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Enhancing Yields in Organic Crop Production by Eco-Functional Intensification

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Abstract

Organic agriculture faces challenges to enhance food production per unit area and simultaneously reduce the environmental and climate impacts, e.g. nitrate leaching per unit area and greenhouse gas (GHG) emissions per unit mass produced. Eco-functional intensification is suggested as a means to reach these objectives. Eco-functional intensification involves activating more knowledge and refocusing the importance of ecosystem services in agriculture. Organic farmers manage agrobiodiversity by crop rotation (diversification in time). However, sole cropping (SC) of genetically identical plants in organic agriculture may limit resource use efficiency and yield per unit area. Intercropping (IC) of annual grain species, cultivar mixes, perennial grains, or forage species and forestry and annual crops (agroforestry) are examples of spatial crop diversification. Intercropping is based on eco-functional intensification and may enhance production by complementarity in resource use in time and space. Intercropping is based on the ecological principles of competition, facilitation and complementarity, which often increases the efficiency in acquisition and use of resources such as light, water and nutrients compared to sole crops, especially in low-input systems. Here we show that IC of cereals and grain legumes in European arable organic farming systems is an efficient tool for enhancing total grain yields compared to their respective sole crops. Simultaneously, we display how intercropping of cereals and legumes can be used as an efficient tool for weed management and to enhance product quality (i.e. cereal grain protein concentration). We discuss how intercropping contributes to efficient use of soil N sources and minimizes losses of N by nitrate leaching via *Ecological Precision Farming*. It is concluded that intercropping has a strong potential to increase yield and hereby reduce global climate impacts such as GHG kg^{-1} grain. Finally, we discuss likely barriers and lock-in effects for increased use of intercropping in organic farming and suggest a roadmap for innovation and implementation of IC strategies in organic agriculture.

Keywords: crop diversification, grain legumes, cereals, intercropping, ecological precision farming

1. Introduction

Organic agriculture is based on a set of principles one of these being the principle of ecology. This principle states that organic agriculture should be based on ecological processes, cycles and systems. To a large extent this is achieved by promoting ecosystem services such as biological nitrogen fixation, soil carbon sequestration, nutrient circulation, pollination and biological pest control. However, this often results in a certain trade-off between the high yield of commodities versus the lower environmental impact and maintenance of natural capital (e.g. biodiversity, soil organic matter) for ecosystem services delivery, also in a longer term perspective. Crop yields only represent one dimension in the range of ecological, social and economic services delivered by farming systems. Simple yield comparisons between organic and conventional systems, without considering externalities, product quality and net margins, are thus inappropriate. However, global food production must increase while considering new ways of better distribution, the global diet, planetary boundaries and ability of agricultural systems to supply ecosystem services in the long term (McIntyre, Herren, Wakhungu & Watson, 2009; Rockström et al., 2009; Foley et al., 2011). The key argument is to ensure future food security and sovereignty and in this context organic agriculture is a system that has much to offer.

Recent meta-analyses have revealed that the "yield gap" of organic agriculture to conventional agriculture is 19-25% (Seufert, Ramankutty, & Foley, 2012; Ponisio et al., 2015). However, yield differences are highly contextual, depending on cropping system and site characteristics, and range from 5% lower yields in organic agriculture (rain-fed legumes and perennials) to 34% lower yields (Seufert et al., 2012). With good management practices, particular crop types such as legumes, fruits and perennials can result in organic yields comparable to conventional yields. Ponisio et al. (2015) indicate that the 19% "gap" may be an overestimate. However, more research and innovations are needed to increase yields in organic agriculture, both in developed and developing countries to safeguard food security and ensure low levels of global environmental impacts, such as GHG emissions (Knudsen, Halberg, Hermansen, Andreasen, & Williams, 2010). Furthermore, while decision makers and public institutions affecting the future of organic agriculture often base their decisions on simple yield comparisons and environmental impact assessments relative to conventional systems, holistic and multi-criteria systems analyses will be required to guide organic agriculture as well as conventional agriculture towards improved sustainability.

