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ESSAY

Diversifying European agricultural systems by intercropping grain legumes and cereals

Erik S. Jensen, Iman R. Chongtham, Nawa R. Dhamala, Carolina Rodriguez, Nicolas Carton, and Georg Carlsson
Swedish University of Agricultural Sciences, Department of Biosystems and Technology, Cropping Systems Ecology. SE- 23053 Alnarp, Sweden.

Abstract

E.S. Jensen, I.R. Chongtham, N.R. Dhamala, C. Rodriguez, N. Carton, and G. Carlsson. 2020. Diversifying European agricultural systems by intercropping grain legumes and cereals. Int. J. Agric. Nat. Resour. 174-186. Cropping system diversification is a key factor in developing more sustainable cropping and food systems. The agroecological practice of intercropping, meaning the simultaneous cultivation of two or more species in the same field, has recently gained renewed interest as a means of ecological intensification in European agricultural research. We discuss some recent research developments regarding 1) intercropping for ecological intensification in agroecological and conventional cropping systems, 2) studies on nitrogen resource use by cereal-grain legume intercropping cultivation, 3) the role of intercropping in the management of biotic stressors, especially weeds, and 4) intercropping as a means of creating cropping systems that are more resilient to the abiotic and biotic stress associated with climate change. Finally, we propose methods for the greater adoption of intercropping in European agriculture by unlocking farming systems from upstream and downstream barriers, with the aim of developing more sustainable agricultural and food systems.

Keywords: Agroecology, ecological intensification, food security, mixed cropping, multi-actor approach, nitrogen use, sustainability

Introduction

The agroecological transition to more sustainable agricultural and food systems is based on principles, some of which are related to the ecology of agricultural systems and some of which are related to the socioeconomics of food systems (Nicholls *et al.*, 2014; Dumont *et al.*, 2016). A number of agroecological practices are instrumental in implementing agroecological principles (Wezel *et al.*, 2014). A key agroecological principle in agricultural production systems is diversification in time and space (Nicholls *et al.*, 2014; IPES-Food, 2016; Meynard *et al.*, 2017). The post-World War II political priorities for increasing food security and the research priorities of some agronomists led to a shift towards intensified and uniform short crop rotations with sole crops and monocultures.

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Corresponding author: erik.steen.jensen@slu.se

This development was facilitated by the use of abundant and inexpensive fossil energy, heavy mechanization and synthetic chemicals and fertilizers, which are required to compensate for the loss of soil fertility and resistance to biotic stresses, two regulating ecosystem services traditionally derived from planned diverse cropping systems within diverse landscapes (Matson *et al.*, 1997; Vandermeer *et al.,* 1998; IAASTD, 2009; Foley *et al.*, 2011). In addition, fossil energy-driven uniform crop production systems cause significant emissions of the greenhouse gases CO_2 and N_2O (Crutzen *et al.*, 2008) and may reduce associated biodiversity and increase the risks or vulnerability to both external and internal stimuli, *e.g.,* crop and fossil fuel prices and diseases (Altieri, 1999; Vandermeer *et al.*, 1998). Facing a future with finite sources of fossil energy and some nutrients, such as phosphorous, requires progress towards the adoption of more diversified, self-sustaining and energy-efficient agroecology-based agricultural systems that provide greater resilience to increasing weather extremes (IAASTD, 2009; Malézieux *et al.*, 2009; IPES-Food, 2016; IPCC, 2019).

