-cereal intercrops have shown advantages in low input systems such as the increase of the overall yield and the grain protein concentration improvement of the cereal. Few papers dealing with sunflower-soybean intercropping are available in the literature; they mainly come from African and Asian conditions. The land equivalent ratio (LER) for yield or gross margin reported for sunflower-soybean intercrops was generally high (1.2 to 1.6), indicating the agronomical and economic advantages of intercrops in comparison to sunflower and soybean sole crops. One of the interests of sunflower-soybean intercrops is based on the ability of the soybean to get the atmospheric nitrogen thanks to its symbiotic fixation, leaving more soil mineral nitrogen available per sunflower plant. Moreover, the two rooting systems (deep for sunflower and shallower for soybean) can explore different soil layers which could lead to niche resource complementarity for nutrients and water. The aim of this study was to analyze the dynamical functioning of sunflower-soybean intercrops and their performances in order to determine their efficiency and the conditions to maximize resources use.
- Three field experiments were carried out in South-West of France at CETIOM and INRA experimental stations in 2010 and 2011. CETIOM experiment was carried out in non-limiting conditions for water and nitrogen. The two other experiments carried out at INRA were cropped in low inputs conditions without irrigation and with only one herbicide spreading at sowing. Two spatial row design corresponding to two structures (2/2 and 2/4 rows, i.e. 2 adjacent rows of each specie and 2 sunflower row alternated with 4 soybean rows) and two types of cultivar (early and late) of each specie were studied. Each crop was also grown in sole crop in order to evaluate the resource use efficiency based on the land equivalent ratio. In intercrop and sole crop, each crop was sown at the same row density. The biomass production, light absorption, N uptake and N₂ fixation, and crop yield formation components of both species were measured during the crop cycle but only results obtained at harvest are presented here.
- Our results clearly indicated that the best performances of sunflower-soybean intercrops were obtained in low inputs conditions. When crops were conducted in high inputs conditions, the sole crops were found more efficient than intercrops (LER lower or equal to 1) due to the strong interspecific competitions of sunflower on soybean in particular for light. Intercropped sunflower always presented a competitive advantage (partial LER higher than its relative density partial LER) on the intercropped soybean leading to low soybean yields. As hypothesized, the N₂ fixation rate was higher in the intercropped soybean than the sole crop. The four soybean rows alternated with two sunflower rows was the most efficient spatial organization in order to re-equilibrate interspecific competitions and optimize natural resources use. Intercropping the late soybean cultivar with the earliest sunflower allowed obtaining the best results. In that case, the overall yield was higher in intercrops than for the two sole crops average; the highest LER was 1.24, indicating a true potential of sunflower-soybean intercrop for yield production in rainfed conditions.
- Our work confirms that intercrops are more efficient in low inputs conditions. This clearly emphasized that there are various possibilities for improving the use of abiotic resources, such as exploring precocity, aerial architecture of genotypes (sunflower and soybean), but also adapting intercrop row structure and management. Further research based on genotype-environment interactions analysis is needed for optimizing interspecific complementarities between both species in intercrop.
- Intraspecific and interspecific interactions were changing within the growth cycle and depended on intercrop structure. This highlights the needs for further researches based on functional intercrop analysis under various conditions and with different sunflower and soybean genotypes.

Key words: sunflower – intercrop – soybean - interspecific interactions - Land Equivalent Ratio (LER)

