Chapter 3
Eco-Functional Intensification by Cereal-Grain Legume Intercropping in Organic Farming Systems for Increased Yields, Reduced Weeds and Improved Grain Protein Concentration

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Abstract Intercropping, i.e., simultaneously growing two (or more) species in the same field for a significant period of time but without necessarily concomitant sowing or harvest, is a practice aimed at eco-functional intensification.

This chapter integrates a comprehensive amount of original data from field experiments conducted since 2001 on spring and winter cereal-grain legume intercrops in experimental and farm contexts in France and Denmark, in an attempt to generalise the findings and draw up common guidelines. We have shown that intercrops appear to be a useful agronomic solution for organic arable cropping,

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particularly in low-N input systems, to enhance: (i) yields because of a general improvement of environmental resource use; (ii) cereal grain protein concentration due to a non-proportional competition for soil mineral N and other plant growth factors; and (iii) weed control compared to legume sole crops.

Therefore, intercropping can be a way to successfully produce organic grain legumes and cereals. However, it is difficult to propose generic crop technical protocols because of the multitude of production objectives and, hence, of combinations of species, varieties, densities, structure and manuring strategies.

Consequently, it should be emphasized that: (i) the species and varietal traits suited to intercropping and organic farming will make it necessary to reconsider the varietal selection criteria; (ii) further mechanistic understanding of the behaviour of intercropping systems is required to be integrated into crop models; and (iii) the development of intercrops cannot take place without the participation of all of the actors in the value chain because of lock-in mechanisms.

Keywords Environmental resource use · Management system · Nitrogen · Eco-functional intensification · Cereal-grain legume intercrop · Protein concentration · Weed · Yield

3.1 Introduction

Organic farming is based on a higher cropping system diversity than its conventional counterpart and is regarded as a prototype capable of enhancing the sustainability of agriculture and cereal-rich cropping systems. Nevertheless, organic arable crop rotations in temperate regions consist mainly of sole crops (SC; pure stands), with the exception of diverse pastures in farming systems with livestock (Hauggaard-Nielsen et al. 2001b).

In organic farming, nitrogen (N) availability can be limiting, especially in the absence of livestock (David et al. 2005a, b), and leads to decreases in cereal yield and lower protein concentration. For these reasons, integrating legumes with symbiotic fixation of atmospheric N_2 is essential for balancing nitrogen exports from the system. New agronomic solutions should be developed that address multifunctionality, including: (i) higher yields; (ii) improved quality; (iii) supply of ecosystem services; and (iv) the adaptation of production systems to climate change (IAASTD 2009). Intercropping (IC) cereals and legumes, i.e., simultaneously growing two (or more) species in the same field for a significant period of time but without necessarily sowing or harvesting them at the same time (Willey 1979; Vandermeer et al. 1998; Malézieux et al. 2008), is a practice for eco-functional intensification, which is considered as a means to enhance yields in organic farming (Niggli et al. 2008). However, due to the intensification of agriculture over the last 50 years (Crews and Peoples 2004), annual intercropping is now rare in European countries (except for animal feeds) and elsewhere in intensive farming systems (Anil et al. 1998; Malézieux et al. 2008). Nevertheless, because of the numerous ecosystem services provided by introducing cereal-legume intercropping (Hauggaard-Nielsen and Jensen 2005), there seems to be a renewed interest in cereal/legume intercrops in

Europe, notably in organic farming (Anil et al. 1998; Malézieux et al. 2008) for the purpose of eco-functional intensification.

Intercropping has been shown to increase and stabilise yields (Hauggaard-Nielsen et al. 2009b; Lithourgidis et al. 2006) and to increase cereal grain protein concentration and baking quality compared to sole crops (Gooding et al. 2007), particularly in low-N input systems and organic farming where N can be a limiting resource (Corre-Hellou et al. 2006; Bedoussac and Justes 2010a, b; Naudin et al. 2010). Intercropping has also been shown to: (i) improve soil conservation (Anil et al. 1998); (ii) favour weed control (Vasilakoglou et al. 2005; Banik et al. 2006; Corre-Hellou et al. 2011); (iii) reduce pests and diseases (Trenbath 1993; Altieri 1999); and (iv) provide better lodging resistance (Anil et al. 1998). In contrast, grain legumes such as peas (*Pisum sativum* L.), grown as sole crops, are known to be weak competitors towards weeds (Wall et al. 1991; Townley-Smith and Wright 1994; Mcdonald 2003), and weed infestations have been shown to severely limit the N nutrition and grain yield of organically-grown grain legumes (Hauggaard-Nielsen et al. 2001b; Corre-Hellou and Crozat 2005). Moreover, grain legume sole crops are sensitive to lodging and affected by numerous pests and diseases, which can cause serious yield losses in organic farming where pesticide use is forbidden. Thus, from these perspectives, intercropping can be a way to successfully produce organic grain legumes (Hauggaard-Nielsen et al. 2007).

