EU CAP Network

Focus Group 'Crop associations including Milpa and protein crops'

Starting paper

Funded by the European Union

Introduction

Agriculture and food systems are facing multiple drivers for change in response to the twin crises of climate warming and biodiversity loss. Policy strategies formulated at EU and national level aim to reduce agricultural fertiliser and pesticide use, reduce nutrient losses and greenhouse gas emissions, increase the use of organic and regenerative farming methods, reduce food waste, and put biodiversity on a path to recovery by 2030 (EU Green Deal, 2020). Alongside this, global events in the past few years have highlighted that farming methods need to be more adaptable to external shocks, such as spiralling energy and fertiliser costs, extreme weather events, and other factors, to increase agricultural resilience. New and alternative farming methods need not be novel *per se*, but instead could build on traditional farming knowledge adapted to modern farming contexts.

European cropping systems are dominated by specialised farms (EUROSTAT, 2020) which grow simplified crop sequences, frequently based on cereals or grasslands (accounting for >60% crop sequences: Ballot et al., 2022). This simplification of cropping systems based on high input monocultures of a small number of crop species has contributed towards environmental degradation and biodiversity losses in agricultural landscapes (Messean et al., 2021). Crop associations offer a method of increasing crop diversity within a field, not only to provide resources for wider agrobiodiversity, but also to improve crop productivity, regulate pests and diseases, increase soil fertility (especially when legumes are included), and reduce pollution through fewer pesticide and fertiliser inputs (Brooker et al., 2015).

The growing together of two or more crop species as ‘crop associations’ can take different forms, depending on the purpose of the practice and the spatio-temporal arrangement. The terminology used most frequently to describe crop associations is explained in **Box 1**. Crop associations might be grown in replacement (or substitutive) designs, where plants of one crop are replaced by plants of another crop, such that the density of each crop is reduced compared with its standard monocrop sowing density. Alternatively, additive designs involve at least one component being grown at its monocrop sowing density and other crop(s) are added in to form a mixture (**Figure 1**).

Although crop associations can increase diversity at field and farm scale and have the potential to boost agricultural production with fewer inputs, they are not practiced widely in European agriculture. This suggests that crop associations are not sufficiently attractive to switch from monoculture-based cropping due to challenges associated with their practical use in current farming systems, such as the availability of technical equipment and know-how for sowing, managing and harvesting mixed crops, the subsequent use of the crop products, and the financial impacts on the farm business.

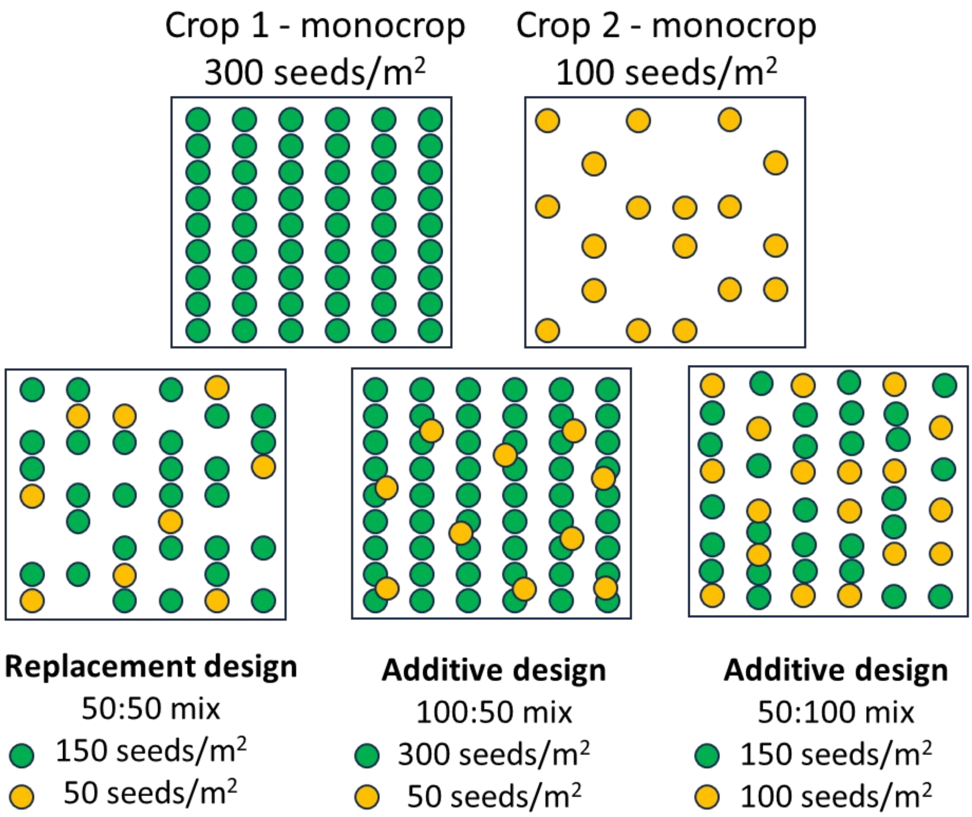


Figure 1. Visual illustration of replacement (or substitutive) and additive designs for crop associations involving two crops. Crop 1 could represent a cereal such as barley and Crop 2 could represent a legume such as pea. Replacement designs do not increase the overall crop density, while additive designs lead to higher total crop density, compared with the monocrop densities of the constituent crops.

Box 1. Explanation of common terms used for different crop associations.

Term	Meaning	Example
Intercrop	Cultivating two or more crops simultaneously on the same piece of land, either as a homogeneous mixture or in alternate rows	Spring barley and pea crops sown together as a mixture
Relay intercrop	The life cycle of one crop overlaps that of another crop but the crops are not entirely synchronised (e.g. a second crop might be seeded into a stand of an established crop) and the crops might be harvested together or consecutively	Soya bean sown in spring into winter-sown wheat
Strip cropping	Planting different crops in alternating narrow strips; often used to follow contours in the land and reduce erosion	Vegetable crops or cereals with grain legumes
Nurse crop (can include*)	A crop planted with another crop to shelter it (e.g. from frost, wind, weeds) during establishment	Annual or perennial crops used to assist

		in the establishment of perennial crops
Companion crop (can include*)	Planting of different crops in proximity for various purposes (e.g. pest repellence, pollination, weed suppression); can include ‘push-pull’ species combinations	Buckwheat, fenugreek, clover sown into oilseed rape to deter flea beetle and provide nutrients
*Cover crops, green manures, living manures	Species mixtures planted to improve soil health by covering the ground during fallow periods, or grown under cash crops to prevent erosion, store/release nutrients etc.	Clover-vetch-ryegrass, which might include subsequent sowing of a cash crop into the cover after establishment
Milpa (or ‘Three sisters’)	Traditional polyculture system from Mesoamerica aiming to maximise food production from small land holdings.	Maize-common bean-squash; can include other combinations focused on maize
Agroforestry	Combinations of trees or shrubs are grown around or among agricultural crops and/or animals and pasture	Alley cropping of fruit trees with cereal crops

Aims of the Focus Group

This Focus Group brings together experts from research and practice to answer the question:

How to integrate crop associations into existing cropping systems and farm landscapes to increase farm resilience and efficient use of natural resources while reducing the dependency on external inputs?