The principles of crop diversification over time through crop rotation and their multiple potential benefits are well known and form the basis of most current organic cropping systems (Karlen *et al.*, 1994; Sebillotte, 1990). However, the basic knowledge of how different crop species may deliver ecosystem services for subsequent crops seems to have been partly lost during the last 60–70 years as crop rotations became shorter in most parts of the world, *e.g.,* in soybean-maize rotations or in continuous wheat production. This is also the case with diversification in space through intercropping (*e.g.,* mixed crops, polyculture, and associated crops), where farmers' and advisors' knowledge and research on the potential benefits and challenges of growing two or more species simultaneously or in relay on the same piece of land has been lost with the industrialization of agricultural cropping systems in Europe and the global North. The pioneering works of R. W. Willey (*e.g.,* 1979), B. Trenbath (*e.g.,* 1976) J. Vandermeer (*e.g.,* 1989) and several others in the last 50 years have increased our scientific understanding of the benefits of intercropping. From their research, we are aware that ecological processes and principles in multispecies crop communities may lead to ecological intensification (Bommarco, Kleijn & Potts, 2012; Bedoussac *et al.,* 2015) via mechanisms of competition, facilitation, complementarity and compensation. Intercropping may sometimes increase yields by more than 25% compared to growing sole crops and deliver several additional services, such as improved nutrient use efficiency and grain quality in food systems (Jensen *et al.*, 2015; Bedoussac *et al.*, 2015). However, farming systems in Europe and the global North are dedicated to sole crops, and farmers face several barriers if they want to implement intercropping in their cropping systems (Meynard *et al.*, 2018; Magrini *et al.*, 2018).

The reintroduction of diversified cropping systems via skill development/design or redesign of longer crop rotations, intercrops, agroforestry systems, cover crops, and other diversifying cropping system components seems to have regained focus on the European research agenda for addressing EU commitments to sustainable agriculture. The EU has recently invested significant research funding to understanding the challenges and potentials of crop diversification in time and space, manifested in several ongoing large research projects based on a multi-actor approach (ReMIX, 2020; DiverIMPACTS, 2020; https://www.cropdiversification.eu/).

The aim of this essay is to discuss recent advances in research on crop diversification in space through the agroecological practice of intercropping annual crops and how intercropping may increase yields with fewer inputs and increase the use efficiency of nutrient resources and improve the resilience of crops to abiotic and biotic stresses. We also discuss priorities in research and innovation for greater adoption of intercropping in European agriculture.

Ecological intensification: increased yields with fewer negative environmental impacts

For more than a decade, there has been a global focus on the sustainable intensification of crop production, meaning increasing yields with reduced anthropogenic inputs (Pretty, 2008) and ecological intensification in which anthropogenic inputs are substituted by an increased reliance on regulating and supporting ecosystem services in cropping systems (Doré *et al*, 2011; Bommarco, Kleijn & Potts, 2013). Intercropping is one of the most feasible practices leading to intensification with fewer negative environmental effects that also adheres to several agroecological principles (Nicholls *et al*., 2014). The observations of Willey (1979) and Trenbath (1976), *i.e.*, that intercropping results in improved use of resources and often greater yields than sole crops, were confirmed by Bedoussac *et al.* (2015) from low input system studies of cereal-legume intercrops and in a Canadian meta-analysis of 126 studies (Martin-Guay *et al*., 2018). The Canadian meta-analysis resulted in an average land equivalent ratio (LER; LER>1 indicates improved land use efficiency by intercropping) of 1.30, indicating that intercropping uses resources on average 30% more effectively than growing the same species as sole crops on a similar area of land. The reason for the improved use of resources and often improved yields is that different species do not exploit growth factors in the same way; *i.e.*, they do not use exactly the same niche (Trenbath, 1976; Vandermeer, 1981), reducing the competition between intercropped plants compared to sole crop plants of the same species. Vandermeer (1989) later developed this concept as the competitive production principle and demonstrated its link with the competitive exclusion/coexistence principle (Vandermeer 1981; 1989). These principles indicate that the use of the same niche by two species may lead to the extinction of one of the species in natural plant communities and no advantage in an intercropping system.