The main objective of this study was to analyse and describe the potential advantages of cereal-grain legume intercrops for grain yield, grain protein concentration and weed control in organic cropping systems. This chapter integrates a comprehensive amount of original data from field experiments conducted since 2001 in France (southern and western, with contrasting soil and climatic conditions), and in Denmark, in experimental and farm contexts, on spring and winter cereal-grain legume intercrops (Table 3.1), in an attempt to generalise the findings in order to draw up more common guidelines.

The intercrops evaluated were as follows: (i) spring barley (*Hordeum vulgare*)-spring pea (*Pisum sativum*); (ii) spring barley-spring faba bean (*Vicia faba*); (iii) soft wheat (*Triticum aestivum*)-winter pea; (iv) soft wheat-spring faba bean; (v) durum wheat (*Triticum turgidum*)-winter pea; and (vi) durum wheat-winter faba bean. The experiments cover a wide range of management practices to evaluate their effects on competition, such as: (i) with or without N fertilisation (up to 100 kg mineral N ha^{-1}); (ii) sowing in separate rows or mixing within the same row; and (iii) different cereal/legume sowing proportions. Intercrops were always compared with the corresponding sole crops sown on the same date, receiving the same N fertilisation and harvested at crop maturity (that of the later crop in intercrops).

3.2 Yield Advantages and Cereal Quality Improvement

Fulfilling the cereal N demand is crucial for obtaining profitable yield and grain quality (Garrido-Lestache et al. 2004). Consequently, cereals are generally fertilised with high levels of N using considerable amounts of organic inputs like animal and

Table 3.1 List of field experiments from which data are derived. Six intercrops (*HW* Durum wheat, *SW* Soft wheat, *B* Barley, *F* Faba bean, *P* Pea) were evaluated in France (southern and western) and Denmark at 13 different sites representing 58 treatments. For each trial, we indicate the cereal and legume densities in intercrops (as a percentage of the sole crop densities), N treatment (*N0* no N-fertilisation, *N* organic N-fertilisation) and cultivars. More information about experiments can be found in Jensen et al. (2006), Hauggaard-Nielsen et al. (2007), Hauggaard-Nielsen et al. (2009a, b), Knudsen et al. (2004) and Naudin et al. (2009)

Crops	Species	Year	Location	Sites (per location)	N treatment	IC densities (% of sole crop)	Cultivar: Cereal/Legurne	Number of treatments
Winter crops	HW-P	2009	France (Toulouse-south area)	1	N	58–93	Dakter/Enduro	1
				1	NO	58–93	Acalou/Livia	1
				1			Dakter/Enduro	1
		2010	France (Toulouse-south area)	1	N	58–72	Dakter/Cartouche	1
				1	NO	58–72	Dakter/Enduro	1
	HW-F	2009	France (Toulouse-south area)	1	N	58–49	Duetto/Irena	1
				2	NO	58–49	L1823/Irena	2
				1			Duettu/Irena	1
		2010	France (Toulouse-south area)	2	NO	66–50	Dakter and L1823/Castel	2
	SW-P	2003 and 2005	France (Angers-west area)	1	NO	50–100 and 50–50	Apache/Lucy	4
		2006	France (Toulouse-south area)	1	N and NO	50–50	Caphorn/Arthur	2
		2009	France (Toulouse-south area)	1	NO	30–70 and 50–50	PR22R58/Livia	2
		2010	France (Toulouse-south area)	2	N	58–72	Aérobic/Enduro	2
				1	NO	30–70 and 50–50	PR22R58/Enduro	2
				2	NO	58–72	Aérobic/Enduro	2
Spring crops	SW-F	2003 and 2004	Denmark (Taastrup)	1	NO and N	100–100 and 50–50		8
	B-P	2001; 2002; 2003	Denmark (Taastrup)	1	NO	50–50	Otira/Agadir and Bohatyr	6
		2003. 2004: 2005	France (Angers-west area) and Denmark	1	NO	50–100 and 50–50	Scarlett/Baccara	12
		2009; 2010	France (Toulouse-south area)	1	NO	30–70 and 50–50	Nevada/Livia	4
	B-F	2001; 2002; 2003	Denmark (Taastrup)	1	NO	50–50	Otira/Columho	3

green manuring. However, in lower N input systems, an eventual limiting N level makes it difficult to reach a sufficient grain yield and protein concentration as required by the agro-food industries both for soft wheat to make bread and for durum wheat to make semolina and pasta. Cereal-legume intercrops might be a way to increase total grain yield per area and grain quality, in particular, protein concentration (e.g., Gooding et al. 2007; Bedoussac and Justes 2010a; Naudin et al. 2010), which are the most obvious advantages emphasized when trying to convince farmers to adopt intercropping strategies in organic farming systems.