The main tasks for the Focus Group are:

1. Identify, describe and classify with adequate examples, existing or new plant associations, adapted to each farming system within their landscapes and local/regional conditions.
2. Analyse the impact of the most promising crop associations on the environment, on the farmers’ productivity, profitability and resilience to climate change.
3. Identify their success and fail factors and barriers for implementation and adaptation in different regions.
4. Explore the role of innovation and knowledge exchange in addressing the challenges identified such as crop selection, crop rotation management, machinery, and product end use.
5. Propose potential innovative actions and ideas for Operational Groups to stimulate the use and improvement of crop associations at farm level considering the impact on the landscape.

6. Identify needs from practice and possible gaps in knowledge related to crop associations which may be solved by further research.

This paper provides a starting point for the first meeting of the Focus Group in November 2023. The document aims to i) summarise existing information about crop associations documented in Europe, ii) assess current knowledge about the environmental and socio-economic impacts of crop associations, and iii) present preliminary information about the factors affecting crop association use as a basis for discussion in the first Focus Group meeting.

Traditional and novel crop associations

Crop associations can be defined in terms of species composition (annual, perennial, or a mixture) and spatio-temporal arrangement (see **Box 1** and **Figure 1**). Common or novel crop associations used or tested by farmers and researchers in Europe were collated from reports and practice abstracts published by recent Horizon 2020 funded projects on intercropping and crop diversification (DIVERSify, ReMIX, DiverIMPACTS, Diverfarming), agroforestry (AFINET), and weed management (IWMPRAISE). The information was supplemented by information about mixtures grown in Europe reported in Li et al (2023). The websites of recently funded Horizon Europe projects were also checked (INTERCROPVALUES, LEGUMINOSE, ReForest, AF4EU, MIXED, AGROMIX and DIGITAF), although these projects do not yet have many published deliverables. The crop associations identified through this process were grouped by crop type: perennial/agroforestry; annual fruit and vegetable crops; cereal and legume crops; pseudo-cereal and oilseed crops; and other multi-species mixtures. The country where the crop association was reported was assigned to pedoclimatic region, as an indication of other countries where it might be suitable for growing (as shown, for example, in the latitudinal distribution of crop sequence types identified by Ballot et al., 2022).

Agroforestry

Agroforestry involves deliberate integration of woody vegetation (trees or shrubs) with crop and/or animal production systems. Although less commonly practiced than in the past, traditional agroforestry systems are still practiced widely in Europe, such as grazed woodland and grazed or intercropped orchards. Interest in agroforestry has been reignited due to its potential for sequestering carbon and improving biodiversity. Agroforestry crop associations are most commonly reported for Mediterranean and continental climates (**Table 1**). They often centre on fruit trees or grapevine and are diverse in composition, ranging from silvo-arable (e.g. walnut or almond trees grown with cereals or legumes), to herbaceous understories (e.g. aromatic herbs or cover crops under grapevine), to perennial mixtures (e.g. intercropped fruit trees). The structural composition typically consists of rows of trees either with a single sward (e.g. of rye, oat, clover-grass) growing underneath and between the rows, or trees with a herb/grass understory where grain or vegetable crops are growing in the alleys between rows. A unique arrangement is the ‘vinha do enforcado’ or ‘hanging vineyard' method of growing grapevines in Portugal and Spain, where vines are supported by tall trees growing around the perimeter of a plot used for arable crops or pasture.


Olive trees under sown with cereals (left) and cherry trees grown with a cover crop (right)

Table 1. Perennial fruit and agroforestry crop associations reported for different European countries and regions.

Component 1	Component 2	Country	Region
Walnut (±grass/herb understory)	Vegetables	BE	Atlantic
	Maize	BE, ES	Atlantic, Mediterranean
	Faba bean	BE, ES	Atlantic, Mediterranean
	Wheat	BE, ES	Atlantic, Mediterranean
	Rye	ES	Mediterranean
	Clover-grass	UK	Atlantic
Grapevine	Herbs	DE	Continental
	Cover crops	HU	Continental
	Plane, Ash, Willow, Elm	PT, ES	Mediterranean
	Mulberry, Walnut	PT, ES	Mediterranean
Olive	Asparagus	IT	Mediterranean
	Oat-vetch	ES	Mediterranean
	Saffron	ES	Mediterranean
	Lavender	ES	Mediterranean
Almond	Oat	ES	Mediterranean
Mandarin	Purslane	ES	Mediterranean
	Faba bean	ES	Mediterranean
Poplar	Maize	FR	Atlantic
	Sulla-Ryegrass	IT	Mediterranean

Horticultural crops

Crop associations involving annual fruit and vegetable crops are infrequently reported in the projects and literature examined here, even though vegetable intercropping is (anecdotally) widely practiced in home gardens and allotments. Although this is surprising given the wide array of potential combinations for horticultural crop associations, this might also reflect a barrier in terms of knowing which vegetables or fruits should be cropped together. More than half of the reported examples focussed on brassica crops (**Table 2**). These crop associations were grown either with living mulches or intercropped with other vegetables, commonly as row intercrops in additive designs where the two crops were sown simultaneously.

Table 2. Annual fruit and vegetable crop associations reported in European countries and regions.