Cereal-grain legume intercropping is a typical example of plant species interactions in which reduced competition may lead to advantages in yield compared to that in sole crops in low-input systems (Bedoussac *et al*., 2015), since legumes are normally able to perform symbiotic N_2 fixation. Intercropping may also lead to significant benefits in terms of yield increases or reduced reliance on external inputs in conventional systems (Ghaley *et al*., 2005; Bedoussac & Justes, 2010). Intercropping of field pea and spring barley in a Danish conventional cropping system showed that it is possible to obtain similar grain yields in an intercropping system without N fertilizer as in a sole barley crop receiving 80 kg N ha^{-1} (Figure 1). These results also show that the intercropping advantage, as determined by the LER value, is reduced with increasing levels of N fertilization and increases with the proportion of pea in the intercropping system (Figure 1). As a result of the better resource use, intercropped pea and wheat without N fertilization perform better than fertilized wheat in terms of having reduced climate change impact, acidification, terrestrial ecotoxicity and energy demand, as demonstrated in a life cycle analysis (LCA) (Naudin *et al.,* 2014). Regarding eutrophication impact, intercropping performed better than sole cropped pea but worse than sole cropped and fertilized wheat (Naudin *et al*., 2014). Furthermore, measurements of nitrate leaching have shown that intercrops have lower leaching rates than grain legumes grown as sole crops and lower N_2O emissions than sole crops (Hauggaard-Nielsen, Ambus & Jensen, 2003; Huang *et al*., 2014; Senbayram *et al*., 2016). These assessments show that real benefits can be obtained with regard to environmental performance while maintaining or increasing yield, which is a requirement for sustainable or ecological intensification. Intercropping may confer additional rotational benefits to cropping systems in addition to the improved resource use and ultimately higher yield than that in sole crops (Fletcher *et al*., 2016). However, further research is required to better understand, *e.g*., the rotational benefits and challenges of intercropping in crop rotations (Jensen *et al.,* 2015; Fletcher *et al*., 2016).

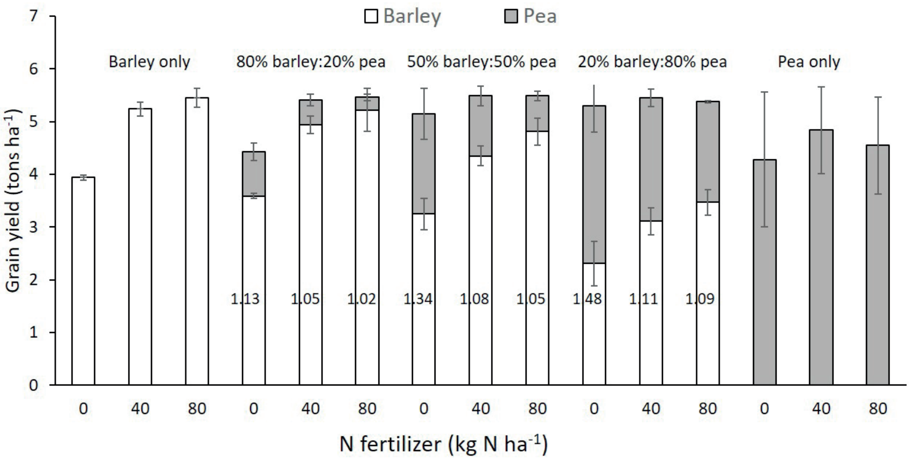

Figure 1. Effects of intercropping and sole cropping of field pea (normal-leaf cultivar) and spring barley in conventional cropping systems at different levels of nitrogen fertilization on grain dry matter yields. The intercrops consisted of mixtures of species in the same rows and had compositions of 80:20%, 50:50% and 20:80% of the barley and pea sole crop plant densities, respectively. The values within the intercrop columns are land equivalent ratio (LER) values. The values are the means over three years of a field experiment and three replicates (n=9) on sandy loam soil in Denmark (Jensen, unpublished).

Most agronomic studies are carried out at experimental stations situated on homogeneous land. Field experiments are often designed to eliminate all other types of variation or growth factor availabilities than the factor(s) under study. This is also the case for most intercropping studies, although farmers fields may be quite heterogeneous in terms of soil properties, inclination, etc. The conventional technology-intensive precision farming concept aims at homogenizing the environment, *e.g.* by supplying varying levels of nutrients in the field. This led us to propose the ecological precision farming concept (Jensen *et al.*, 2015), in which we hypothesized that intercropping systems will perform better than sole crops on heterogeneous land. This concept is based on the assumption that complementary resource use in intercrops will function as a buffer against heterogeneity in the availability of growth resources such as light, nutrients and water. Examples include intercropping of species with more or less drought resistance on land with a heterogeneous supply of water, cereal species mixtures with differences in sensitivity to soil acidity or cereal-legume intercropping on land with different availability of soil nitrogen (Jensen *et al.*, 2015). Thus, the aim of the ecological precision farming concept is to make use of plant-plant competitive-facilitative interactions for adapting to variability in soil properties and growth resource availability, thereby optimizing resource use and reducing dependency on external inputs.