Niggli, Slabe, Schmid, Halberg, and Schluter (2008) introduced the principle of eco-functional intensification of agriculture. According to the definition by the International Federation of Organic Agriculture Movements organic agriculture relies on ecological processes, agrobiodiversity, cycles adapted to local conditions, and agro-ecological approaches. Eco-functional intensification in organic agriculture means intensifying the beneficial effects of ecosystem services, including soil fertility and biodiversity, and using the biological elements of the ecosystems in a structured, organized and more efficient way. Therefore, eco-functional intensification with improved nutrient cycling techniques and agroecological methods for enhancing diversity and health of soils, crops and live-stock is a priority in organic agriculture. In addition, eco-functional intensification is based on the knowledge of stakeholders; it relies on powerful information and decision-making tools and the cooperation and synergy between different components of agriculture and food systems (Niggli et al., 2008). Subsequently, the Royal Society (2009) in their report "Reaping the Benefits" awakened the principle of "sustainable intensification" (from Pretty, 1997), which they define as agriculture where yields are increased without adverse environmental impact and without the cultivation of more land. Later, Bommarco, Kleijn and Potts (2013) developed the principle of "ecological intensification" into entailing the environmentally friendly replacement of anthropogenic inputs and/or enhancement of crop productivity, by including regulating and supporting ecosystem services management in agricultural practices, which do not differ from the principles of eco-functional intensification.

Planned functional agrobiodiversity in time and space of cropping systems are fundamental to agroecological and organic production systems (Altieri, 1995; Vandermeer, van Noordwijk, Anderson, Ong & Perfecto, 1998). Agrobiodiversity is achieved through crop rotations, which include the use of cover crops, to reduce weeds, pests and soil-borne diseases, enhance nutrient use efficiency and improve soil quality (Karlen, Varvel, Bullock and Cruse, 1994). Agrobiodiversity in space may be implemented by annual or perennial grass-legumes mixtures, within species varietal mixtures, annual or perennial grain intercrops, agroforestry and field spatial design. Even though intercropping offers many significant advances and was common before "fossilization" of agriculture, it may appear as if organic agriculture did not strongly enough consider the possibility of redesigning systems to include more intercrops, but rather adapted the SC principle from conventional agriculture. An important question could be raised whether organic agriculture while expanding the cropping area forgot to re-designing the agroecosystem for planned spatial crop diversity as an important management tool? The aim of this review is to analyse the potential of crop diversification in space, exemplified by intercropping cereal and grain legumes, as a means of eco-functional intensification, which can contribute to enhancing crop yields in organic agriculture potentially without enhanced negative environmental impact.

2. Intercropping – the Intentional Use of Functional Agrobiodiversity

It has been demonstrated that intercropping (IC), the growing two or more crop species on the same piece of land at least during part of their development (Willey, 1979; Figure 1) significantly improves the use of plant growth resources, frequently reduces pests, diseases and weeds, enhances the yield per unit area over SCs and the yield stability over years, makes the crop more resilient to stress and improves the quality of the grain in conventional and organic agriculture (Willey, 1979; Vandermeer, 1989; Jensen, 1996a; Hauggaard-Nielsen, Jørnsgaard, Kinane, & Jensen, 2008, Bedoussac & Justes, 2010).

Intercropping is based on the intentional use of functional agrobiodiversity to maintain and intensify the use of associated ecosystem services, such as soil fertility, control of pests and diseases, pollination and improvement in nutrient use and water use across both spatial and temporal scales due to species complementarity (Jackson, Pascual, & Hodgkin, 2007; Kremen, Iles, & Bacon, 2012; Costanzo & Barberi, 2014). Besides functional agrobiodiversity, intercropping is based on the ecological principles of competition, complementarity and facilitation. If interspecific competition for growth factors is lower than intraspecific competition, species share only part of the same niche and reduced competition or the competitive production principle is in action (Vandermeer, 1989). This principle says that two different species occupying the same space (based on the soil surface) will use all of the necessary resources more efficiently than a single species occupying that same space, e.g. via a better use of the whole soil volume and various nutrient biogeochemical niches (Vandermeer, 2011). In the case of high input cropping systems, including use of mineral fertilizers, pesticides, irrigation, and mechanization, resource complementarity is less likely to occur, due to the high availability of growth resources. However, in such cases, intercropping may deliver other services such as regulating weeds and improving the product quality. In organic agriculture which often may have greater environmental variability than in intensive conventional agriculture, yield advantages through the competitive production principle often occur (Vandermeer, 2011). Crop species may complement one another in both time and space when species differences give rise to a better overall use of resources in intercrops than in the separate sole crops. Facilitation describes species interactions that benefit at least one of the participants and cause harm to neither. This process may occur when plants ameliorate the environment of their neighbors and increase their growth and survival, as an example one species may solubilize soil P which otherwise would be unavailable to the other companion species in the intercrop stand (Zhang & Li, 2003; Hinsinger et al., 2011).