Component 1	Component 2	Country	Region
Broccoli	Vetch	ES	Mediterranean
	Clover	IT	Mediterranean
Cauliflower	Clover	IT	Mediterranean
Aubergine	Clover	IT	Mediterranean
Melon	Cowpea	ES	Mediterranean
Cabbage	Broccoli	ND	Global analysis
	White cabbage	ND	Global analysis
	Cauliflower	ND	Global analysis
	Onion	ND	Global analysis
	White clover	ND	Global analysis

Arable crops

Cereal- or legume-based intercrops are the most frequently reported crop associations, often grown as cereal-legume mixtures. The frequency of cereal-legume intercrop combinations in each pedoclimatic region is summarised in **Figure 2** (for details of each combination, see **Annex 1: Supplementary Table 1**). Intercrops of wheat and barley with legumes are most common, followed by oat and maize, then triticale and rye. These cereals are grown with a diverse array of legume crops: peas are the most common partner, followed closely by faba bean, and these pairings are observed across all pedoclimatic regions. Lupin is selected as a crop partner for cereals in cooler climates (Denmark, Switzerland, France) while lentil and chickpea are selected in warmer countries (Turkey, Spain); the latter legume crops are also reported from the UK, France and Germany, where they are not widely grown as commercial crops, suggesting they represent novel crops and intercrop combinations. Soyabean and Lathyrus are reported infrequently (Denmark, France) and might also represent novel intercrop partners for some parts of Europe. The remaining legume crops are usually grown for fodder or as living mulches (alfalfa, lucerne, clover, trefoil, vetch) in all parts of Europe. Note that Milpa-type systems of maize grown with common bean or squash are reported for Switzerland, Austria and the UK. Some cereal-cereal crop associations are reported, suggesting that traditional maslins (cereal species mixtures such as wheat, barley, rye, oats) are still grown in Europe; a few legume-legume crop associations are also reported.

The design of these crop associations includes intercrops grown as alternating strips or rows, or as homogenous mixtures, with the latter two including both additive and replacement designs.

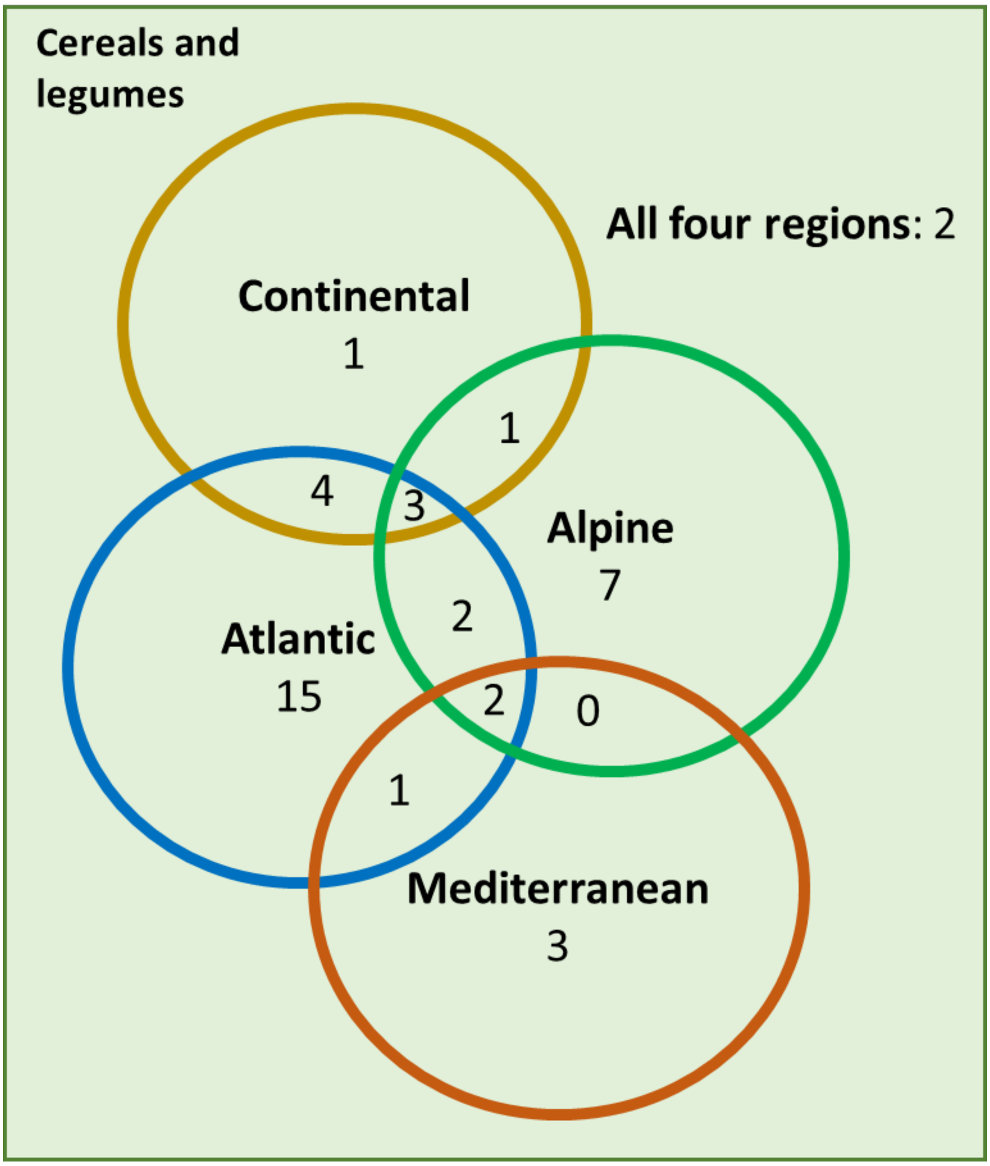


Figure 2. A summary of the frequency of different cereal-legume intercrop combinations reported in pedoclimatic regions of Europe, indicating the number of combinations shared between regions. See **Annex 1** (**Supplementary Table 1**) for details of each combination.

Pseudocereals are reported as crop association components in cooler climatic zones (**Table 3**), although sorghum, which is more typical of tropical countries, is reported as a combination with faba bean in Austria and might represent a novel intercrop combination for Europe. Sorghum also features in multi-species mixtures reported from Austria (**Annex 1: Supplementary Table 2**). Oilseed rape and sunflower are present as intercrops with grain and forage legumes, mainly in France and Switzerland, and occasionally with other crops (**Table 3**). A variety of annual crop species are grown as multi-species mixtures and cover crops, particularly in Atlantic climates (**Annex 1: Supplementary Table 2**).

Table 3. Pseudocereal- and oilseed-legume intercrops in European countries and regions.