The ecological precision farming concept may relate to the stress gradient hypothesis in ecology (Brooker *et al.* 2015; He, Bertness & Altieri, 2013), which assumes that the outcome of plant-plant interactions is context dependent; the greater the environmental physical stress (*e.g.,* from temperature or grazing) is, the greater the positive plant-plant interactions (facilitation). Similarly, we predict that in parts of a field with suboptimal growth factors for one species (*e.g.,* soil nitrogen availability), an intercrop of two species would result in an LER>1 if one species can fix dinitrogen from the atmosphere. We are currently testing the ecological precision farming concept in large field-scale experiments in Germany and Sweden (Figure 2).

Figure 2. A field experiment (approximately 1 ha) with strips of sole cropped and intercropped oat and field pea in SLU Alnarp, Sweden, was performed to test the ecological precision farming principle in the Horizon 2020 ReMIX project. The experiment had five blocks of three strips (pea sole crop, oat sole crop and 50:50% pea:oat intercrop). Each strip had 10 plots, making a total of 50 plots of each crop within the experimental area. Photo: Ryan Davidson, SLU.

Improved use of nitrogen sources and reduced need for N fertilizer in grain legume-cereal intercropping systems

Intercropping of cereals and grain legumes will reduce competition for soil N sources, since legumes can use atmospheric dinitrogen in symbiosis with *Rhizobium* bacteria and may in this way reduce the intensity of the competition for soil nitrogen (N), allowing the cereals to use a larger proportion of the soil N in relation to the plant density. This was documented in a meta-analysis based on stable nitrogen isotope studies by Rodriguez *et al.* (2020), showing that the response ratio of soil N accumulation in intercropped cereal to solely cropped cereal was greater than 1. This indicates that on average, each plant in the intercropping system accumulated 53–67% more soil nitrogen than a cereal plant grown alone (Rodriguez *et al*., 2020). Similarly, the response ratio of intercropped legumes and legumes as the sole crop was much lower than 1, with the average soil N accumulation per legume plant in intercropping systems being 47–53% lower than that in solely grain legume crops. Therefore, the nonproportional sharing of the soil N source and the increase in symbiotic N_2 fixation by an average of 16% per plant in intercropping systems compared to that in sole legume crops (Rodriguez *et al*., 2020) results in an overall better use of N resources (Bedoussac *et al.,* 2015; Rodriguez *et al.,* 2020).

In a global-scale study, Jensen, Carlsson & Haugaard-Nielsen (2020) made a similar observation (Figure 3), and based on these observations, it was estimated that global N fertilizer use could be reduced by at least 26% if the total sole grain legume crop area (241 Mha) plus an additional 307 Mha sole cereal crop area was intercropped as cereal-grain legume intercrops. In addition, 115 million ha sole cereal crops could be converted to the cultivation of other species for additional diversification in time and space, since intercropping increased the yield per unit area due to ecological intensification (Jensen, Carlsson & Haugaard-Nielsen, 2020).

Additional potential for improved nutrient use by intercropping exists for nutrients other than N, *e.g.,* phosphorous, iron, zinc and manganese (Li *et al*., 2014; Xue *et al*., 2016). Soil fertility should be considered in light of the increased production and greater use of soil nutrient sources (P, K, etc.) in intercropping systems than in sole cropping systems (Stomph *et al.,* 2020).