INTRODUCTION

Intercropping (IC) is the simultaneous growing of two or more species in the same field for a significant period (Willey and Osiru, 1972). Intercropping could be considered as a way of ecological intensification allowing the increase of natural resources use efficiency by positive interspecific interactions (Altieri, 1999; Hauggard-Nielsen and Jensen, 2005). Previous studies have shown advantages offered by grain legume-cereal intercrops in low input systems such as the overall yield increase and the grain protein concentration improvement of the cereal (e.g. Bedoussac and Justes, 2010). Few papers dealing with sunflower-soybean intercropping are available in the literature; they mainly come from African and Asian conditions. The land equivalent ratio (LER) reported for sunflower-soybean yield and gross margin for intercrops was generally high (1.2 to 1.6), indicating the agronomical and economic advantages of intercrops in comparison to sunflower and soybean sole crops (Shivaramu and Shivashankar, 1992; Mondal et al., 1998; Olowe and Adebimpe, 2009). To our knowledge, for temperate climates, the main researches were carried out in Argentina; the LER was found lower with values of ca. 1.05 (Currudo, thesis 2007). One of the interests of sunflower-soybean intercrops is based on the ability of the soybean to get the atmospheric nitrogen thanks to its symbiotic fixation, leaving more soil mineral nitrogen available per sunflower plant. Moreover, the two rooting systems (deep for sunflower and shallower for soybean) can explore different soil layers which could lead to niche resource complementarity for nutrients and water. The aim of this study was to analyze the dynamical functioning of sunflower-soybean intercrops and their performances in order to determine their efficiency and the conditions to maximize the resources use.

MATERIALS AND METHODS

Three field experiments were carried out in South-Western France at experimental stations of CETIOM and INRA in 2010 and 2011 in South-Eastern France. The main field trial characteristics are presented in table 1.

Site	Year	Soybean cultivar	Sunflower cultivar	Spatial row structure	Cover crops	Irrigation	Nitrogen conditions	
							Fertilization	Initial soil N content
INRA Auzeville	2010	Isidor (Soy1) Ecuador (Soy2)	Fabiola (Sun1) Melody (Sun2)	Soybean sole crop Sunflower sole crop 2/2 2/4	No	No irrigation	Partial fertilization (soybean)	76 kg N/ha
CETIOM En Crambade	2010	Ecuador (Soy2)	Melody (Sun2)	Soybean sole crop Sunflower sole crop 2/2 2/4	No	Irrigation (30mm and 20mm)	No fertilizer	361 kg N/ha
INRA Auzeville	2011	Ecuador (Soy2)	ES Ethic (Sun3)	Soybean sole crop Sunflower sole crop 2/4	C1 : Phacelia/Oat C2 : No	No irrigation	No fertilizer	C1 : 62 kg N/ha C2 : 82 kg N/ha

Table 1. Experimental designs and crop conditions for the three field trials

In 2010, INRA experiment tested two soybean cultivars (Isidor earlier than Ecuador) and two sunflower cultivars (Fabiola earlier than Melody). In 2011, a much earlier sunflower cultivar (ES Ethic) was chosen in order to increase the gap for the crop developmental stages between an early sunflower and a late soybean. In 2010, two spatial row structures were evaluated: i) a 2/2 structure meaning 2 adjacent rows of each species and ii) a 2/4 structure meaning 2 sunflower rows alternated with 4 soybean rows. CETIOM experiment was non-limiting for water and nitrogen (irrigated and high level of nitrogen available). The others trials had a partial fertilization on soybean, corresponding to 150 kg N/ha, in order to compensate the unusual inefficiency of the inoculation of symbiotic bacteria (Rhizobia) at sowing. Cover crops effect was evaluated in INRA experiment in 2011 in which a cover crop (phacelia and oat mixture) was established before sowing (field C1) in order to reduce nitrate leaching before summer crops. The other part (field C2) stayed a bare soil during the fallow period. The sowing of soybean and sunflower were carried out at the same time at the end of May or beginning of June. Crops were harvested in two times because of the maturity gap between sunflower (mid-September) and soybean (end of September to beginning of October). Each crop was also grown in sole crop in each experiment in order to compare them to intercrops. In both sole crops and intercrops species density on the row was similar.