3.2.1 Intercropping Increases Total Grain Production

Over a wide range of intercropping studies, the total grain yield of the intercrop (cereal plus legume) is on average 3.3 ± 1.0 Mg ha^{-1}, which is: (i) nearly always (in 91 % of our trials) more than the mean yield of the respective sole crops (2.7 ± 0.9 Mg ha^{-1}; Fig. 3.1a); (ii) greater (in 64 % of our trials) than the sole cropped cereal yield (2.9 ± 0.9 Mg ha^{-1}; Fig. 3.1b); and (iii) greater (in 83 % of our trials) than the sole cropped legume yield (2.4 ± 1.4 Mg ha^{-1}; Fig. 3.1c). Independent of cropping strategy, the cereal is most often more productive than the legume. Furthermore, the proportion of cereal in the intercrop is greater than that calculated on the basis of the sole crops, which indicates that the cereal is more competitive (Vandermeer et al. 1998). The relative advantage of the intercrops seems to be greater when the yield of the respective sole crops is quite low and when the quantity of soil mineral N is limited.

3.2.2 Intercropping Improves the Protein Concentration of the Cereal Grain

Our results confirm that the protein concentration of the intercropped cereal is almost always greater than that of the respective cereal sole crop (11.1 ± 1.7 % and 9.8 ± 1.7 %, respectively; Fig. 3.2a). The complementarity between the cereal and legume is observed when the cereal sole crop protein concentration is at the low end. In the case of legumes, there is no difference between the intercrop and the sole crop condition in grain protein concentration (24.8 ± 3.9 % and 24.9 ± 4.3 %, respectively; Fig. 3.2b).

Our results confirmed those obtained both in conventional agriculture and organic farming, showing a general improvement of environmental resource use when intercropping (e.g., Jensen 1996a; Bedoussac and Justes 2010a; Hauggaard-Nielsen et al. 2009b). Moreover, present results confirm that the relative advantage of the intercrops seems to be greater when the yield of at least one of the sole crops is limited in one way or another, which can quite often happen in organic farming and low-N systems (Hauggaard-Nielsen et al. 2003; Corre-Hellou et al. 2006; Bedoussac and Justes 2010b).

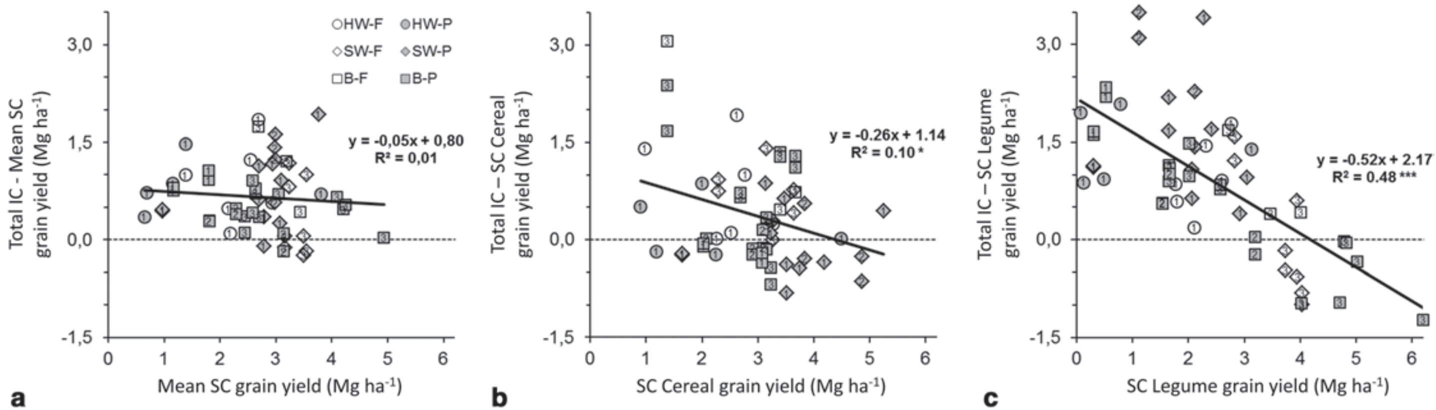

Fig. 3.1. Intercropping increases total grain production. Relationship between total grain yield of the intercrop (*IC* cereal + legume) and **a** mean sole crop (SC), **b** cereal SC and **c** legume SC. Numbers inside the symbols indicate the experimental site (*1* Southern France; *2* Western France; *3* Denmark). *HW* Durum wheat, *SW* Soft wheat, *B* Barley, *F* Faba bean, *P* Pea. Single asterisks (*) and triple asterisks (***) indicate that linear regression is significant at $P=0.05$ and $P=0.001$, respectively ($N=58$)