Figure 1. Intercrop of fababean and wheat in Swedish in organic agriculture (Photo: ES Jensen)

3. Intercropping – the Case of Cereals and Grain Legumes in Organic Agriculture

Research on IC in organic agriculture has increased during the recent decade, especially in France, Denmark and Sweden. A study was undertaken to integrate and analyse a comprehensive amount of data (Bedoussac et al., 2014; Bedoussac et al., 2015) from 22 IC experiments at 13 sites in Toulouse and Angers (France) and near Copenhagen (Denmark) during 2001-2010 with two grain legumes (fababean, *Vicia faba* L. and pea, *Pisum sativum* L.) and three cereals (durum wheat, *Triticum durum* L.; soft wheat, *Triticum aestivum* L. and spring barley, *Hordeum vulgare* L.).

In 91% of the experiments, total grain yields of cereal and grain legume intercrop were greater than the mean SC yield, with mean intercrop yields being 3.3 Mg ha^{-1} compared to mean SC yield being 2.7 Mg ha^{-1} (Figure 2a). At an average sole crop yield of ca. 3 Mg ha^{-1} the yield advantage of the intercrop is up to 66% (Bedoussac et al., 2014). Similarly, total intercropping yields were greater than SC cereal yields (Figure 2b) and SC grain legume yields (2c), when SC grain legume or cereal yields were lower than 4.0 to 4.5 Mg ha^{-1}. However, comparing dry matter production of different qualities such as cereal grains with protein rich grain legumes only gives an indication of the yield advantage. Several indexes have been developed to be able to better evaluate the performance of an intercrop compared to the SCs grown on similar area of land, but split into the same proportion as the components in the intercrop. The most commonly used index is the Land Equivalent Ratio (LER), which gives the relative area required from growing SC to obtain the same yield (of both species) as in the intercrop (Willey, 1979; Vandermeer, 1989). The LER value for an intercrop is calculated as sum of the ratios (partial LER of each species or pLER) of the intercrop yield and the SC yield of each component. If the LER is greater than 1 there is an advantage from IC in terms of yield and land use, e.g. $pLER_{legume} + pLER_{cereal} = 0.5+0.7 \Rightarrow LER = 1.20$, indicating that 1.2 m² of SCs are required to obtain the same production as from 1 m² of IC, i.e. there is 20% advantage from intercropping. If LER ≤ 1 there is no advantage from intercropping. A basic requirement is that the farmer is interested in growing both crops.

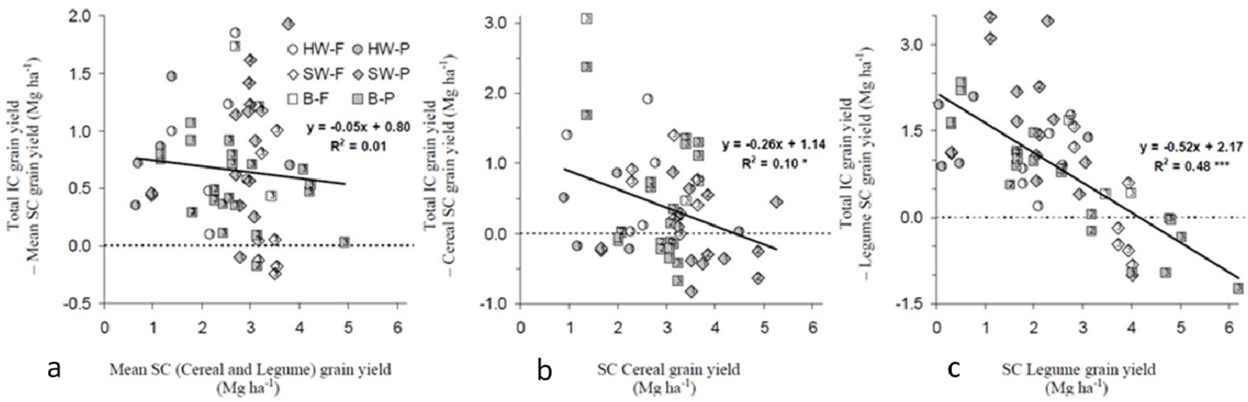

Figure 2. Difference between intercrop and sole crop yields as function of sole crop yields

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: Toulouse; 2: Angers and 3: Denmark). HW: Durum wheat; SW: Soft Wheat; B: Barley; F: Faba bean and P: Pea. Single asterisk and triple asterisks indicate that linear regressions are significant at P=0.05 and P=0.001, respectively. (N=58). Source: Bedoussac et al. (2014). Copyright Springer Science + Business Media.

