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Bedoussac, Laurent; Journet, E-P; Hauggaard-Nielsen, Henrik; Naudin, C; Corre-Hellou, G; Jensen, Erik Steen; Justes, Eric

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L. Bedoussac[1]; E-P. Journet[2,3]; H. Hauggaard-Nielsen[4]; C. Naudin[5] and G. Corre Hellou[5]; E. S. Jensen[6]; E. Justes[3]

[1]AGIR, Université de Toulouse, INRA, INPT, INP-PURPAN, ENSFEA, Castanet Tolosan, France

[2]LIPM, Université de Toulouse, INRA, CNRS, Castanet-Tolosan, France

[3]AGIR, Université de Toulouse, INRA, INPT, INP-PURPAN, Castanet Tolosan, France

[4]Department of Environmental, Social and Spatial Change, Roskilde University, Denmark

[5]USC LEVA, INRA, Ecole Supérieure d'Agricultures, Angers, France

[6]Department of Biosystems and Technology, Swedish University of Agricultural Sciences, Sweden

E-mail: laurent.bedoussac@inra.fr

1 Introduction

Intercropping involves simultaneously growing two or more crops in the same field for a significant period of time that could be the whole period of cultural season for some arable crops such as in cereal-legume intercrops (Willey 1979; Vandermeer et al. 1998; Malézieux et al. 2008; Jensen et al. 2015). The practice is ancient as early records from many human societies all over the world have shown (Willey 1979a). According to Altieri (1999), intercropping systems are estimated to still provide as much as 15–20% of the world's food supply. In Latin America farmers grow 70–90% of their beans with maize, potatoes and other crops and maize is intercropped on 60% of the region's maize-growing area (Francis, 1986). In rural sub-Saharan Africa, intercropping is considered as a traditional cropping system with the predominant crop combinations being maize, bean/cowpea and pumpkin (Matusso et al. 2014). Intercropping, has been also practiced in China for thousands of years and it has been estimated that surfaces are about 30 million ha (Li et al., 2007) representing 20-25% of arable land (Li, 2001). The practice was widespread in some European farming systems up until the 1950s – before the so-called fossilisation of agriculture (Matson et al. 2007). At that time as much as 50 % of all available nitrogen (N) may have originated from symbiotic N_2 fixation by leguminous food, forage and green manure crops used in rotation which limited the reactive N coming from fertilizer-N and then the negative impact of NO3, NH3 and N2O on the environment (Peoples et al. 2009). In those systems, land was dedicated to fertility generating legume rotations, which potentially also contributed to other ecosystem services such as carbon sequestration and biodiversity (Peoples et al. 2009). Despite these advantages, grain legume cropping is less favoured now, even in organic crop rotations, because of a reputation of low yield and instability related to several factors like intolerance to water stress, harvest difficulties because of lodging, pathogen attacks, sensitivity to insect pests and weed competition. Aiming at higher crop diversity, intercropping is an interesting option to introduce legumes in cropping systems in a more efficient way compare to sole cropping rotations. Therefore, grain legumes were often grown in different cereal intercrop combinations to secure yield stability and soil fertility, lowering nutrient losses and reducing weeds, diseases and pests (Hauggaard-Nielsen et al. 2001, 2007). This suggests that intercropping is a way to improve adaptability to climate change taking into account both biotic stresses (Padulosi et al. 2002) as well as abiotic stresses (e.g. of more and more unpredictable weather patterns (IAASTD 2009)). These intercrops were found all the more efficient and productive when grown in low input systems, and in particular in organic farming (Bedoussac et al. 2015). Since the 1950s, intercropping declined in Europe and some other parts of the world in the post-war period due to intensification of agriculture focusing on maximising yields of sole crops using external inputs (artificial fertilizers and pesticides) together with optimization of mechanical management (Crews and Peoples 2004; Anil et al. 1998; Malézieux et al. 2008).