Different measurements were made in order to evaluate biomass production, yield and resources acquisition. In this framework, biomass production, light absorption, N uptake, N₂ fixation, and crop yield formation components of both species were measured at 3 sampling dates (sunflower anthesis and

maturity and soybean harvest) but only data obtained at harvest of sunflower and soybean are presented here. The land equivalent ratio (Willey and Osiru, 1972) was used to evaluate the resource use efficiency. The land equivalent ratio, or LER, is defined as the relative land area required growing sole crops to produce the yields achieved in intercrops. The LER of species *i* intercropped with species *j* is equal to the sum of both partial LER (LER_{*i*} and LER_{*j*}) and can be calculated thanks to the following formula:

$$LER_{ij} = LER_i + LER_j$$

$$LER_i = Y_{i-IC} / Y_{i-SC} \text{ and } LER_j = Y_{j-IC} / Y_{j-SC}$$

where Y_{i-SC} and Y_{j-SC} are yields per unit area of sole crops *i* and *j* respectively, and Y_{i-IC} and Y_{j-IC} those in intercrops.

The Land Equivalent Ratio is a simple but relevant tool to use and interpret the intercrop efficiency. When LER is higher than 1, that means that less area is needed in intercrop to produce the same yield for both species. Moreover, this can be interpreted as the fact the intercrop is much more efficient in terms of resources use than sole crops. Conversely, when LER is lower than 1, resources are used more efficiently by sole crops than by intercrops, which can be occurred by strong competition for resources within intercropped species. In order to know what were the interactions in intercrop and notably the competitions between both species, partial LER can be interpreted in relation to density of each species in the intercrop.

In order to know if soybean-sunflower intercropping has an influence on symbiotic nitrogen fixation of soybean, the rate of nitrogen acquired from atmosphere (%Ndfa) was calculated as follows:

$$\%Ndfa = 100 * (\delta^{15}N_{ref} - \delta^{15}N_{measured}) / (\delta^{15}N_{ref} - \beta)$$

This formula had been developed by Shearer and Khol (1986) and is based on differences in ¹⁵N isotope, expressed in delta (δ), between a nitrogen-fixing crop (legume) and a non nitrogen-fixing crop. In this formula, $\delta^{15}N_{ref}$ (reference isotopic enrichment) represents the ¹⁵N in shoots of the reference non nitrogen-fixing crop, here sunflower, corresponding to an estimation of soil $\delta^{15}N$. The $\delta^{15}N_{measured}$ represents the isotopic composition of soybean shoots. The correction factor β is reflecting the $\delta^{15}N$ of legume shoots that are fully dependent upon N₂ fixation. For soybean, β was taken equal to -0.98‰.

The analysis of variance was performed using Statgraphic software, with all measured variables assuming to be normally distributed. The significance of difference between treatments was estimated using Newman-Keuls test at a 0.05 probability level.

RESULTS

Grain yield

The total intercrop yields (soybean yield and sunflower yield) were all higher than sole crop soybean yield but were all lower than sole crop sunflower yield for all experiments (Figure 1). Moreover, for the INRA 2010 experiment, the intercrop yields of the 2/4 structure were all higher than those of the 2/2 structure, even if these differences were not statically significant. However, inversed results were obtained in the CETIOM 2010 experiment; i.e. the 2/2 structure had a better yield than the 2/4 structure. That can be explained by the fact that these “high” input conditions (high mineral nitrogen level and irrigation based on sunflower needs), increased the advantage for the sunflower: it produced more dry matter and more grains per plant which increase the competition for light and finally strongly affect the soybean production per plant.

There was a difference of compartment between soybean rows in structure 2/4. Indeed, central rows tended to have higher yield than soybean rows next to sunflower rows caused by shadow effect and/or water and soil nutrients acquisition, even if these differences were not significant. Then, in average soybean rows yield was higher in the 2/4 structure than in the 2/2 structure, thanks to the central rows “yield-catching up”. The interspecific competition of sunflower on soybean was clearly higher than the interspecific competition of soybean on sunflower. This phenomenon was also observed for the two other experiments, indicating that the sunflower had systematically an advantage to be cultivated in intercrop due to a lowest interspecific competition than intraspecific competition in sole sunflower crop.