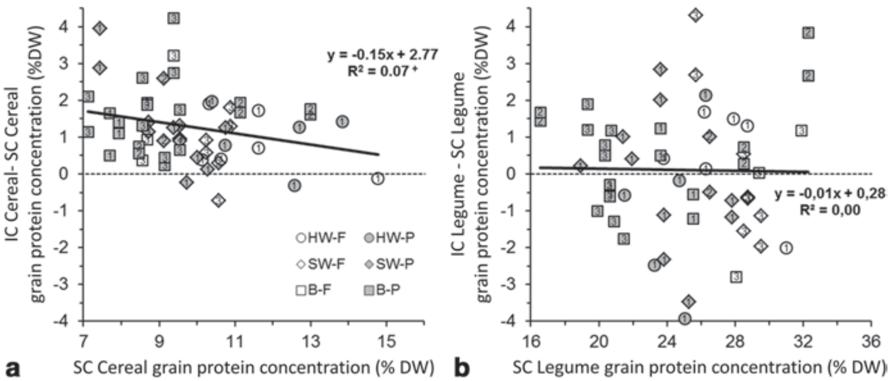

Fig. 3.2 Intercropping improves the protein concentration of the cereal grain. Relationship between grain protein concentration in intercrops and **a** the sole cropped (SC) cereal and **b** the SC legume. The grain protein concentration was calculated by multiplying the nitrogen concentration by 6.25 for the legume and the barley (animal consumption) and by 5.7 for soft and durum wheat (human consumption). Numbers inside the symbols indicate the experimental site (*1* Southern France; *2* Western France; *3* Denmark). *HW* Durum wheat, *SW* Soft Wheat, *B* Barley, *F* Faba bean, *P* Pea. A single plus (+) indicates that linear regression is significant at $P=0.10$ ($N=58$)

3.3 Complementarity and Competition Between Associated Species for Use of Resources

3.3.1 Improved Light Interception

In the absence of limiting or reducing abiotic and biotic factors such as water or nutrient availability, pests, diseases and weeds, the crop dry matter yield depends mainly on the radiation absorbed (Loomis and Williams 1963), and this applies both to the sole crop (Shibles and Weber 1966; Monteith 1977; Kiniry et al. 1989) and intercrop growing conditions (Natarajan and Willey 1980; Sivakumar and Virmani 1984; Bedoussac and Justes 2010b).

Intercrops are known to be more efficient compared to sole crops for light interception and use (Jahansooz et al. 2007) because of species complementarity in space—when crops differ in their shoot architecture—and time—when crop life cycles differ (Trenbath 1986; Tsubo et al. 2001; Tsubo and Walker 2002). These differences and interspecific complementarities allow a better dynamic occupation of the space and, hence, an increase in light interception throughout the growth of the intercrop and, finally, higher global biomass and grain yield.

3.3.2 Non-Proportional Competition for Soil Mineral N and Other Plant Growth Factors in the Intercrop Results in Higher Soil Nitrogen Availability Per Cereal Grain

To increase yield and improve grain protein concentration, it is necessary to obtain more remobilised N in the grain during the final part of the crop cycle. Using a simplified theoretical scheme representing crop yield and mineral N available for the intercrops and cereal sole crops (Fig. 3.3), it can be demonstrated that a greater quantity of N per kg of grain is available for the intercropped cereal than for the pure cereal, i.e.:

$$\left(\frac{\mathrm{Nmin}_{\text{IC-Cereal}}}{\mathrm{Y}_{\text{IC-Cereal}}} > \frac{\mathrm{Nmin}_{\text{SC-Cereal}}}{\mathrm{Y}_{\text{SC-Cereal}}}\right), \text{ only if } \frac{\mathrm{Y}_{\text{SC-Cereal}} - \mathrm{Y}_{\text{IC-Cereal}}}{\mathrm{Y}_{\text{SC-Cereal}}} > \frac{\mathrm{Ndfsoil}_{\text{IC-Legume}}}{\mathrm{Nmin}_{\text{SC-Cereal}}}$$

where $\mathrm{Nmin}_{\text{SC-Cereal}}$ and $\mathrm{Nmin}_{\text{IC-Cereal}}$ are the quantity of available soil mineral N for the SC cereal and IC cereal, respectively, $\mathrm{Ndfsoil}_{\text{IC-Legume}}$ is the mineral N absorbed by the IC legume, and $\mathrm{Y}_{\text{SC-Cereal}}$ and $\mathrm{Y}_{\text{IC-Cereal}}$ are the grain yield of the SC cereal and IC cereal, respectively.