There is now renewed interest in intercropping in Europe in achieving 'sustainable, ecological or eco-functional intensification' of agricultural production, particularly in organic farming (Anil et al. 1998; Hauggaard-Nielsen and Jensen 2005; Malézieux et al. 2008; Bedoussac et al. 2015). Exploiting the ability of legumes to fix free atmospheric N_2 means potentially less reliance on use of N fertilizer input (Fustec et al. 2010), thus reducing equivalent CO_2 emissions (Nieder and Benbi 2008) and the carbon footprints of agricultural products (Gan et al. 2011). Because intercrops could be an efficient way to reduce the damages due to some pests (e.g. aphids), weeds and shoot diseases in comparison to legume sole crops, intercropping is of particular interest in organic farming systems (Jensen, 1996a; Corre-Hellou et al. 2011; Ndzana et al. 2014; Bedoussac and Justes 2010a, b; Naudin et al. 2010). Intercropping is also known as a method to boost crop productivity (Qin et al. 2013), improve land utilization (Agegnehu et al. 2008), reduce reliance on fertilisers and risks of nitrate leaching compared to sole cropping (Hauggaard-Nielsen et al. 2003; Adad et al. 2004; Corre-Hellou 2005) and reduce greenhouse gas emissions compared to the use of sole cropping strategies (e.g. Oelhermann et al. 2009; Naudin et al. 2014). Intercropping is of particular interest in temperate regions where organic arable crop rotations often comprise sole crops, i.e. pure stands, including annual legumes (Hauggaard-Nielsen et al. 2001b) with a number of abiotic and biotic factors influencing yields. Moreover, Jensen et al. (2015) proposed the concept that intercropping could be an efficient way of precision ecological farming allowing the improvement of resource use efficiency due to adjustment of the mixed cover to resource spatial variability.

This chapter summarises data from over 50 field experiments undertaken since 2001 on cereal-grain legume intercropping in 13 sites in southern and western France as well as in Denmark using spring and winter cereal-grain legume intercrops (Bedoussac et al. 2014, 2015). More detailed information concerning these experiments can be found in Hauggaard-Nielsen et al. (2007, 2001a, 2001b); Knudsen et al. (2004), Naudin et al. (2009) and Bedoussac and Justes (2010a, 2010b) and Bedoussac et al. (2014, 2015). The following combinations of intercrops were evaluated:

- spring barley (*Hordeum vulgare*)-spring pea (*Pisum sativum*)
- spring barley-spring faba bean (*Vicia faba*)
- soft wheat (*Triticum aestivum*)-winter pea
- soft wheat-spring faba bean
- durum wheat (*Triticum turgidum*)-winter pea
- durum wheat-winter faba bean

The experiments covered a range of intercropping methods mostly in substitutive design such as:

- sowing in separate rows or mixing within the same row;
- sowing different proportions of cereals and legumes in a field.

They also tested the effects of using synthetic fertiliser-N on the interspecific competitive interactions taking place in the crop stand. Yields of intercrops were compared to yields of the corresponding sole crops sown on the same date, with the same level of fertiliser-N and harvested at crop maturity (i.e. of the later crop in the case of intercrops).

2 Effects on yields and quality

Intercropping has been shown to increase crop yields in low-N input systems in particular (Hauggaard-Nielsen et al. 2009b; Lithourgidis et al. 2006). In the French and Danish intercropping studies, the total grain yield of the intercrop (cereal plus legume) was on average 3.3 ± 1.0 Mg ha−1. This was typically more than the mean yield of the comparable sole cereal crop (2.9 ± 0.9 Mg ha−1) and the comparable sole legume crop (2.4 ± 1.4 Mg ha^{-1}) (Bedoussac et al. 2014, 2015). These results confirm others analysing both conventional and organic farming which also show a higher grain yield from intercrops compared to sole crops, particularly for cereal-legume combinations (e.g. Jensen 1996a; Bedoussac and Justes 2010a, 2010b; Hauggaard-Nielsen et al. 2009b).