Furthermore, a cultivar effect was observed in the 2010 INRA trial. Late soybean cultivar (Soy2), presented higher yield compared to early soybean cultivar (Soy1). For sunflower, early cultivar (Sun1) seems better adapted to intercropping with soybean as indicated by a better yield than late cultivar (Sun2).

In 2011, no significant yield difference was observed between soybean and sunflower intercrops with or without phacelia and oat preceding cover crop mixture.

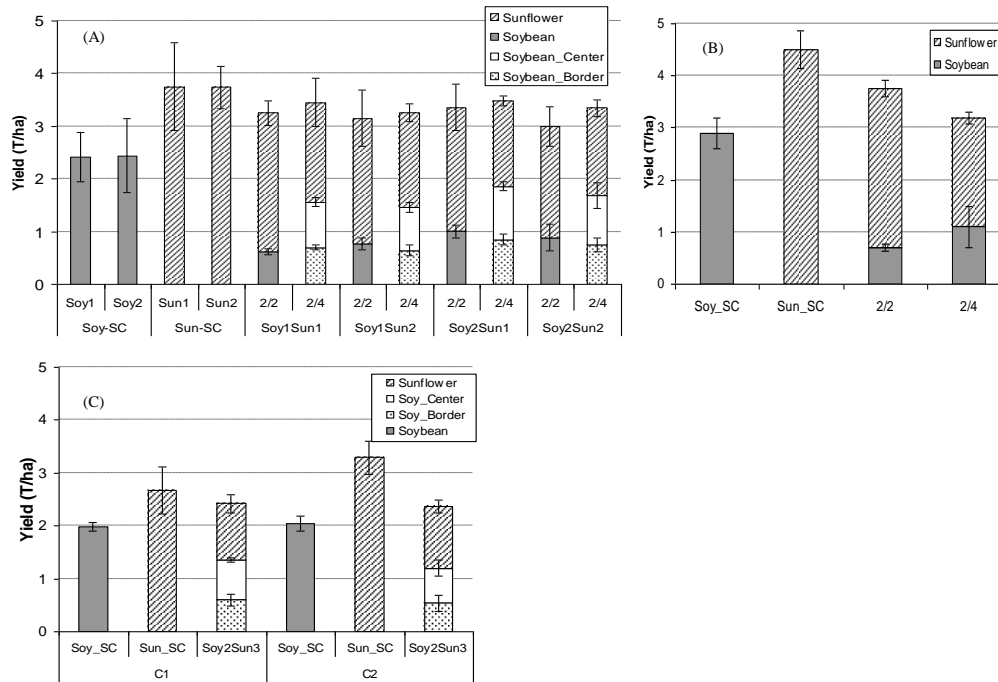


Fig. 1. Grain yield for the 3 experiments (A): INRA Auzeville 2010; (B): CETIOM En Crambade 2010; (C): INRA Auzeville 2011. SC indicates sole crop.

Sunflower partial LER depending on soybean partial LER whatever the intercrop row structure

LER of soybean-sunflower 2/2 structure were slightly lower than 1 except for Soy2Sun1 (Figure 2), meaning that this structure did not performed well in terms of resources use efficiency compared to sole crops due high interspecific competition of sunflower on soybean. However, LER of 2/4 structure were mostly higher than 1 and the highest LER was obtained with the Soy2-Sun1 intercrop (LER=1.24).