For a partial data set ($N=19$[1]), we found that on average, these conditions were verified because: (i) $(\mathrm{Y}_{\text{SC-Cereal}}-\mathrm{Y}_{\text{IC-Cereal}})/\mathrm{Y}_{\text{SC-Cereal}}=0.33$[2]; and (ii) soil mineral N accumulated in the shoots of the intercropped legume ($\mathrm{Ndfsoil}_{\text{IC-Legume}}$) represented barely 17±14% (on average 21±24 kg N ha^{-1})[3] of the total available soil mineral N[4] to a first approximation.

The greater efficiency generally observed in intercrops can be explained by the fact that the two intercropped species use N sources (mineral soil N and atmospheric N_2) in a complementary way (Jensen 1996a; Bedoussac and Justes 2010a; Corre-Hellou et al. 2006). Indeed, the legume is forced to rely on N_2 fixation because the cereal is more competitive for soil mineral N (Hauggaard-Nielsen et al. 2001a; Bellostas et al. 2003), which leads to a rapid decrease in the quantity of available mineral N in the surface soil layer (the zone of symbiotic fixation), causing an increase in the N_2-fixing activity of the legume compared with sole crops (Jensen 1996a; Corre-Hellou et al. 2006; Hauggaard-Nielsen et al. 2009b; Naudin et al. 2010). When combining the different experiments and growing conditions in organic farming, our results confirmed a higher percentage of N derived from

[1] We considered the data subset for which all the variables needed for the calculation were available.

[2] $\mathrm{Y}_{\text{SC-Cereal}}=2.9 \pm 0.6$ Mg ha^{-1} and $\mathrm{Y}_{\text{IC-Cereal}}=2.0 \pm 0.7$ Mg ha^{-1}on average.

[3] The nitrogen accumulated in the shoots of the intercropped legume was on average 54 ± 36 kg N ha^{-1}, of which only 21 ± 24 kg N ha^{-1} came from the soil (the percentage of plant N derived from N_2 fixation was determined using the ^{15}N natural abundance method for unfertilised treatments, according to Amarger et al. (1979), Unkovich et al. (2008) and Bedoussac and Justes (2010a).

[4] Total available nitrogen (112 ± 38 kg N ha^{-1}) was estimated as the sum of the N accumulated by the SC cereal (62 ± 21 kg N ha^{-1}) and the soil N residue at harvest of the SC cereal (50 ± 28 kg N ha^{-1}).

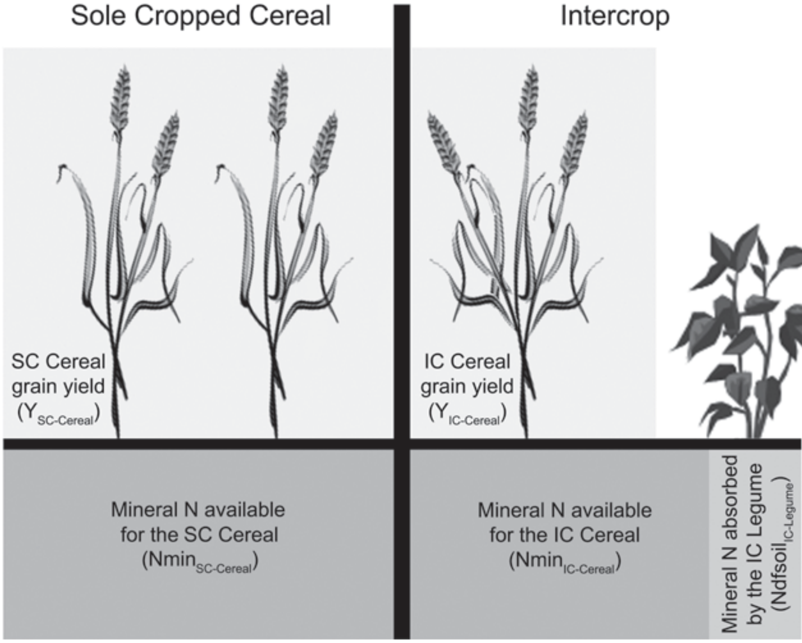

Fig. 3.3 Theoretical scheme linking grain production and the availability of mineral nitrogen for an intercropped and sole cropped cereal

air (%Ndfa) in intercropped legumes than in sole crops (on average, 75 ± 18 % and 62 ± 16 %, respectively).