Numerous studies suggest that intercrops are particularly suited to low-N-input systems (Willey 1979a, 1979b; Ofori and Stern 1987; Vandermeer 1989; Willey 1990; Fukai and Trenbath 1993; Jensen 1996a; Hauggaard-Nielsen et al. 2003; Corre-Hellou et al. 2006 and Bedoussac and Justes 2010a, 2010b; Bedoussac et al. 2015). A study of durum wheat-winter pea intercrops by Bedoussac and Justes (2010a) showed that, when fertilizer-N is applied, whilst wheat yields increased, intercropped legume growth and yield were reduced leading to a lower yield of the intercrop compared to the fertilized sole crop wheat. This implies that intercropping may be advantageous when N availability (soil N plus fertilizer-N) is below a determined threshold (12 g N m^{-2} in the French and Danish experiments). Similar results have been reported for several cereal-legume intercrops grown in arid, semi-arid, tropical and temperate climates (Fujita et al. 1992; Ofori and Stern 1987; Jensen 1996a; Naudin et al. 2010).

The land equivalent ratio (LER) is a widely used indicator to compare the efficiency of sole crops and intercrops. The LER is defined as the relative land area required when growing sole crops to produce, for example, the yield achieved in an intercrop with the same species proportion (Willey and Osiru 1972). LER>1 indicates a per-area advantage of intercropping compared to sole cropping in terms of improved use of resources such as light, water and N. The French and Danish studies show grain yield-based LER values are greater than 1 for almost all the experiments (1.27 on average), indicating an advantage to intercropping compared to sole cropping (Bedoussac et al. 2015). It is important to note that the LER is dependent on the conditions relating to the sole crop (Mead and Willey 1980; Jolliffe 2000) and that relative and absolute production performances are not necessarily linked (Bedoussac and Justes 2011). Species mixtures with the highest LER values do not necessarily have the highest absolute productivity (Garnier et al. 1997; Jolliffe and Wanjau 1999). Others indices can also be useful for evaluating species interactions and intercrop efficiency (Weigelt and Jolliffe 2003). A comparison of commonly used indices has been done by Bedoussac and Justes (2011) on durum wheat-winter pea intercrops demonstrating the interests and limits of LER, that must be analysed in the framework of level of yield produced.

To obtain profitable yield and grain protein concentration, cereals are generally fertilized with high levels of nitrogen not only in conventional cropping systems but also in organic systems. On the contrary, in lower-nitrogen-input systems, limiting nitrogen resource makes it difficult to reach a sufficient grain protein concentration as required by agro-food industries either for soft wheat to make bread or for durum wheat to make semolina and pasta. Yet, in addition to interesting increases in yield and productivity (global performance of both species), intercropping has also been shown to increase cereal grain protein concentration and baking quality (Gooding et al. 2007). Results from the French and Danish studies show 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), although no significant difference in grain protein concentration was observed between the intercrop and sole crop legume (Bedoussac et al. 2014). A number of studies have shown the effect of intercropping on wheat grain protein concentration is due to a higher mineral soil N availability for the cereal on a per plant or a per grain basis in intercropping compared to sole crops (Gooding et al. 2007; Bedoussac and Justes 2010a, 2010b). In a review of wheat-faba bean intercrops in five regions across Europe, Gooding et al. (2007) concluded that, despite a 25-30 % reduction in wheat yield compared to conventional sole cropping cereal with high levels of N fertilisation, intercropping could still have an overall economic benefit resulting from the higher protein concentration of the intercropped wheat, combined with the added value of the legume crop. There is therefore an economic benefit in intercropping in sectors such as organic agriculture.

Intercropping can also offset problems of low and variable yields in organic grain legume cropping associated with water stress, lodging, diseases and competition from weeds.