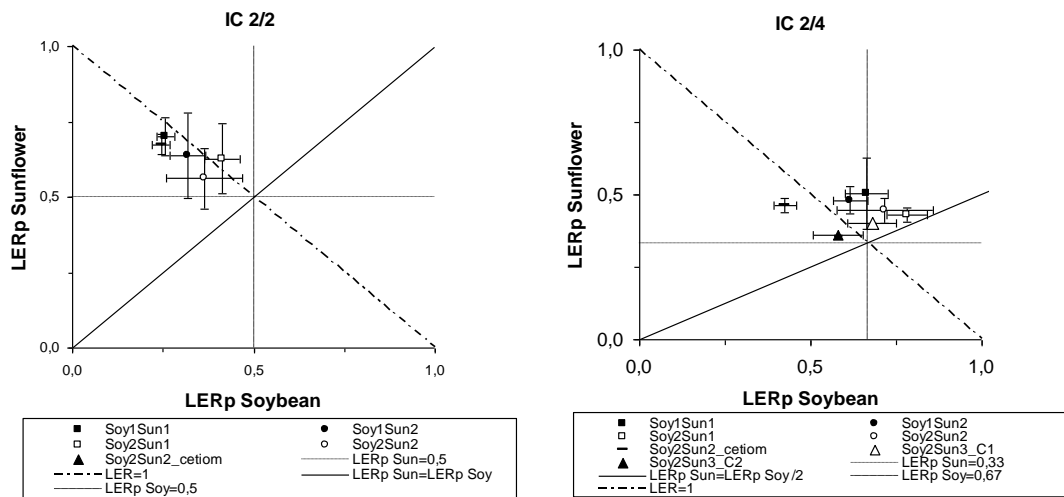


Fig. 2. Sunflower partial LER as a function of soybean partial LER for both intercrop row structure (2/2 on the left and 2/4 on the right)

The structure alternating 2 sunflower rows and 4 soybean rows seems to be the most efficient to increase the total grain yield per hectare. In order to know the contribution of each specie to the total grain yield, the partial LER were confronted (Figure 2). In 2/2 and 2/4 structures, sunflower (any cultivar) had an advantage being grown in intercrop as indicated by its partial LER values higher than its theoretical reference based on plant density (respectively 0.5 for 2/2 and 0.33 for 2/4 structures). On the contrary, soybean was penalized when intercropped due to sunflower competition in the 2/2 structure as

indicated by partial LER values lower than their reference (0.24 to 0.41). However, in the 2/4 structure, all partial LER values of soybean were close to or higher than the reference (0.62 to 0.78), excepted for the CETIOM experiment where it was clearly lower (0.43). This means that in the 2/4 structure, a complementarity between the two crops occurred for resources use in the INRA 2010 experiment.

Nitrogen acquisition in crops and intercrops at harvest

In CETIOM 2010 experiment, sunflower acquired more nitrogen than in 2010 INRA experiment, both in the sole crop and the intercrop due to the higher mineral nitrogen in soil at sowing. This result explains why the grain yield was higher in CETIOM 2010 trial. Intercropping allowed sunflower to acquire high level of nitrogen which was clearly detrimental for the soybean growth.

In INRA 2010 experiment (results not shown), intercrops acquired more nitrogen than sunflower sole crop but less than soybean sole crop. Soy2Sun1 in 2/4 structure acquired the most N amount which could explain the highest grain yield and LER higher than 1. However, these results did not correspond to those found in CETIOM trial. Indeed, 2/4 structure gained less nitrogen than 2/2 structure and both intercrops acquired less nitrogen than both sole crops (Figure 3). This is certainly due to the high competition between the two species in high inputs conditions and could explain LER values lower than 1.

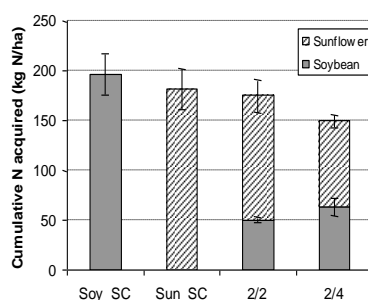


Fig. 3. Nitrogen acquisition in CETIOM 2010 experiment

Atmospheric nitrogen fixation of soybean

Usually the symbiotic fixation rate is maximal at the beginning of grain filling and stays to a high level until it gets close to the physiological maturity. The symbiotic fixation rate of soybean had been measured in CETIOM 2010 experiment (Figure 4). Soybean in 2/2 row structure and border rows in 2/4 structure had a higher symbiotic fixation rate (57%) than soybean in central rows in 2/4 (22%) and particularly higher than in sole crop which was very low (12%) and these differences were significant (Newman-Keuls test at $P < 0.05$). The low N_2 fixation rate in soybean sole crop was certainly due to the high initial soil mineral N content (361 kg N/ha). The highest soybean N_2 fixation rate in intercrop was due to the effect of sunflower on the reduction of soil mineral nitrogen. Indeed, Sunflower is much more competitive than soybean for acquiring mineral nitrogen in soil, which had probably strongly reduced the soil mineral nitrogen at the vicinity of soybean rows closed to sunflower rows which consequently forced soybean to increase its nitrogen fixation.