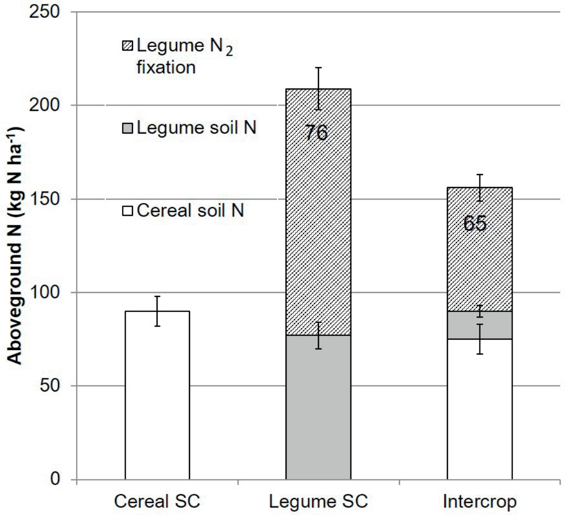

Figure 3. Total nitrogen acquisition in cereal and grain legume sole crops (SC) and intercropping systems from 13 published studies that used ^{15}N methodology for distinguishing soil-derived and symbiotically fixed N. The percentages shown in the columns are the N (%) derived from symbiotic N_2 fixation. The values are the means (± SE, n=13–16) of crop treatments from 13 studies (for details see Jensen *et al.,* 2020).

Management of weeds, diseases and pests

In Europe, there is a movement towards developing cropping systems with no or less use of pesticides by implementing more organic farming, integrated pest/weed management, and pesticide-free agroecological systems. In particular, France has a strong policy for reducing the use of pesticides by developing more diversified agroecological cropping systems.

Crops with slow early growth are often challenging in terms of weed management. This is the case with most grain legumes in systems without the use of herbicides, but intercropping of grain legumes with nonlegumes, which are more competitive for soil N use, can better control weed development than legumes grown as sole crops (Liebman & Dyck, 1993; Hauggaard-Nielsen, Ambus & Jensen, 2001a; Corre-Hellou *et al.,* 2011). This effect of intercropping on weed management in grain legumes is likely to be common in cropping systems, since it relates to the competitive ability of crops and weeds to use soil N, light and water sources; the rate of crop soil cover; and root growth (Hauggaaard-Nielsen, Ambus & Jensen, 2001b). A recent study in Sweden on intercropping lentil and oat demonstrated that in an intercropping system, oats were able to make better use of resources, which would have otherwise been used by weeds in fields with lentil as the sole crop in an organic farming system (Figure 4).

Intercropping has also been shown to contribute to the control of plant diseases (Boudreau, 2013). Studies (*e.g.,* Kinane & Lyngkjaer, 2002; Hauggaard-Nielsen *et al.*, 2008; Zhang *et al.,* 2019) have shown that plant diseases in both grain legumes and cereals are reduced in intercrops compared to sole crops. Crop diversification also significantly contributes to the management of insect pests (Altieri, 1999; Kremen, Iles & Bacon, 2012) by creating improved conditions for associated biodiversity and more ecosystem services, *e.g.,* by increasing the abundance and activity of the natural enemies of pests, the dilution of the host species and confusion of insect pests through a more diverse crop canopy. Stomph *et al.* (2020) extracted information from 153 papers on annual intercropping in field experiments and found that in 68% of the sole crop and intercrop comparisons, insect pests were reduced by intercropping, whereas in 8% of the comparisons, pests were increased.

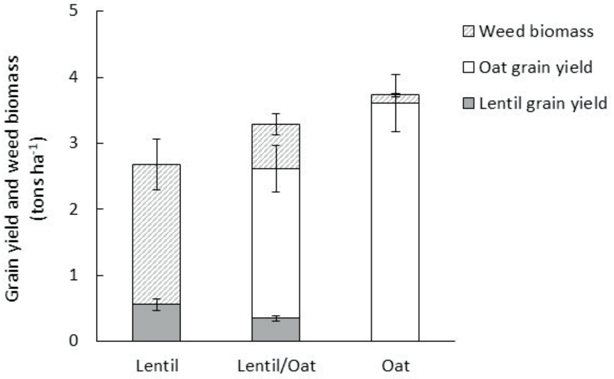

Figure 4. Sole and intercropping of lentil and oat for human consumption in a Swedish organic farming system. The lentil and oat crops were grown in the same row (80:20% of the sole crop density of each species). The error bars indicate the standard errors (n=24) for the average of six site-year experiments (2015–2018 at one site, 2017–2018 at another site), with four replicate blocks in each site-year (Carlsson, unpublished).