3 Processes and factors explaining the agronomical performances of intercropping

3.1 Ecological processes involved in intercrops

One key pathway to ecological intensification is the exploitation of diversity in cropping systems by increasing the number of cultivated species and varieties cropped in species mixtures, potentially including a larger proportion of legumes in cropping systems. **The interactions between species** taking place in species mixtures are complex and can be **described by the 'four Cs'**: 1) **Competition** for resources, 2) **Complementarity**, allowing a more efficient use of resources by the mixtures compared with sole cropping, 3) **Cooperation** through facilitation, when the modification of the environment by one species is beneficial to the other(s) (Hauggaard-Nielsen et al. 2005), e.g. by reducing disease attack (Finckh and Wolfe 2015), weed competition (Hauggaard-Nielsen et al. 2001) or by increasing mineral N and P availability (Hinsinger et al. 2011), and 4) **Compensation**, when species differ in their sensitivity to abiotic and/or biotic stress and the demise of one is compensated by the other(s) through release from competition. The relative contribution of these processes to yield advantages of mixtures depends on species composition and varies in time and space.

There are a number of factors explaining the performances of intercropping and the processes involved that can boost the agronomical intercrop performance.

3.2 Soil nitrogen availability

Some studies have shown a higher quantity of N accumulated per kg of grain in intercropped cereals compared to sole cropped cereals. A number of studies have demonstrated the way the intercrop legume also facilitates the absorption of soil mineral N by the intercrop cereal (Stern 1993; Xiao et al. 2004) together with the transfer of N from the legume to the cereal which represent in annual barley/peas intercrops only up to 19 % (Jensen 1996b). The amount of N exchanged between plants is higher when soil mineral N is low and when roots are intermingled (Jensen 1996a; Xiao et al. 2004; Fustec et al. 2014). However, within the growth time of annual intercrops, Fustec et al. (2014) show that the net balance between the legume and the companion crop was negligible because the transfers from pea into wheat were not significantly different from those from wheat towards pea. Then, this higher efficiency in intercrops is mostly the result of the complementary way intercropped species use available N from the soil or atmosphere (Jensen 1996a; Bedoussac and Justes 2010a; Corre-Hellou et al. 2006). Legumes in an intercrop are "forced" to rely more on atmospheric N because cereals strongly compete for soil mineral N (Hauggaard-Nielsen et al. 2001a; Bellostas et al. 2003). This increases legume N proportion from N_2-fixation and expands niche complementarity increasing the global N availability for the intercrop (Jensen 1996a; Corre-Hellou et al. 2006; Hauggaard-Nielsen et al. 2009b; Naudin et al. 2010).

3.3 Light interception and utilisation

Intercrops are known to be more efficient users of light compared to sole crops (Jahansooz et al. 2007; Bedoussac and Justes 2010b). This reflects differences in their shoot architecture and crop life cycles which allow them to intercept light in ways that are more complementary and less competitive, supporting higher overall biomass and yield (Trenbath 1986; Tsubo et al. 2001; Tsubo and Walker 2002). There is a general agreement that the partition of radiation when intercropping different species is primarily influenced by vertical competition (Spitters and Aerts 1983; Caldwell 1987; Cudney et al. 1991; Cenpukdee and Fukai 1992a, 1992b) and secondly by the crop row orientation and the light extinction coefficient of the leaves of each species. As an illustration, modern pea varieties differ in morphology, primarily in stem length and leaf type. Then, semi-leafless varieties with short stems and all the leaflets transformed into tendrils could be more adapted for intercropping. Indeed, compared to the normal-leafed varieties with large leaflet area, semi-leafless varieties allow more light available for the initial growth of the companion crop (Mikić et al. 2015). Similar results can be expected when considering different legume growth habits (indeterminate, semi-determinate and determinate) which could have an important influence on competition and complementarity.

