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Review Article

Intercropping with legume for agroecological cropping systems: Complementarity and facilitation processes and the importance of soil microorganisms. A review

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ABSTRACT

Intercropping is a powerful way to promote a more diversified plant community in the field, thereby enabling complementary and facilitative relationships. In these systems, legumes are a key functional group, and are highly valued for the agroecological services they provide. This review identifies the different complementarity and facilitation processes in soils in intercropped legume/cereal systems and the key role of soil microorganisms in these processes.

The intercropped legumes/cereal systems reduce inter-specific competition by enhancing complementarity/facilitation processes thereby improving the exploitation of resources, which is, in turn, reflected in the increase in plant production corresponding to greater efficiency of the agroecosystem as a whole.

Plant production, including above- and belowground biomass, is positively correlated with microbial abundance and diversity. This microbial life is assumed to play a significant role in the availability and transfer of soil nutrients to plants as well as in plant health and soil fertility. Although we are currently unable to identify a reliable and exhaustive pattern of plant-microbe interactions, perhaps simply because no universal relationship exists between plants and microorganisms, reliable scenarios reveal strong trends and define the conditions required for successful intercropping systems and microbial interactions.

Given our incomplete knowledge of facilitation processes and belowground interactions, intercropping systems must learn from and apply the experience gained in successful experiments. Intercropping dynamics play a critical role in explaining the establishment of facilitative root interactions and finally suggest perennial plant associations may be more effective than annual ones.

Contents

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1. Introduction

Modern agriculture, which produces high yields through the generous use of chemical inputs and non-renewable energy, is currently being called into question. The recent past has revealed how costly this model can be in terms of public health and environmental integrity (Altieri, 2000; Tilman et al., 2002). The latest research underlines the importance of designing cropping systems using ecological principles and ecosystem services to enhance agroecosystem sustainability and production efficiency, offloading chemical inputs and non-renewable energy (Clergue et al., 2005; Moonen and Bàrberi, 2008; Wezel et al., 2014). This approach is known as '*agroecology*' (Gliessman, 1990; Wezel et al., 2014).

Following agroecological guidelines, a wide range of practices has been developed to improve the ecological functioning of cropping systems including intercropping, crop rotations, cover cropping, green manure, reduced tillage, and agroforestry (Wezel et al., 2014). Intercropping, i.e. growing two or more crops together on the same land at the same time (Willey, 1990), has great potential, and is expected to substantially optimize cropping systems thanks to diversification.

So far, a large body of literature has investigated the widespread practice of cereal/legume intercropping. Based on the observation that, in natural ecosystems, legumes are normally found among grasses, many authors have considered legumes as a key species in promoting ecosystem efficiency (Altieri, 1999; Anil and Phipps, 1998; Malézieux et al., 2009; Vandermeer, 1995; Vandermeer et al., 1998). Their use in intercropping system is largely explained by their nitrogen (N) fixing capacity, which makes them very valuable as green manure, especially in cropping systems with chronic nitrogen deficiency, i.e. organic farming (Bedoussac et al., 2015; Hauggaard-Nielsen et al., 2008). Intercropped legumes have proved to be capable of providing a wide range of additional services (Table 1) and of producing substantially higher yields than a sole crop– expressed as a land equivalent ratio (LER) higher than 1 (Willey, 1979).

Recent studies have demonstrated the particular importance of facilitative plant root interactions in mitigating stressful conditions and increasing yields. New insights into facilitation processes in particular emphasize the importance of intercropped roots in mobilizing limited or unavailable nutrients such as phosphorus in harsh environmental conditions (Betencourt, 2012; Hauggaard-Nielsen and Jensen, 2005; Latati et al., 2014, 2016; Li et al., 2014) and suggest a key role for soil organism diversity in the rhizosphere in these processes (Hinsinger et al., 2011b; Tang et al., 2014).

However, belowground interactions between intercropped roots and soil organisms are still largely unexplored and a very few data are available on facilitation processes (Brussaard et al., 2007). The involvement and role of the diversity of soil organisms is an open question, especially when we consider the importance of soil microorganisms. The abundance, role and function of microbial communities are poorly accounted for in plant facilitation and appear to be the missing link in understanding plant growth, nutrition and their interactions with the plant's immediate environment (Lemanceau et al., 2014; Philippot et al., 2013). Intercropping favors the development of different types of roots and changes overall root distribution and architecture, as well as exudation processes in the rhizosphere (Bargaz et al., 2015a;

Table 1
Agroecological services provided by cereal/legume intercropping systems.

Services		Evidence for	References
Provisioning	Yields	- Higher intercropping yields than for sole crop in low-input systems *(Land Equivalent Ratio >1)*	Bedoussac et al. (2015), Hauggaard-Nielsen et al. (2008), Jensen (1996), Willey (1979, 1990)
		- Stable and better yield quality through maintaining or improving grain protein content	Bedoussac et al. (2011, 2015), Jensen et al. (2006), Pelzer et al. (2012)
	Nitrogen dynamics	- Better use of symbiotic nitrogen fixation	Corre-Hellou et al. (2006), Hauggaard-Nielsen et al. (2009), Jensen (1996), Latati et al. (2014, 2016), Parsons et al. (1993)
		- Soil N enrichment	Amossé et al. (2014), Bergkvist et al. (2011), Fustec et al. (2010), Mahieu et al. (2014), Wichern et al. (2008)
	Use of resources	- Improved resource use efficiency *(light, nitrogen, water)*	Bedoussac and Justes (2010a, 2010b), Brooker et al. (2015), Matusso et al. (2014), Midmore (1993), Morris and Garrity (1993), Vandermeer et al. (1998), Willey (1990)
Regulation & Maintenance	Weeds	- Improved weed control	Amossé et al. (2013a,b), Haramoto and Gallandt (2004), Kruidhof et al. (2008), Liebman and Dyck (1993), Valantin-Morison et al. (2014)
	Pests	- Reduced attacks and damages caused by pests	Ratnadass et al. (2012), Risch (1983), Smith and McSorley (2000), Trenbath (1993)
	Soil	- Increased soil stability, aggregation and permeability	Carof et al. (2007), Karlen et al. (1997), Latif et al. (1992), Oelbermann and Echarte (2011), Wezel et al. (2014)
		- Increased soil organisms biomass, activity and diversity	Boswell et al. (1998), Latati et al. (2016), Qiang et al. (2004), Singh et al. (1986), Song et al. (2006), Tang et al. (2014), Whipps (2001)