Component 1	Component 2	Country	Region
Buckwheat	Faba bean	FR	Atlantic
	Vetch	UK	Atlantic
	Clover	UK	Atlantic
	Soyabean	FR	Atlantic
Camelina	Lentil	UK, FR	Atlantic
	Pea	CH	Alpine
	Nigella	UK	Atlantic
	Soyabean	CH	Alpine
Sorghum	Common bean	AT	Continental
Oilseed rape	Clover	FR, UK	Atlantic
	Fenugreek	FR	Atlantic
	Lentil	FR	Atlantic
	Faba bean	FR	Atlantic
	Lucerne	CH	Alpine
Sunflower	Clover	CH, FR	Alpine
	Buckwheat	FR	Atlantic

Discussion points:

- Cereal-legume crop associations appear the most frequent crop association in Europe. What knowledge can be transferred from this system to other crop associations? What markets are these crops sold into?
- In addition to the combinations reported here, are there other less reported crop associations used in small- or large-scale cropping systems?
- Are horticulture (fruit, vegetable) systems under-reported or less favoured? If the latter, what are the reasons?
- Are novel crop associations emerging, for example in response to a warming climate?

Benefits, disbenefits and influencing factors

The environmental benefits of growing mixtures of crop species have been tested in studies across the globe, and include improved biocontrol, reduced weed burden, decreased frequency of pests and diseases, and improved soil quality and nutrient use efficiency. The extent to which these environmental outcomes are observed across European regions and cropping systems, or whether there are context-specificities, needs to be dissected carefully from the global literature, particularly to explore whether crop associations can contribute towards preventing soil and nutrient losses, reducing greenhouse gas emissions, and reducing pesticide and fertiliser use, which are key policy targets in Europe (EU Farm-to-Fork, 2020), or increasing resilience towards more frequent drought/flooding events. Importantly, the socio-economic outcomes of crop associations in European farming need to be understood, going beyond crop yield or quality assessments to examine effects on input costs, labour, and profit margins (Sears et al., 2021).

Environmental outcomes

Current knowledge about the impacts of crop associations on ecosystem services is summarised in **Figure 3** (see **Annex 2, Supplementary Table 3** for supporting evidence), focussing on information from recent reviews and meta-analyses, and extracting Europe-relevant information where possible. This builds on a recent analysis (Huss et al., 2022) reporting the impacts of crop associations on a suite of regulating and supporting ecosystem services (biocontrol, soil health, weed control). In general, positive or neutral environmental outcomes of crop associations have been reported in large scale analyses. Biodiversity *per se* is infrequently quantified, but increased species richness of beneficial arthropods (predators, parasitoids, pollinators) was detected in annual intercrops, particularly in cereal-legume combinations. In agroforestry systems, bird biodiversity was increased in silvo-pastoral agroforestry systems, although not in silvo-arable systems, and there were no effects on the biodiversity of plants, fungi or insects.

The need for methods of weed suppression is often a motivation for growing crop associations in low input farming systems, and reduced weed biomass has been shown in several large-scale analyses of annual crop associations. Better control of the parasitic weed Broomrape has also been reported for fruit tree agroforestry systems. Successful weed control depends on the baseline used for comparison: in annual cash crops (mainly cereal- or maize-legume intercrops), weed biomass is significantly reduced in intercrops, but only compared with monocultures of the less weed-suppressive crop component (usually the legume) and not compared with the more strongly suppressive crop (i.e. the cereal). Notably, this analysis highlighted that additive mixture designs led to better weed control than replacement designs, probably due to weeds being outcompeted by higher overall densities of crop plants.

Pest and pathogen control are frequently improved in diverse crop stands. Soil-borne disease damage was reduced by more than half in an analysis of annual crop associations, with combinations including Amaryllidaceae (includes alliums) being more effective than Poaceae (cereals, grasses) or Fabaceae (beans). In a global study of cereal-legume intercrops, disease control was on average 45% more effective compared with monocrops, with greater control achieved in early and mid-season than in late season, and there was no effect of nitrogen fertilisation on the disease suppressive effects of the intercrops. Herbivorous invertebrate pests are frequently lower in abundance, and pest damage is reduced, in annual intercrops, whether cereal- and maize-legume intercrops, or vegetable-intercrops, with best outcomes observed for crop associations including legumes and those sown with alternating rows or homogenous mixtures compared with strip cropping. Decreased pest issues frequently correlate with higher abundances of predators and parasitoids known to provide biological control of arthropod herbivores.

Soil health is primarily reported for fruit-based crop associations and cover crops. Crop associations in these systems have been shown to increase soil organic carbon and carbon stocks, although legume-based cover crops were more effective than grass-based cover crops. Soil nitrogen availability is often higher in perennial crop associations compared with monocrops, although there are conflicting trends between studies. Soil phosphate availability was reduced in fruit tree intercrops. In addition, there is evidence that microbial biomass and microbial respiration is higher in soils under mixtures, with stronger effects observed as species richness of the crop association increases and with the age of the perennial crop stand. Notably, the effect of mixture diversity on microbial respiration is stronger for colder climates. There was limited information about the effects of crop associations on air and water quality (**Annex 2: Supplementary Table 3**).