3.4 Weed control

Intercropping reduce weed infestation level, in particular compared to sole crop of legume (e.g. Hauggaard-Nielsen et al. 2007) reducing the needs for chemical or mechanical weed control (Vasilakoglou et al. 2005; Banik et al. 2006; Corre-Hellou et al. 2011). It has been shown that more competitive cereals especially for soil mineral N uptake such as barley can help reduce weed growth in grain legumes such as peas which are less able to take up soil mineral N and thus compete with weeds (Corre-Hellou et al. 2011). These crops could strongly control or supress weed growth by competing for resources such as light and nutrients (Bedoussac and Justes 2010b; Anil et al. 1998). Results from the French and Danish studies show that weed biomass within the intercrops or the cereal sole crops at harvest are comparable (0.04 kg m^{-2}) but significantly lower compared to the legume sole crops (0.14 kg m^{-2}). These results are consistent with those obtained by Corre-Hellou et al. (2011) on pea-barley intercrops where weed control was high and consistent even with a low percentage of barley in the total biomass, whereas it was lower and more variable in pea sole crops.

3.5 Pests and diseases control

Intercropping has been found to reduce some pests and diseases (Trenbath 1993; Altieri 1999; Hauggaard-Nielsen et al. 2007; Corre-Hellou and Crozat 2005; Ratnadass et al. 2012). Andow (1991) analysed 209 studies on crop mixtures involving 287 different species of parasitic insects. The insects were significantly fewer in 52% of cases (149 species) compared with monocultures, and greater in 15% of cases (44 species). This has been linked to physical barrier effects and possible chemical effects against insect and disease spread from the use of particular intercrops (Vandermeer 1989; Hauggaard-Nielsen and Jensen 2005; Ndzana et al. 2014). As an illustration, *Acyrthosiphon pisum* Harris (Aphididae: Hemiptera), the pea aphid, can be significantly decreased when intercropping winter pea with durum wheat (Ndzana et al. 2014). Ndzana et al. (2014) suggest that a mechanism related to the resource concentration hypothesis may explain the associational resistance of the intercrop towards *A. pisum* since substitutive systems were less infested than additive systems and row mixtures less infested than mixtures on the row.

4 Cultivation practices in intercropping

In multi-species mixtures such as intercrop, the interactions between species can be represented as the effect of one species on the environment and the response of the other species to this change (Vandermeer 1989; Goldberg 1990). The interactions are complex, occur dynamically over time and space (Connolly et al. 1990) and depend, amongst other things, on the availability of nutrients, soil-climatic conditions and the companion species and cultivars. Despite this complexity which make generalisation difficult, it is possible to identify cultivation practices which will improve overall performance.

4.1 Agricultural management practices adapted to intercrop

Naudin et al. (2010) has suggested cultivation needs to match the farmer’s overall production objective, whether:

- 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
- producing legumes using intercrops by reducing weed pressure and spread of diseases and pests because of a cereal competition or physical barrier effect, respectively.

In the former case, one would favour an early-developing cereal to rapidly deplete the mineral N pool available to the legume. For the legume, one would choose species and varieties with a root development able to cover its early N needs, including an early start of leguminous symbiotic N_2 fixation. If the focus is on legumes, one would choose high legume densities close to those of sole cropping and lower densities for the companion cereal without the use of N fertilization. The main role for the cereal in such intercrop is to reduce weed pressure and the spread of diseases and pests and, in the case of peas, to provide mechanical support to avoid lodging.

4.2 Management practices to optimise use of light and nitrogen

Whatever the intercrop species mixture, two general principles in improving output are to:

- improve the use of light energy; and
- improve the use of N sources.

Looking at use of 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). As an example, in the case of durum wheat-winter pea intercrops, a short-strawed durum wheat variety would be selected to intercrop with winter peas, and a long-strawed variety for intercropping with faba beans (Bedoussac 2009).

Nitrogen availability strongly affects species complementarity. Increased availability of soil mineral N in early growth stages will result in reduced amounts of fixed N, a reduced legume yield and an increased cereal yield (Hauggaard-Nielsen and Jensen 2001; Bedoussac and Justes 2010a; Naudin et al. 2010). As an example, Naudin et al. (2010) showed that mineral N fertilization applied after the beginning of pea flowering stops its symbiotic fixation activity compared to the unfertilized treatment. This was confirmed by experiments on pea plants grown in greenhouse conditions (Naudin et al. 2011). Conversely, late availability of soil N will have little or no effect on 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 processes including 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 (Andersen et al. 2007).