Figure 3 shows that almost all of the 58 intercrops in this analysis had LER greater than 1 as indicated by the dotted line. The average LER is 1.27, indicating on average 27% yield advantage and improved resource use from IC compared to sole cropping. Furthermore, Figure 3 shows the variability of LERs within different groups and treatments.

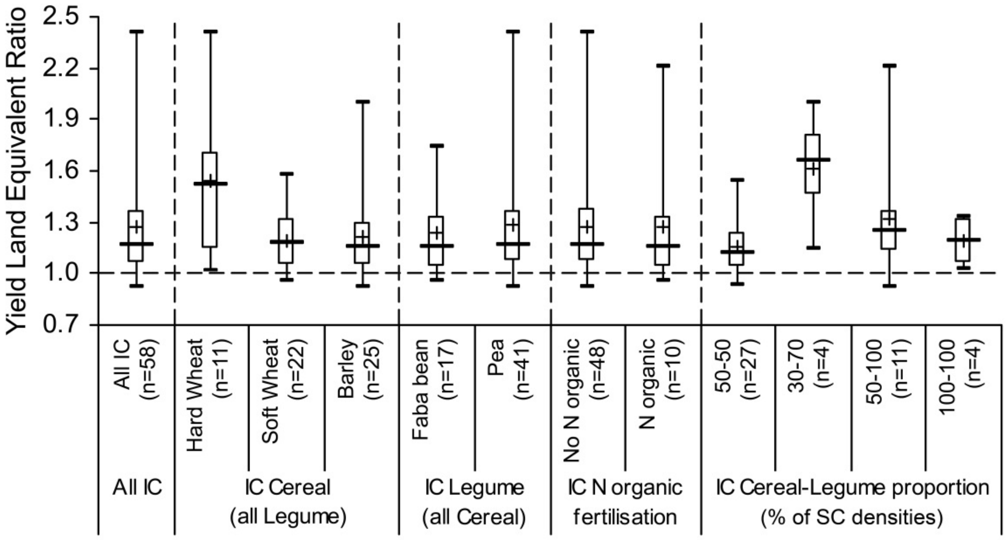

Figure 3. Land Equivalent Ratio based on grain yield of 58 intercrops from France and Denmark

Grain yield-based LERs shown as overall means for selected groups of ICs. Base of the vertical rectangle: first quartile; Lowest horizontal bar: minimum; Wide bar in rectangle: median; +: mean, Highest horizontal bar: maximum; Top of the vertical rectangle: Third quartile. Source: Bedoussac et al. (2014).

In the intercrops the cereal is normally more competitive than the grain legume and the final intercropping grain yield usually contains a greater proportion of cereal than the original proportion sown in the intercrop (Bedoussac et al., 2014). It has also been shown that the available soil mineral nitrogen (N) is an important factor for determining the outcome of the competitive interaction between species and the advantage of IC compared to SC (Jensen, 1996a; Hauggaard-Nielsen et al., 2008, Bedoussac & Justes, 2010). The greater the level of available soil mineral N, the less the IC advantage. This is explained by the uneven sharing of soil mineral N between the cereal and the grain legume. The cereal will, due to its better competitive ability for soil mineral N, use a much higher proportion of the soil mineral N than its "share" as defined from the intercrop composition. This will make the grain legume fix a greater proportion of its N requirement from atmospheric N_2 (Jensen, 1996a; Hauggaard-Nielsen et al., 2007; Hauggaard-Nielsen et al., 2009). Facilitation from the annual legume in terms of N transfer to the cereal, is normally not significant or only modestly contributing to the N supply of the cereal (Jensen, 1996a; Jensen, 1996b; Shen & Chu, 2004), due to the lack of synchrony between mineral N release from decomposing grain legume residues and the narrow window of N acquisition of the cereal in an annual intercrop.