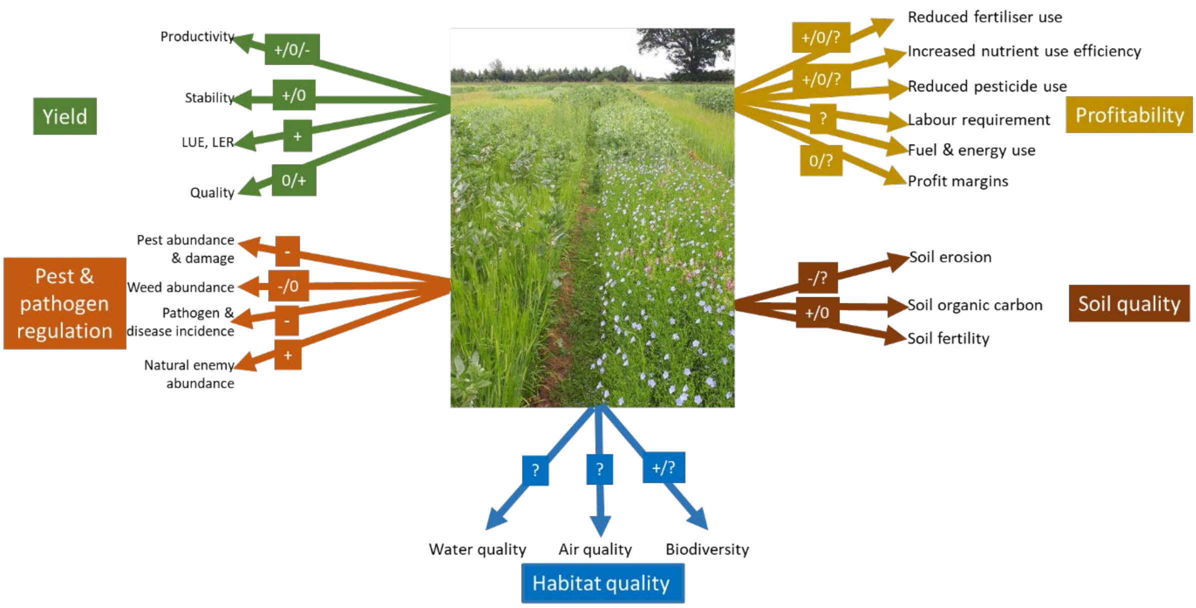


Figure 3. A summary of the environmental and socio-economic outcomes reported in meta-analysis studies of crop associations grown in Europe and globally, illustrating where outcomes are positive (+), neutral (0), negative (-) or variable/lacking information (?). See **Annex 2** (**Supplementary Tables 3** and **4**) for details of each study. LER = Land Equivalent Ratio. LUE = Land Use Efficiency.

Socio-economic outcomes

Current knowledge about the impacts of crop associations on socio-economic ecosystem services is summarised in **Figure 3**. The effect of crop associations on yield is the most frequently used metric for measuring outcomes from annual and perennial systems (**Annex 2, Supplementary Table 4**). Increased land use efficiency (often measured as Land Equivalent Ratio*) of 20-30% is often reported in annual and perennial crop associations, along with increased relative yield (i.e. yield that has been adjusted to account for different sowing densities in mixtures *vs.* monocrops). Replacement designs can be more effective than additive designs for increasing yield above the values expected from monocrops. Transgressive overyielding is rarely reported (see Li et al., 2022), which means that the intercrop yield is typically less than the most productive crop component grown as a monocrop. This could be a drawback of using crop associations if the priority is to increase the yield of one cash crop rather than all component crops.

*LER values indicate the amount of land area using monocropping needed to produce the same yield as the intercrop (LER>1 indicates more yield is produced per unit land area than monocrops).

Yield stability can be of specific interest, particularly for crops like legumes that often show fluctuating inter-annual yields; there is some evidence that yield stability of legume crops is improved when intercropped, but this outcome appears dependent on the legume species, the spatial design (replacement designs are more stable than additive designs), and growing conditions (yield stability is higher in more productive growing conditions). Effects on yield quality include reduced pest spoilage (vegetable crops), increased sugar content (fruit crops), and higher calorie output per unit of added nitrogen in cereal-legume intercrops, with additional benefits from maize-legume intercrops as protein production is also higher.

Evidence is patchy for the contribution of crop associations towards other social and economic components of profitability. In legume-containing intercrops, there is less requirement for soil mineral nitrogen addition, which means that fertiliser use can be reduced. Increased phosphate uptake by cereal intercrops using faba bean or chickpea suggests that phosphate fertiliser inputs could be reduced. Pesticide use is likely to be reduced when better pest and disease control is achieved (**Supplementary Table 3**). Quantitative information about the labour and energy/fuel requirements of crop associations appears lacking: one study (Dahlin et al., 2019) is included as an example from African smallholder farming systems to illustrate the types of data that would be useful to collect for European farming systems. This information is needed to assess overall effects on profit margins.

Discussion points:

- What are the motivations of farmers for using crop associations?
- Which environmental benefits are most valued by practitioners?
- Can crop associations encourage cooperation among farmers to improve ecosystem services at landscape scale?
- What balance needs to be struck between the economic and environmental outcomes of crop associations for this practice to become more attractive?

Barriers and enablers of crop associations

The widespread adoption of farming practices designed to improve agricultural sustainability is often constrained by the existing infrastructure (economic, technical, social) of established supply and value chains (Morel et al., 2020). Modern farming systems are typically organised around the growing of crop monocultures, rather than growing different crop species together, whether in strips, rows, blocks, or complete mixtures. Standard farming practices might need to be adapted or replaced by alternative methods to allow crop components to be sown, managed, and harvested, including post-harvest operations to clean or separate the crop products for downstream use.

A recent analysis (Brannan et al., 2023) summarised the barriers experienced by practitioners involved in crop diversification, included intercropping and cover crops, using evidence gathered from work conducted by Horizon 2020 projects in the Crop Diversification Cluster (www.cropdiversification.eu). These projects highlighted barriers experienced pre-farm gate (e.g. availability of seed of suitable crop varieties, availability of appropriate machinery), at farm-level (e.g. biophysical conditions affecting crop performance, access to knowledge or advice), and post-farm gate (e.g. product markets, consumer demand) (**Figure 4**). Barriers relating to farming techniques were mentioned most frequently by farmers and other stakeholders using cereal-legume intercrops (Bedoussac et al., 2021; Pearce et al., 2018).

The solutions to these practice barriers vary with the product type and farm systems. For example, the mechanism by which crop diversification strategies are integrated into value chains in Europe depended on whether the farms were organic or conventional, selling into local or commodity markets, or whether they involved practices or new value chains that avoided the issues encountered with established systems (Morel et al., 2020).

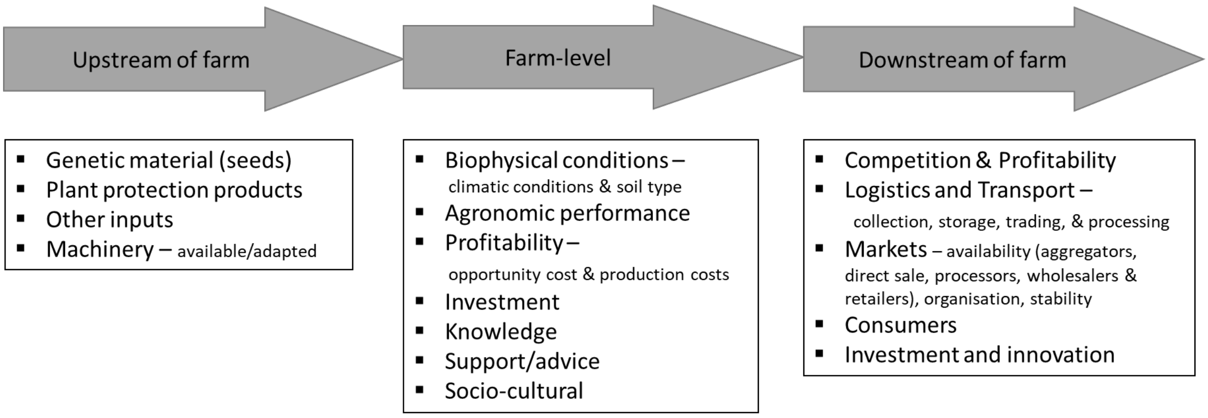


Figure 4. A framework, based on the supply chain-farm-value chain, for characterising barriers and opportunities to uptake of crop associations in European cropping systems. Adapted from Brannan et al (2023).