4.3 Sowing designs

Hauggaard-Nielsen et al (2006) showed in a pea-barley intercrop field study how changes in plant density and relative crop frequency had a marked effect on the interspecies dynamics, obviously influencing the functioning of intercrops and their potential benefits. In intercrops, the optimal total plant density can be greater than that of each of the sole crops because of the complementarity between species (Willey and Osiru 1972). The increase in plant density increases the competition between the components of the mixture which tends to favour the dominant species (Willey 1979). This suggests a higher density of the dominated species (more than 50 % of that in sole cropping) and a lower density of the dominant species (less than 50 % of that in sole cropping) to manage competitive effects. As an example, Bedoussac (2009) has shown that in mixtures with durum wheat, the density of peas could be the same as that of the sole crop with a proportion of cereal grain in the intercrop of about 50 %.

Variations in spatial structure of intercrops (such as mixtures within the row, alternate rows or strips of varying width) and row orientation will also modify the distribution of radiation, water and nutrients. Such effects have been 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). This suggests densities should be chosen according to the spatial arrangement of the species and how they compete as well as production objectives. The sowing pattern also needs to take mechanical weeding operations into account, for example using a tine harrow (an effective tool widely used in organic farming).

4.4 Harvesting intercrops

Intercrops can only be marketed if the grains of each species can be correctly sorted. One of the main obstacles in intercropping is the capacity for sorting large volumes efficiently, quickly and cheaply. On the basis of the French studies, it is possible to correctly separate the grains of the two species, i.e. wheat and pea or fababean, provided that they sufficiently differ in size and/or shape and that the mixture does not contain too many broken grains (Bedoussac et al. 2015). To achieve this requires both species of intercrop reach maturity at similar dates and that adjustments are made to combined harvesters to suit the more fragile species (at the risk of loosing some of the grain of the other species). This practical question thus poses various difficulties not only in terms of choice of machinery and its adjustment but also from the logistic point of view of the companies collecting and storing seeds. Indeed, their organizational structure can play the role of a self-reinforcement mechanism that reduces the incentives to adopt new practices (Fares et al. 2012).

5 Conclusions

This chapter has shown the potential for increasing the use of grain legume-cereal intercropping reviewing primarily work conducted in low-N input conditions such as organic agriculture. However, the complexities of different species combinations and production objectives of intercrops make generalisation difficult. As an example, varietal selection criteria typically used for sole crops are not necessarily appropriate for intercrops (Carr et al. 1998). This highlights the limits of field experiments and the value of modelling multi-species cropping systems to optimize decisions on combinations to use as well as cultivation practice and production outcomes (Brisson et al. 2004; Corre-Hellou et al. 2009; Barillot et al. 2012, 2014a, 2014b). 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 better represent inter- and intraspecific competition (Launay et al. 2009). Furthermore, increased focus on farmer driven objectives for intercropping use and stakeholders needs for markets are required to challenging perceptions, routines, rules and regulations at the level of the cropping system and the social and economic context in which farmers and actors of the agro food chain operate. Re-introduction of intercropping strategies has to be negotiated and locally adjusted by relevant stakeholders to be effective. Such dedicated intercropping systems are not restricted to cereal/grain legume mixtures, so it would certainly be appropriate to establish linkages with other strategies such as perennial grasslands and agroforestry by sharing knowledge and tools to create a generic model of the behaviour of multi-species canopies. Such approach should be a way to extend these knowledges to more traditional intercropping systems practiced by farmers notably in Africa and Asia. Indeed, research works dedicated to these intercrop systems are limited compared to those focusing on cereal-legume intercrops in Europe. Finally, intercropping is one option with crop rotation to increase diversification which must be combined with the spatial distribution of crop at farm scale in order to increase the delivery of ecological services.

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