Adaptation to and mitigation of climate change

Climate change has several potential effects on agricultural crop production, but crop diversification is a means to develop cropping systems, which are more resilient and better adapted to the biotic and abiotic stresses associated with climate change (Lin, 2011). Crop diversification may prevent the spread of new pests and diseases. Intercropping systems in which species have different sensitivities to abiotic stress, such as drought, may be able to better buffer conditions of low water availability through a compensatory mechanism. In a field study in southern Sweden in 2018, sole cropping and intercropping of field pea and oat under conditions of almost complete growth season drought resulted in no harvestable yield of pea in the sole cropping and intercropping systems, while the oat yield harvested in the intercropping system (50% seed sowing density of oat as a sole crop) was 85% of the oat yield harvested in the oat sole crop (Chongtham *et al.,* unpublished). In an intercropping experiment codesigned by researchers, livestock farmers and advisors in Sweden, intercropping of faba bean with wheat (50% seeding density of the sole crop) resulted in a grain yield 77% of that in solely cropped wheat and reduced weed abundance compared to that in faba bean alone under severe drought conditions (Chongtham, Dhamala & Jense, 2020). Raseduzzaman & Jensen (2017) carried out a meta-analysis on the grain yield stability of intercrops over time and between sites. They found that the grain yield variability in grain legume-cereal intercropping was similar to that in sole cereal crops (coefficient of variance, CV: 22–25%), which was significantly ($p<0.05$) lower than that in sole grain legume crops (CV: 32%), indicating the stabilizing effect of intercropping compared to grain legume cultivation.

Similarly, intercropping may contribute to the mitigation of climate change, *e.g.,* by reducing the need for fossil-based N fertilizer, mechanical weed control and the associated N_2O and CO_2 emissions. It has also been reported that intercropping can increase carbon sequestration, mainly due to increased root production in strip intercrops compared to crop rotation (Cong *et al.,* 2015).

Removing barriers to increased crop diversification by intercropping

Barriers and restrictions may block the adoption of a greater degree of diversification in European agriculture (Meynard *et al.*, 2018). Upstream of farms, there is a lack of university teaching, training and research on diversification methods;

advisory service engagement; farmer education in intercropping; breeding of cultivars that are suitable for intercropping; and development of machinery for harvest and grain sorting. Furthermore, most agronomic researchers are focusing on incremental research on mainstream cropping systems using sole crops. In addition, farmers wishing to implement intercropping are hindered by downstream actors, *e.g.,* EU policies on subsidies for sole crops, grain companies being reluctant to agree to contracts or buy intercropped grains and the trade/food sector requirements for homogeneous and "clean" grain. A similar restricted situation was faced by organic farming pioneers, and these restrictions were circumvented by setting up supply chains and creating added value. Perhaps intercropping could benefit from similar developments.

Given the many potential benefits of ecological intensification in crop production by intercropping outlined above, there is a need to move towards a more disruptive research approach involving whole food systems. Thus, integrative research projects involving stakeholders, such as farmers, advisors and other actors in the value chain and interdisciplinary scientists, are required to move intercropping forward in European industrialized cropping systems. It is not feasible to concentrate on incremental agronomic research alone, *e.g.*, by demonstrating yield benefits in small plots. However, it is necessary to address more of the technical barriers to intercropping to increase farmer's adoption (Lemken, Spiller & von Meyer-Höfer, 2017). In this study, the authors also found that proponents of reduced tillage and legumes seemed more likely to adopt intercropping in their cropping systems. Crop mixtures may need to be separated after harvest to be marketable, and if the costs associated with sorting are high, it may result in the loss of the economic gains obtained from the increased yields of the intercropping system. There are also barriers in relation to societal acceptance, willingness to pay for ecological services, the development of new products from crop mixtures, and weak links between actors in the value chain/food system. More decisive policies on the implementation of diversification practices in line with sustainable development goals are required. These policies must encourage and support more radical changes in food systems.