Discussion points:

- What/where are the common barriers to uptake of crop associations; who needs to be involved in overcoming them?
- Which barriers are specific to certain crop associations, and what are the generic barriers?
- Are crop association products sold into existing, adapted or novel markets?

Technical and knowledge solutions

Recent research and innovation projects have had a significant focus on identifying existing solutions to facilitate the use of crop associations. Often, barriers relate to the practicalities of sowing, managing and harvesting multiple crops grown together. Solutions adopted in Europe include:

- **Spatio-temporal arrangement**: Choosing a spatial arrangement that facilitates crop management by growing species in strips, alleys or alternate rows, can alleviate some of the practical issues, while still allowing some of the benefits of growing crops together to be achieved. Relay intercropping can overcome the challenges of growing crops together with different maturity timings and/or architectures.

- **Precision tools**: Where intimate spatio-temporal crop associations are preferred, technical solutions have been identified in terms of mechanical equipment, precision tools (see example in **Box 2**), and other products for the management and agronomy of species mixtures (George et al., 2020; Bedoussac et al., 2021).
- **Post-harvest operations**: Grain crops grown and harvested together typically need to be separated before further processing. A range of grain separation methods are available (George et al., 2020; Bedoussac et al., 2021) for separating and cleaning mixed grain products (see example in **Box 3**).

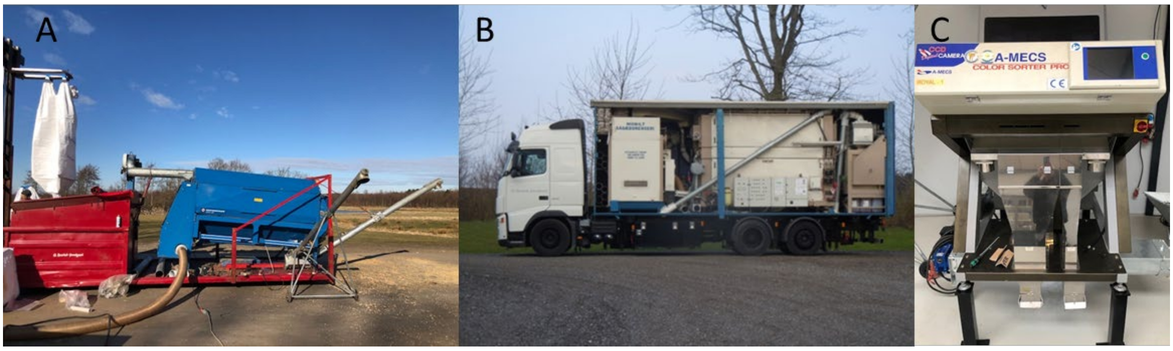
Box 2. A role for precision agriculture in managing crop associations.

At the Stockbridge Technology Centre (UK), continuous, in-crop clover living mulches are grown with a cereal crop in a minimum-tillage and integrated production system. Winter wheat or spring oats are sown into a pre-established cover of white clover, comparing direct drilling into bare soil (cereal monocrop) with direct drilling, or strip-tilling and wide-row drilling, into the clover living mulch.

Cereal germination and yield were suppressed in clover living mulches compared with a bare soil monoculture control, but this was partly mitigated by using strip-till technology in winter wheat and completely mitigated in spring oats. When the living clover mulch was well-managed, spring oats benefited from better weed suppression, increased soil nitrogen availability, and higher yield. Source: Jen Banfield-Zanin and David George (STC, UK), Andrew Manterra (Manterra Ltd, UK).

Box 3. Seed separation at farm scale.

Test separations of mixed grains harvested from barley-pea, wheat-lupin, and oat-lentil crop associations were carried out using a rotary seed cleaner (A), a mobile separating and cleaning unit (B) and a spectrum colour sorter (C).



The barley-pea mixture (D) was cleaned and separated using the rotating sieve with three different sieve sizes and air suction, resulting in less than 1% grain impurity (E). Wheat and lupin were separated with the same method and gave final products that were >99% lupin seed and >92% wheat seed, although it was noted that the cereal impurity in legume grains would mean the product is not acceptable for gluten-free foodstuffs. Separating oat and lentil (F) was more challenging and required a final step using the colour sorter, which resulted in a nearly clean fraction of lentil with only 0.2% residue (G).
Source: Lars Egelund Olsen (Landbrug & Fødevarer F.m.b.A., SEGES, Denmark), Visti Møller (Buurholt, Denmark).

A survey amongst agricultural stakeholders about machinery solutions for sowing, managing and harvesting crop associations showed that many solutions existed for crop agronomy and harvesting, but fewer solutions for crop drilling, especially for crops that are sown at different times (**Figure 5**). In unstructured crop associations (i.e. homogeneous mixtures), 18 solutions resolving 29 specific barriers were found, while in structured crop associations (e.g. row or strip intercrops), 27 solutions resolving 55 specific barriers were identified.