Several additional services are obtained from the IC of grain legumes and cereals. The more efficient use of soil mineral N and the more balanced carbon-to-nitrogen ratio of the crop residues compared to sole crops contributes to a more balanced mineralization-immobilization turnover of N. This may result in reduced net mineralization of N and nitrate leaching losses in the autumn as compared to SC grain legumes (Hauggaard-Nielsen, Ambus, & Jensen, 2003) and reduced net immobilization of N in the spring as compared to the incorporation of SC cereal crop residues. Even though the cereal is able to recover a higher proportion of the soil N than "its share", competition occurs for other growth factors such as non-N nutrients and water. This results in increased protein concentration and baking quality of the cereal as compared to the SC cereal even if the SC cereal is supplied with extra N (Hauggaard-Nielsen et al., 2008; Gooding et al., 2008; Bedoussac & Justes, 2010; Bedoussac et al., 2014; Figure 4a). In almost all intercropped cereals the protein concentration was greater than in the sole cropped cereals, but the greater the SC cereal protein concentration the lower the IC advantage (Figure 4a).

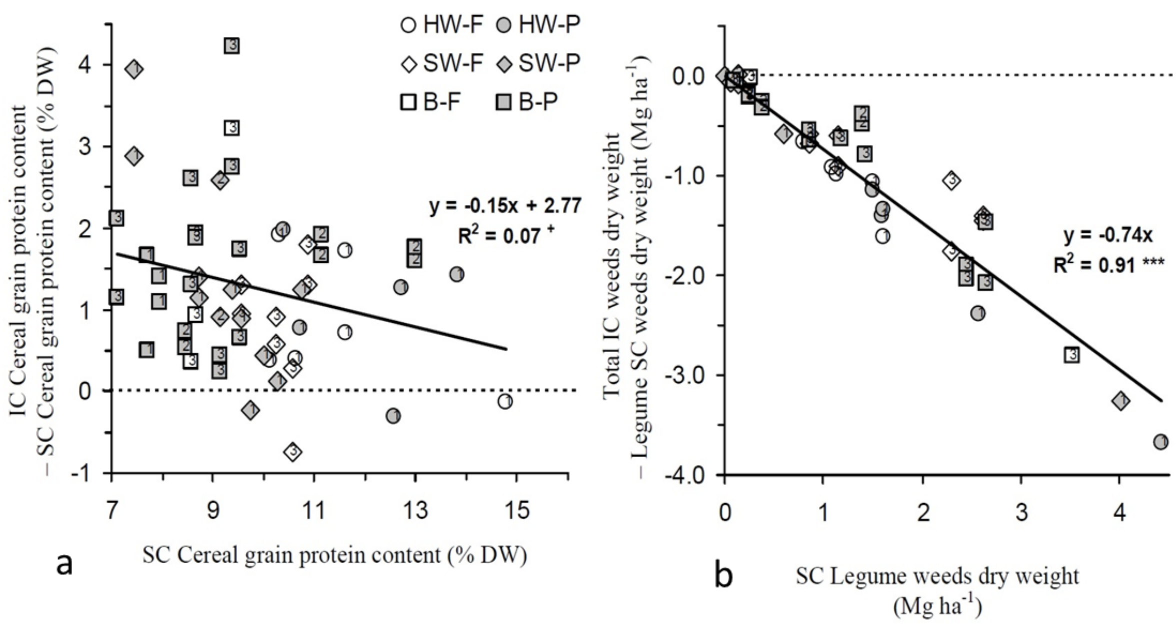

Figure 4. Effect of intercropping on the cereal protein concentration (a) and the weed biomass (b) compared to SC cereal and SC legumes, respectively. See Figure 2 for explanation to figures. Source: Bedoussac et al. (2014). Copyright Springer Science + Business Media

In addition to N use efficiency and cereal grain quality, IC significantly reduces the weed pressure as compared to SC grain legumes in organic agriculture (Corre-Hellou et al., 2011; Bedoussac et al., 2014). In the analysis of the IC experiments in France and Denmark, IC almost eliminated weeds as compared to SC legumes resulting in the relationship shown in Figure 4b. Furthermore, it has been shown that the yield stability over several years may be greater in ICs than the SCs especially compared to SC grain legumes (Jensen, 1996a). Part of these effects are explained by reduced grain legume lodging in IC, more efficient use of light and nutrients such as S, P, K, and reduced plant diseases (Hauggaard-Nielsen et al., 2008).