A second hypothesis (which does not exclude the first one) that explains the improvement in the protein concentration of the intercropped cereal is based upon a better fit of the N availability to the cereal requirements, depending on the developmental stage and the yield level. This supports the previous explanation that the effect of intercropping is small or absent when large quantities of soil mineral N are available.

These hypotheses might only be part of the explanation because several authors have shown the effects of the legume on facilitating the absorption of soil mineral N by the cereal (Stern 1993; Xiao et al. 2004) and the transfer of N from the legume to the cereal (Jensen 1996b). However, in view of the total quantity of N available in agricultural systems, these processes of N transfer from the legume to the cereal are regarded as small, even if they can contribute up to 15 % of the N absorbed by barley in intercrops with peas (Jensen 1996b).

3.3.3 Less Light and Nitrogen Available to Weeds

Intercrops can potentially reduce weeds (Vasilakoglou et al. 2005; Banik et al. 2006; Corre-Hellou et al. 2011), often regarded as key factors influencing crop production (Liebman 1988; Liebman and Davis 2000; Hauggaard-Nielsen et al. 2001b).

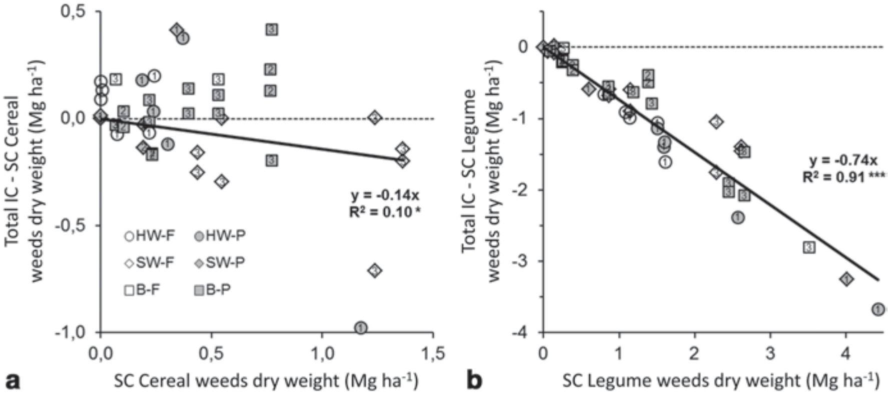

Fig. 3.4 Intercropping improves the weed control of the legume. Relationship between weed dry weight below intercrops (IC) and **a** the sole cropped (SC) cereal and **b** the SC legume. Weed dry weight below intercrops (IC) as a function of **a** Cereal sole crops (SC) and **b** Legume SC. Numbers inside the symbols indicate the experimental site (*1* Southern France; *2* Western France; *3* Denmark). *HW* Durum wheat, *SW* Soft wheat, *B* Barley, *F* Faba bean, *P* Pea. Single asterisks (*) and triple asterisks (***) indicate that linear regression is significant at $P=0.05$ and $P=0.001$, respectively ($N=43$)

In particular, intercrops can help to suppress weeds in not very competitive crops such as peas and other grain legumes, even with a low percentage of cereal in the total biomass, as observed in pea-barley intercrops (Corre-Hellou et al. 2011). In our experiments, the weed biomass within the intercrops or the cereal sole crops are comparable (0.40 Mg ha^{-1}; Fig. 3.4a) and significantly lower than within the legume sole crops (1.38 Mg ha^{-1}; Fig. 3.4b).

This weed reduction can be explained by improved resource use leaving less resources available for the weeds. Nitrogen and light are two main growth parameters involved in such weed suppression because of the intercropped species complementarity such as: (i) use of N (soil mineral N and atmospheric N_2); (ii) capture of light energy (e.g., Bedoussac and Justes 2010b); and (iii) soil cover (Anil et al. 1998).

3.4 Designing Appropriate Intercrop Management Systems

Designing crop management systems—the logical and sequentially arranged techniques applied on a farm field to achieve a given production objective (Sebillotte 1974)—is much the same for intercrops and sole crops, except that the choices have to be made for several crops instead of just one.