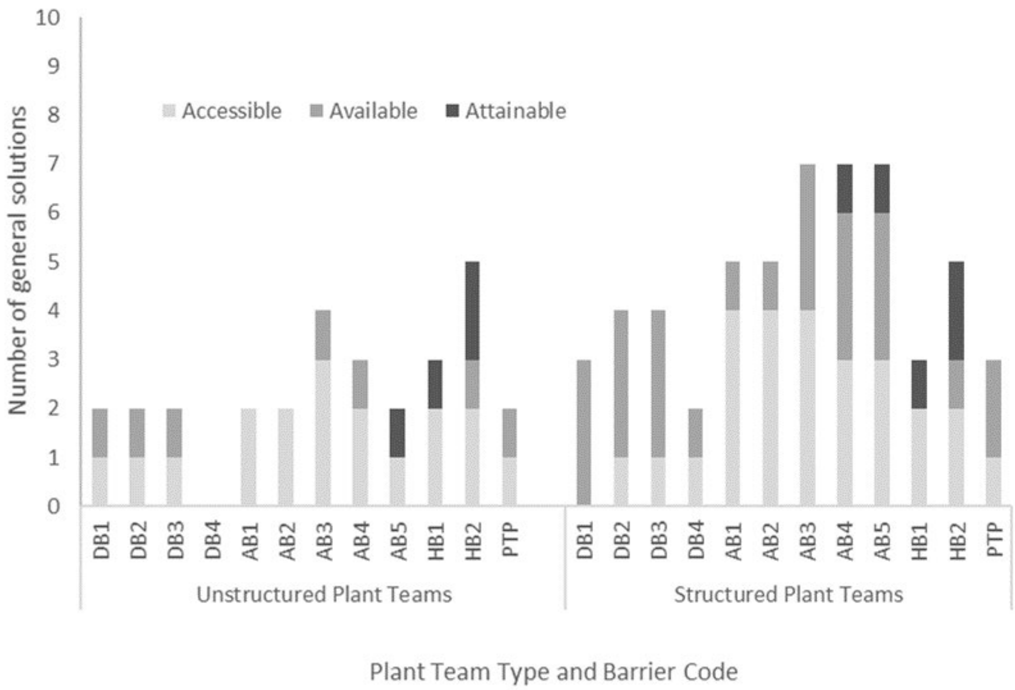


Figure 5. The number of available precision/machinery solutions identified to overcome barriers to unstructured and structured 'plant team' cropping (i.e. intercrops). Solutions are shaded according to their expected relative accessibility to end users where ▒ = 'accessible' solutions (e.g. suited to most operations, requiring minimal investment), ▒ = 'available' solutions (requires investment), and ■ = 'attainable' solutions (theoretically available, but relies on highly specialised equipment).

Barrier codes refer to: Drilling/Establishment Barriers (DB), these being: Multiple seed sizes (DB1), Multiple seed rates (DB2), Multiple seed depths (DB3) and Different sowing times (DB4); Agronomy Barriers (AB), these being: Pest control (AB1), Disease control (AB2), Weed control (AB3), Crop-crop competition (AB4) and Nutrition complexity (AB5); Harvest Barriers (HB), these being: Timing (HB1) and Separation (HB2); and Other Barriers not covered above, grouped here under Plant Team Planning (PTP). From George et al., 2020.

Further innovations to assist with the adoption of crop associations might include improved knowledge (access to information and training), availability of machinery and other equipment for crop management, understanding storage and processing barriers, and identifying opportunities for adding value to crop products.

Discussion points:

- Can existing farm equipment be adapted to crop associations, or is novel machinery needed?
- Can novel solutions be used to optimise environmental and economic outcomes? Could these include digital tools?

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Annex 1

Supplementary Table 1. Cereal- and legume-based intercrops in European countries and regions.

Component 1	Component 2	Country	Region
[1]Oat	Triticale	FR	Atlantic
	Barley	UK	Atlantic
[1]Barley	Maize	FR	Atlantic
	Sorghum	CH	Alpine
[1]Wheat	Triticale	CH	Alpine
[2]Faba bean	Pea	FR, DK	Atlantic
	Lathyrus	AT	Continental
Wheat	Pea	BE, DK, LT, CH, GR, UK, PL	Atlantic, Continental, Alpine, Mediterranean
	Faba bean	DK, IT, FR, NL	Atlantic, Mediterranean
	Lupin	DK, CH	Atlantic, Alpine
	Alfalfa	FR	Atlantic
	Clover	FR, CH	Atlantic, Alpine
	Lentil	FR, ES	Atlantic, Mediterranean
	Lucerne	FR	Atlantic
	Chickpea	TR, ES	Mediterranean
	Soyabean	DK	Atlantic
Durum wheat	Faba bean	IT	Mediterranean
	Lentil	TR	Mediterranean
	Pea	FR	Atlantic
Barley	Pea	FR, AT, LT, IT, CH, UK, ES	Atlantic, Continental, Mediterranean, Alpine
	Lentil	DE, FR	Atlantic, Continental
	Lupin	DK	Atlantic
	Faba bean	CH	Alpine
	Lucerne	UK	Atlantic
	Lathyrus	FR	Atlantic
Oat	Faba bean	DK, CH, PT, ES, UK, FR	Atlantic, Alpine, Mediterranean
	Pea	CH, FI, DE, LT, AT, FR	Alpine, Continental
	Lentil	DE, FR, UK	Atlantic, Continental
	Vetch	FR, AT	Atlantic, Continental
	Lupin	CH	Alpine
	Chickpea	UK	Atlantic
Maize	Soyabean	FR	Atlantic
	Common bean	UK, AT, CH	Atlantic, Continental, Alpine
	Squash	CH	Alpine
	Peanut	CH	Alpine
	Clover	FR	Atlantic
Triticale	Pea	FR, LT, CH, AT	Atlantic, Continental, Alpine

	Lupin	FR, DK	Atlantic
	Faba bean	CH	Alpine
	Vetch	AT	Continental
Rye	Pea	CH, AT, NL	Alpine, Continental, Atlantic
	Vetch	CH, AT, DK	Alpine, Continental, Atlantic
	Clover	NL	Atlantic

[1]Cereal-cereal crop associations; [2]Legume-legume crop associations.

Supplementary Table 2. Multi-species crop associations and cover crops in European countries and regions.

Species mixture	Country	Region
Maize-Common bean-Buckwheat	AT	Continental
Maize-Common bean-Phacelia	AT	Continental
Oilseed rape-Vetch-Buckwheat	UK	Atlantic
Oilseed rape-Clover-Buckwheat	UK	Atlantic
Oilseed rape-Oat-Fenugreek	FR	Atlantic
Oilseed rape-Fenugreek-Lentil	FR	Atlantic
Oilseed rape-Pea-Faba bean-Clover	FR	Atlantic
Oilseed rape-Camelina-Clover	FR	Atlantic
Oilseed rape-Clover-Lucerne	FR	Atlantic
Oilseed rape-Mustard-Lucerne	UK	Atlantic
Barley-Oat-Pea-Lupin-Mustard-Linseed	DK	Atlantic
Oat-Barley-Wheat-Triticale-Pea	DK	Atlantic
Barley-Clover-Rye	UK	Atlantic
Barley-Oat-Pea	FR, DK	Atlantic
Oat-Linseed-Vetch-Clover-Buckwheat	UK	Atlantic
Oat-Clover-Trefoil	UK	Atlantic
Sorghum-Common bean-Buckwheat	AT	Continental
Sorghum-Common bean-Phacelia	AT	Continental
Sorghum-Buckwheat-Pea	FR	Atlantic
Red/White/Berseem Clover-Trefoil	UK	Atlantic
Camelina-Lentil-Lupin	CH	Alpine

Annex 2

Supplementary Table 3. Environmental outcomes of intercropping in annual (light grey) or perennial (dark grey) crops. Arrows indicate an increase (↑) or decrease (↓) in parameter values. Green shading indicates benefits, orange indicates disbenefits, and blue indicates variable outcomes. See Annex 1 for further details.