Furthermore, it is essential to know more about the effects of intercropping on the quality of the harvested produce. It is well known that the protein concentration of intercropped cereals is often higher than that in cereals cropped alone, at least under low-input management (Gooding *et al.*, 2007; Bedoussac *et al.*, 2015). Less is known about other nutrient concentrations in legumes and cereals, and it is likely that competition between species may influence the nutritional composition of crops, either positively or negatively, compared to that of sole crops (Stomph *et al.*, 2020). Despite the many benefits of crop diversification, which have been demonstrated by several researchers, there is a very low adoption of such practices by farmers. Thus, an agroecological approach considering the sustainability of the whole food system is required to support the increased adoption of intercropping in European cropping systems. Recent EU Horizon 2020 projects focusing on intercropping and other types of crop diversification have adopted this transdisciplinary approach, involving multiple actors (farmers, advisors, food companies, and scientists) in developing and promoting more diverse cropping systems (ReMIX, 2020; DiverIMPACTS, 2020; and other projects in the crop diversification cluster). In multi-actor platforms, participatory research methods involving codesigning, testing, learning and evaluation of intercrops and new crop rotations have been used in close collaboration with farmers, advisors, researchers and other value chain actors. This method aims to do away with the conventional top-down approach and promote the development of agroecological farming practices that suit local conditions (*e.g.*, climate, knowledge, technology, and market), supporting greater adoption. The actors in these platforms may be the first movers and can act as ambassadors for the increased cultivation of intercrops in European agriculture.

Conclusions

Intercropping of different plant species is an agroecological practice for crop diversification. Intercropping is a feasible and realistic means of ecological intensification of agricultural systems. There is significant evidence showing that increased and more stable yields are achieved through cereal-grain legume intercropping than through sole cropping and that intercropping systems require less N fertilizer and often require fewer weed control measures than grain legumes cropped alone. The greater adoption of intercropping in European agriculture requires solving technical, societal and educational challenges related to crop production and the long-term effects of diversification and identifying and eliminating restrictions and barriers prohibiting diversified cropping in food systems. The way forward seems to be the association of multi-actor platforms with interdisciplinary scientists in integrative projects of a more disruptive nature to design and evaluate locally feasible and relevant diversified agricultural systems.

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This manuscript summarises the authors' intended contribution at the Workshop on Challenges for Agroecology Development for the Building of Sustainable Agri-Food Systems (CRP), which was due to take place at the Faculty of Agricultural Sciences, University of Chile, Santiago de Chile, on 11–13 November 2019, and which was sponsored by the OECD Co-operative Research Programme: Biological Resource Management for Sustainable Agricultural Systems. Although due to the circumstances the workshop did not take place as a physical meeting and contributions intended to be supported by the OECD CRP are published in this Thematic Issue.

Disclaimer

The opinions expressed and arguments employed in this manuscript are the sole responsibility of the authors and do not necessarily reflect those of the OECD or of the governments of its Member countries.

Resumen

E.S. Jensen, I.R. Chongtham, N.R. Dhamala, C. Rodriguez, N. Carton, y G. Carlsson. 2020. Diversificar los sistemas agrícolas europeos mediante el cultivo intercalado de leguminosas y cereales. Int. J. Agric. Nat. Resour. 174-186. La diversificación de los sistemas de cultivo es un factor clave para desarrollar sistemas agrícolas y alimentarios más sostenibles. La práctica agroecológica del cultivo intercalado, es decir, el cultivo simultáneo de dos o más especies en el mismo espacio ha ganado recientemente un renovado interés como método de intensificación ecológica en la investigación agrícola europea. Discutimos algunos avances recientes de la investigación con respecto a 1) cultivos intercalados para la intensificación ecológica en sistemas de cultivos agroecológicos y convencionales, 2) estudios sobre el uso de los recursos de nitrógeno en cultivos intercalados de cereales y leguminosas, 3) el papel del cultivo intercalado en el manejo de factores de estrés bióticos, especialmente malezas y 4) el cultivo intercalado como medio para crear sistemas de cultivo que sean más resilientes al estrés abiótico y biótico asociado con el cambio climático. Finalmente, proponemos métodos para extender la implementación de cultivos intercalados en la agricultura europea desbloqueando los sistemas agrícolas de barreras, desde los aportes necesarios para la producción hasta el procesamiento de los alimentos, con el objetivo de desarrollar sistemas agrícolas y alimentarios más sostenibles.

Palabras claves: Agroecología, intensificación ecológica, seguridad alimentaria, cultivos mixtos, enfoque multi-actores, uso de nitrógeno, sostenibilidad

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