In multi-species mixtures (two or more), the interactions between species can be represented as the effect of one species on the environment and the response of the other (one or more) species to this change (Vandermeer 1989; Goldberg 1990). The interactions are complex, occur dynamically over time and space (Connolly et al. 1990) and depend, *inter alia*, on the availability of nutrients, soil-climatic conditions and the companion species and cultivars.

As discussed by Naudin et al. (2010), adoption of intercropping strategies might be guided by several production objectives such as: (i) *improving the quality of the cereal* by maximising the availability of soil mineral N and by increasing the symbiotic fixation rate of the legume; or (ii) *producing legumes using intercrops* by reducing weed pressure and spread of diseases and pests because of a cereal physical barrier effect, and by providing mechanical support to avoid pea lodging.

The choices of species, varieties, plant densities, patterns and N fertilisation levels are regarded as the determining factors of the functioning and performance of intercrops. Interactions between these various technical choices in relation to the production objective make generalisations rather difficult. However, two general rules can be defined: (i) improve the use of light energy; and (ii) improve the use of N sources.

With respect to light, the dominant species should have a shoot architecture and biomass production that allows a reasonable amount of light to reach the understorey (Berntsen et al. 2004; Jahansooz et al. 2007). In the case of durum wheat/winter pea intercrops (Bedoussac 2009), a short-strawed durum wheat variety would be favoured to intercrop with winter peas, and a long-strawed one for IC with faba beans. Moreover, with the objective of improving the protein concentration for the cereal, a cereal variety with good sole crop characteristics (grain protein concentration, vitreousness, bread-making quality, etc.) would be preferable, but at the same time, should have sufficient sensitivity to leguminous interspecific competition to secure complementary interactions.

In intercrops, the optimal total plant density can be greater than that of each of the sole crops because of the complementarity between species (e.g., maize/bean mixtures) (Willey and Osiru 1972). The increase in plant density increases the competition between the components of the mixture, which, as Willey (1979) noted, tends to favour the dominant species. Consequently, an increase in the density of the dominated species would be favoured (more than 50 % of that in sole cropping) and/or a reduction of that of the dominant species (less than 50 % of that in sole cropping) to manage competitive effects.

Apart from species, varieties and densities, variations in spatial structure of intercrops (such as mixtures within the row or alternate rows or strips of varying width) and row orientation will modify the distribution of radiation, water and nutrients. Such effects were reported on maize-pigeon pea mixtures (Dalal 1974), maize/soya and sorghum/soya mixtures (Mohta and De 1980) or barley/pea intercrops (Chen et al. 2003). Consequently, densities should be chosen according to the spatial arrangement of the species, their competitivity and the production objectives.

Nitrogen availability as a result of organic N fertilisation strongly affects species complementarity. Increased availability of soil mineral N in early growth stages will result in: (i) reduced amounts of fixed N; (ii) reduced legume yield; and (iii) a correspondingly increased cereal yield. Conversely, late availability of soil N will have little or no effect on the overall symbiotic fixation and yield of the legume but will improve the protein concentration of the cereal. Unlike mineral N, which is immediately available, organic manures undergo soil microbial mineralisation. Consequently, only early applications of organic N from animal manure, green manuring, etc., can have an effect on the behaviour of the intercrop and, in particular, on the proportions of the two species at harvest. Early competitive advantages are often found to form the basis for a competitive dominance throughout the growing season (Andersen et al. 2007).

Mechanical weeding using a tine harrow (an effective tool widely used in organic farming) can be very efficient provided that the operation is correctly timed. However, the optimal growth stages for its use on each of the two species can differ enough so that the time window for using the tine harrow in an intercrop is shorter. Hence, this technique must be applied with care and certainly requires more technical skill when applied to intercrops.

Evaluation of intercrops should not only be considered in terms of crop management practices but should also include the cropping system. Integration of intercrops within traditional rotations and their subsequent crop effects and minimum time of return between two intercrops, among other issues, needs to be clarified in future studies. For example, if the intercrops significantly reduce the pest and disease pressure, it may be possible to reduce the return times compared with sole crops. It is also reasonable to imagine the successive cropping of different cereal/grain legume intercrops whose possible combinations are numerous and, for the more southerly climates of Europe, to consider summer crops (e.g., sunflower/soya).

3.5 What is the Economic Benefit of Intercropping?

Crop rotation, soil fertility, commodity price and the availability of a market, etc., are some factors that influence crop preference by farmers and the adoption of intercrops. The potential economic advantage of intercrops depends on the selling prices of the crops and, in particular, on the differential between cereals and legumes, which is a difficult figure to obtain when prices are volatile. In general, we observe that the sale price of organic grain legumes is higher than that of standard quality wheat and comparable to that of high quality wheat.