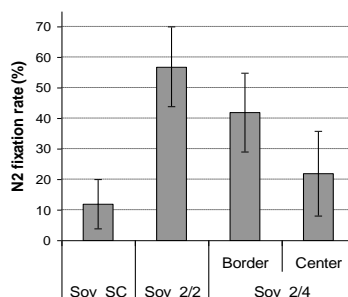


Fig.4. Atmospheric nitrogen fixation rate of soybean on CETIOM 2010 experiment

DISCUSSION AND CONCLUSION

It is likely that two intercropped species have grain yield advantage as a result of complementarity in terms of resources use efficiency by crops. Our results indicate that intercrops tend to have higher yield than soybean sole crop but lower or equal to those of sunflower sole crop. Therefore it can be

hypothesized that strong competitions occurred for the use of water, light and nutrients resources in intercrops. The interspecific competition would be probably higher than the intraspecific competition within soybean in sole crop. In the present study sunflower was clearly the dominant component of the intercrop in all treatments in the 2/2 structure. Then sunflower is more involved into intercrop yield than soybean. Similar results have been brought by Shivaramu and Shivashankar (1992) and Olowe and Adebimpe (2009). In a structure composed by 2 sunflower rows and 4 soybean rows, LER were higher than 1, indicating a better use of resources by the intercrop compared to sole crops. This intercrop structure allowed favouring a niche complementarity for resources use thanks to different above and below ground growth and morphological characteristics of intercropped species. It also appeared that soybean-sunflower intercrops were less efficient in terms of resources use with irrigation because of the higher sunflower development and so the competition exerted on soybean. Similar results were found with “high” soil mineral nitrogen level and then in high inputs conditions.

Intercrops with a legume are often presumed to be more efficient for N acquisition thanks to the potential complementary use of nitrogen sources (soil and air). Indeed, legumes have the ability to increase their atmospheric nitrogen fixation rate in intercrop to fulfil their demand (e.g. Bedoussac and Justes, 2010). In the present study the complementary for nitrogen acquisition did not always occurred due to the high level of mineral nitrogen at sowing. The total amount of N fixed by soybean in intercrops varied according to the structure with lower amount fixed in 2/2 structure and in 2/4 structure for the border rows. Sunflower being more competitive for mineral nitrogen acquisition, the mineral content in the soil probably decreased and then soybean rows close to the sunflower had to increase their N₂ fixation rate to fulfil soybean demand. This suggests that the lower the initial soil mineral content, the higher the complementarity within the two species occurs (Bedoussac and Justes, 2010).

Choice of intercropped cultivars seems a key to provide a better complementarity between sunflower and soybean. Intercropping a late soybean with a early sunflower (Soy2Sun1) presented the best LER for grain yield and nitrogen acquisition, suggesting a potential temporal complementarity favouring soybean grain ripening without reducing sunflower productivity, as ever shown by Olowe and Adebimpe (2009).

Surprisingly, cropping a cover crop before sunflower-soybean intercrop reduced sunflower grain yield compared to bare soil situation, probably due a slight decrease of N availability.

In the present study a range of different situations were tested in order to assess the best performances of soybean-sunflower intercrop leading to efficient resources use acquisition and best grain yields. Despite the variability in intercrop efficiency our results indicate that the proportion of both crops and the row structure are key factors, particularly for optimizing light complementarity. Thus, further works are needed to assess other row structures for obtaining the best complementarities.

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