		Pest & pathogen regulation				Soil health & quality			Water quality		Air quality		Habitat quality
Study	**Features**	**Herbivory/pests**	**Weeds**	**Pathogen/disease**	**Natural enemy/biocontrol**	**Soil erosion**	**Soil organic carbon**	**Soil fertility (N, P)**	**Nutrient leaching**	**Water use efficiency**	**Greenhouse gas emissions**	**Other pollutants**	**Biodiversity and function**
Gu et al 2021	39 studies Annual cash crops (maize/cereal-legume dominated) Global range		↓weed biomass										
Iverson et al 2014	26 studies Maize-legume dominated Tropical, temperate	↓ herbivore abundance and pest damage			↑ predator abundance								
Verret et al 2014	34 studies Annual cash crops (cereals, maize, other)+legume companion crop		↓weed biomass										
Chadfield et al 2022	52 studies Annual crops			↓soil-borne disease damage									
Weih et al 2021	Seven trials Cereal-legume Europe												
Zhang et al 2019	17 studies Cereal-legume China			↓disease									
Raseduzzaman & Steen Jensen 2017	37 studies Cereal-legume, noncereal-legume Global												

Rakotomalala et al 2023	63 studies Intercrops with cereal, legume, other annual fruit/veg crops Global (mostly China, USA, Brazil)	↓ arthropod pest abundance			↑ beneficial arthropod abundance								↑ species richness of predators, parasitoids, pollinators
Carrillo-Reche et al 2023	76 studies Cabbage-intercrops Global	↓plant injury											
Jian et al 2020	131 studies Cover crops Global - 60% USA, then Europe, S America, Africa/Asia						↑ Soil organic carbon						
Marotti et al 2023	37 studies Fruit trees-annual crop-medicinal plant intercrops Mediterranean basin	↓ pests of sugar beet, cotton, faba bean	↓ broomrape in legume annual crops		↑ predators, parasitoids in olives and some other crops		↑ SOC in some studies			↑ soil moisture in some studies			
Torralba et al 2016	53 studies Agroforestry - silvo-pastoral/silvo-arable Europe					↓ erosion		↑soil fertility					↑ bird biodiversity in silvo-pastoral
Morugan-Coronado et al 2020	46 studies Fruit orchards intercropped with annual or perennial crops Mediterranean climates						↑SOC	↑ soil N ↓soil P					
Chen et al 2019	106 studies Natural/planted forests, grasslands, croplands, pot studies Global - Europe, Asia						↑SOC, soil C stocks, microbial C						↑soil microbial biomass, microbial respiration
Senbayram et al 2016	Single field study in Germany Legume-based intercrops										↑ N2O in silvo-arable		
Fung et al 2019	Modelling study of ammonia and particulate emissions China										↓NH3	↓ PM2.6	

Supplementary Table 4. Socio-economic outcomes of intercropping in annual (light grey) or perennial (dark grey) crops. Arrows indicate an increase (↑) or decrease (↓) in parameter values. Green shading indicates benefits, orange indicates disbenefits, yellow indicates neutral, and blue indicates variable outcomes. See Annex 1 for further details.

		Yield			Profitability					
Study	**Features**	**Absolute or relative yield**	**Yield quality**	**Yield stability**	**Fertiliser use**	**Nutrient use efficiency**	**Pesticide/ herbicide use**	**Labour requirement**	**Fuel/energy costs**	**Profit margins**
Iverson et al 2014	26 studies Maize-legume dominated Tropical, temperate	↑ per-plant yields								
Verret et al 2014	34 studies Annual cash crops (cereals, maize, other)+legume companion crop	Neutral effect on yield								
Weih et al 2021	Seven trials Cereal-legume Europe	↑yield		↑yield stability of pea						
Raseduzzaman & Steen Jensen 2017	37 studies Cereal-legume, noncereal-legume Global			↑yield stability						
Rodriguez et al 2020	29 studies Cereal-legume					Neutral effect on legume Ndfa ↑total Ndfs vs legume but neutral vs cereal monocrops				
Li et al 2023	226 experiments Cereal/maize-legume intercrops Global analysis	↑LUE ↑grain yield			Transgressive overyielding in maize-legume intercrops without N fertiliser Maize intercrops without legumes overyielded more with N fertiliser	↑ NUE for grain/calories Neutral effect on NUE for protein vs most productive sole crop (except maize-legume intercrops)				Transgressive overyielding most likely when more productive sole crops grown together

Tang et al 2021	17 studies Cereal-legume Global	↑LER ↑ LUE in maize-based systems				↑LER for P uptake				
Carrillo-Reche et al 2023	76 studies Cabbage-intercrops (broccoli, cauli, white cabbage, onion, white clover) Global	↓productivity	Neutral effect on cabbage grade ↑ injury-free produce		Synthetic fertiliser ↓productivity in intercrops vs monocrop Neutral effect of organic fertilisation		↓injury without pesticides vs monocrop			
Marotti et al 2023	37 studies Fruit trees-annual crop-medicinal plant intercrops Mediterranean basin	↑yield, LUE/LER	↑ fruit sugar content							↑ economic returns
Torralba et al 2016	53 studies Agroforestry - silvo-pastoral/silvo-arable Europe	↓ total biomass Neutral effect on timber production								
Morugan-Coronado et al 2020	46 studies Fruit orchards Mediterranean climates	Neutral effect on crop yields								
Fung et al 2019	Modelling study of ammonia and particulate emissions China				↑net economic benefit from reduced fertiliser use and health costs saved from reduced air pollution					
Dahlin et al 2019	28 studies Maize crops Africa - smallholders							Neutral effect on labour demand		