From the micro-economic point of view, there is an economic advantage of intercropping in organic farming due to the increase in total grain yields in intercrops compared to the respective sole crops, especially the grain legume sole crops and, particularly, for years when one of the respective sole crops produces low yields. In some years, intercropping might lead to an intermediate net income for the farmer, but it is regarded as a better safeguard for the farmer's earnings compared to sole grain legume cropping. Indeed, grain legumes have a reputation for low yield and low yield stability in organic crop rotations, which is linked to several factors such as water stress intolerance, harvest difficulties due to lodging or late maturity, diseases (e.g., *Ascochyta* spp., *Botrytis* spp., *Erypsiphe* spp.) or because they are weak competitors for weeds.

The economic value of intercrops will increase through quality improvements such as increased wheat grain protein concentration and reduced hard wheat vitreousness, giving access to the market for direct human consumption with higher selling prices. Focusing on wheat-faba bean intercrops over five regions across Europe and three seasons, Gooding et al. (2007) showed an economic benefit of intercrops, despite a 25–30 % reduction in wheat yield. This resulted from the added value of a higher crude protein concentration of intercropped wheat, combined with the effective marketing of the legume crop.

However, intercrops can be sold for the human consumption market only if crops can be correctly sorted. For that reason, the main obstacle to the development of intercrops for the companies collecting and storing the seeds is the capacity for sorting large volumes efficiently, quickly and cheaply. On the basis of a preliminary survey of French companies that collect and store the seeds, it seems possible to correctly separate the grains of the two species, provided that they sufficiently differ in size and/or shape and that the mixture does not contain too many broken grains. To reach the latter objective, it has to be ensured that: (i) the species and varieties reach maturity at similar dates; and (ii) the combined harvester adjustments are made to suit the more fragile species (at the risk of losing some of the grain of the other species). Another option is that the companies collecting and storing the seeds adjust already available equipment to deal with seed mixtures, obviously at some cost for the farmer.

This practical question thus raises various issues in terms of the choice of machinery and its adjustment, as well as from the logistic point of view for the companies collecting and storing the seeds. Indeed, their organisational structure can play the role of a self-reinforcement mechanism that reduces the incentives to adopt new practices (Fares et al. 2012). Conversely, the adoption of intercropping to produce animal feed on farms seems less problematic as it is possible to either crudely sort the grain or else to adjust the diet by adding either one of the two species to the harvested mixture.

3.6 Conclusions and Perspectives

We have shown that intercrops present numerous advantages and appear to be a useful agronomic solution for organic arable cropping. However, it is difficult to propose scientifically proven and generic crop technical protocols because of the multitude of possible production objectives and, hence, of combinations of species, varieties, densities, structure and organic manuring strategies. Therefore, it is necessary to emphasize:

- That the identification of the species and varietal traits suited to intercropping and, more generally, to low-input systems and organic farming is therefore an important issue that will make it necessary to reconsider the varietal selection criteria. Indeed, those used for sole crops are probably not ideal for intercrops, and especially for organic farming systems, as illustrated by Carr et al. (1998), who showed that the yields of barley-peas or oats-pea forage intercrops were higher when the varieties used had been selected in multi-species stands.

- The limitations of experiments and the value of modelling multi-species cropping systems (Brisson et al. 2004; Corre-Hellou et al. 2009; Launay et al. 2009). In fact, for a given production objective, this would allow: (i) the performance and behaviour of intercrops to be evaluated under a wide range of conditions; (ii) to help with the determination of varietal characteristics suited to intercropping; (iii) to optimise the crop technical protocols according to multiple criteria; and (iv) to devise a decision-aid model. However, this requires a better mechanistic understanding of the behaviour of multi-species cropping systems and the integration of this knowledge into current crop models or the development of new models that correctly represent the inter- and intraspecific competition (Launay et al. 2009).
- That the development of intercrops cannot take place without the assent and participation of all the actors in the value chain because the low degree of integration of the supply chain can be viewed as a lock-in mechanism (Fares et al. 2012) with, in particular: (i) farmers who need technical support since the new generation of farmers may not possess the know-how; (ii) companies that collect and store the seeds that will have to adapt their collecting, sorting and storage equipment in order to satisfy the processors' quality demands; (iii) breeders who are expected to select varieties suited to intercropping; (iv) technical institutions that must acquire technical and cognitive knowledge; (v) national and European authorities who must consider relevant policies and subsidies to help reintroduce these cropping strategies; and (vi) research institutions.

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