4. Discussion

This analysis clearly demonstrates the significance of intercropping as means to enhance yields and improve use of growth factors in organic agriculture. From an organic agricultural perspective the complementarity in use of N sources by the components of the cereal-grain legume intercrop is important in relation to N use efficiency. First, available soil mineral N is often a limiting resource in organic agriculture, whereas N_2 from fixation in principle is unlimited. Growing a SC cereal will not result in N_2 fixation. Growing a SC legume will result in the use of available soil mineral N, while the legume could cover its N supply by N_2 fixation, i.e. the legume SC could be considered a soil mineral N “wasting”. Secondly, soil mineral N is varying at the landscape and at minor scales depending on the C-N cycling. In conventional farming, N-fertilization, and especially using precision farming technology with differential supply over the field, aims at reducing the variability in available soil N.

We propose that intercropping is considered as an *Ecological Precision Farming* Technique, since the intercrop will adjust its botanical composition and acquisition of N from both sources – soil mineral N and N_2 fixation - according to available soil mineral N by competitive interactions. The cereal will thrive in the places of the field with the higher availability of soil N and use it efficiently while in places with lower soil mineral N availability legumes will thrive. Thirdly, the improved use of N sources may reduce losses of N from nitrate leaching and nitrous oxide emission as compared to SC of grain legumes without a subsequent cover crop.

There is a significant potential of using functional agrobiodiversity, e.g. by intercropping, to a greater extent in organic agriculture and one can wonder why IC technology in a modern context has not been implemented to a greater degree. The yield advantages are obvious and Ponisio et al. (2015) in their recent meta-analysis found that the “yield gap” is only 9% in favour of conventional sole crops relative to organic intercrops.

However there are barriers, lock-in and challenges to be solved research and development in participatory learning and action research with stakeholders in the food system, including the farmer to the consumer. Challenges and some key points in a roadmap for research are:

a. *Farmer and advisory service values and knowledge*. Intercropping might be considered as old-fashioned technology, and there is insufficient knowledge among organic and conventional "sole crop farmers" about the potential of intercrop systems.

b. *The homogeneity paradigm.* Lock-in effects by wholesalers and retailers, who are not used to handle mixed grain (Magrini, Triboulet & Bedoussac, 2013). Thus, the current market for intercrops are restricted to on-farm use for feed, or alternately on-farm sorting of intercrop grains before selling - sorting machinery is readily available.

c. *Breeding of cultivars suitable for IC, including perennial cereals and legumes*. Currently arable crops are only bred for sole cropping. Breeding programmes should be established for developing cultivars suited for intercropping in organic agriculture, including the matching of cultivars for simultaneous harvest.

d. *Integration of intercrops in the crop rotation.* Long-term research is needed to study the integration of intercrops in crop rotations without diminishing the important crop rotation effects, especially in term of reducing soil-borne diseases. Analysis of how the pre-crop value of sole crop legumes in term of N effect is affected by intercropping should be integrated in the research programme. A study with a rotational sequence of pea SC, oat SC and a pea-oat intercrop followed by two subsequent cereal crops was encouraging. No significant difference was found between pea and pea-oat as pre-crop to the subsequent two cereal crops (Hauggaard-Nielsen, Mundus & Jensen, 2012).

e. *Climate-smartness of intercropping.* There is a need for knowledge and data on GHG emissions from intercrops as compared to sole crops.

f. *Multicriteria sustainability assessment of IC systems.* Analyses of the sustainability of intercropping systems are required, based on the use of appropriate tools for analysing environmental, economic and social effects of intercropping systems.

5. Conclusions

We conclude that there is great potential for functional agrobiodiversity to strengthen eco-functional intensification in organic agriculture. Intercropping enhances ecosystem services including crop yield, N use efficiency, pest and weed management, and reduces nitrogen losses to the environment. Developing and implementing intercropping systems in organic agriculture will be an important means to further reduce the organic to conventional "yield gap", while considering additional ecosystem services and low environmental impact. We support the statement of John Vandermeer (2011): "nevertheless, little doubt exists that in the future, as systems become more ecologically sophisticated, intercropping and agroforestry are likely to be more important components of overall productive systems".

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