DIVERSify: Designing InnoVative plant teams for Ecosystem Resilience and agricultural Sustainability

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Report on socio-economic factors affecting farmer adoption of plant teams (Report, Public)

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Executive Summary

Although organic farmers may use intercropping[1] more than conventional farmers, both organic and non-organic farmers seem to adopt similar approaches to intercropping. For organic farmers, the use of plant teams provides a source of nitrogen (N) in particular since they rely solely on biological N_2 fixation by legumes or/and organic manure for N inputs. Conventional farmers provide N from inorganic fertilisers and intercropping with legumes offers an option for reducing fertiliser costs. Surveys, face-to-face, and phone discussions with Participatory Farmers (PFs) that were delivering on-farm trials as part of the DIVERSify project allowed the main socio-economic barriers for implementing intercropping to be established. PFs involved in the project were interested in or already including intercropping in their cropping systems, and collaboration to systematise barriers to its implementation was crucial for this study. The barriers can be classified as straightforward socio-economic barriers, such as limited market for mixed grains and limited market for legumes, or as a consequence of a significant number of agronomic limitations such as: lack of advice and support from extension services on selecting the right crop combinations for their pedoclimatic condition; the need for adapted machinery; how plant team management *per se* affects weed and pest control. Certain PFs pointed out the need for clearer mechanisms for supporting intercropping through the Common Agricultural Policy.

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1. Introduction

The bottom line for the global population is sustainability: "Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). If practices in production, consumption, and water management damage that bottom line of sustainability, those practices should change. While the global population depends on agriculture for survival, agriculture has become a major cause of biodiversity decline, erosion and soil quality loss, and greenhouse gas (GHG) emissions. Unsustainable agricultural practices cause a decrease in production capacity of agro-ecosystems, environmental pollution, and damaging chemical exposure for flora and fauna. The European Union (EU) launched strategies for Integrated Production (IP) practices, which included Integrated Pest Management (IPM) to diminish environmental impact of agriculture. These IP practices were developed by each Member State (e.g. see here for Spain), so that farmers had to follow these practices in IP and IPM. It is also interesting to highlight other initiatives such as EISA: European Initiative for Sustainable Development in Agriculture, 2012) and the Opinion of the European Economic and Social Committee on 'Integrated Production in the European Union' (2014/C 214/02). Through its Framework Directive 4, the European Commission promotes the use and implementation of IPM techniques, in particular the Annex III of the Directive; further action was also required at the local and regional level (see here). In parallel, organic production and labelling was establish in 2007 (No. 834/2007), to be later updated in 2018 via Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/200).

The EU Regulations for IP and Organic Agriculture (OA), however, have not been sufficient for improving sustainability. The last few generations of farmers have benefited from advances in technical and scientific farming that massively increase yields and reduce labour. Agricultural training schools and extension services widely adopted high-input technical farming. Despite policy efforts and a movement towards sustainable agriculture, damage to the environment, including biodiversity loss, and increased difficulty in pest and weed control continue to occur. Improvements in agricultural practice can reverse these trends and contribute to different sustainable development goals (SDGs). This requires further development of crop management practices that have positive economic, environmental, and social justice outcomes (IPBES 2019). The recent European Green Deal, the EU Farm to Fork Strategy with a target for 25% OA, and the EU Biodiversity Strategy 2030 have been established to work towards this.

The use of intercropping[1] (i.e., growing two or more crops in close proximity) is a polyculture practice that has proven to deliver ecological benefits while improving yields and reducing inputs

[1] We use the terms "plant teams" and "intercropping" interchangeably in this report.

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(Villegas Fernández et al. 2019, Scherber et al. 2020). Intercropping implies cohabitation in space and time of two or more plant species and involves varying degrees of niche differentiation and competition. Intercropping practice can be very diverse. Agro-silvo-pastoral systems, for example, where woody vegetation is integrated with a pasture or crop, are a classic polyculture system. Intercropping with herbaceous components is common in forage production and pastures, however grain-based mixtures have been emerging as an opportunity to achieve sustainable intensification of agriculture (Martin-Guay et al. 2018).

There is some evidence that intercropping is ecologically beneficial, but results vary widely. It can increase crop productivity and stabilize crop yields (Raseduzzaman and Jensen 2017), and improve the land utilization ratio (Li et al. 2020, Xu et al. 2020). Where legumes are included, intercropping can reduce fertiliser inputs (Jensen et al. 2015, Rodriguez et al. 2020) and use of herbicides (Verret et al. 2017). Intercropping is especially relevant in organic farming systems, where nitrogen (N) is a limiting nutrient and herbicides are not used (Bedoussac et al. 2015). Intercropping can in some cases increase water retention and use efficiency (Yin et al. 2020), but results vary.

While increasing agro-biodiversity is an important goal, and intercropping shows promise in helping towards this aim, one of the key questions that remains is how intercropping affects the farmer's overall bottom line: their profit. If farmers have access to innovations and incentives that will support their economic bottom line, they may be willing to try them. The returns on using plant teams in Europe are mixed. Some intercrops reduce costs but also reduce production (and, thus, revenue); others increase costs in some areas (e.g., labour) while reducing costs in others (e.g., nutrient inputs); and yet others reduce inputs and increase yields. The economic outcome of using plant teams is difficult to generalise.

The DIVERSify project has focussed specifically on the practice of cereal-legume and species-rich grassland intercropping and aimed to design innovative plant teams for ecosystem resilience and agricultural sustainability. This project has worked with organic farmers and integrated livestock and crop production to introduce, encourage, and support them to further adopt sustainable agricultural practices.

The benefits of using intercrops evaluated in this project are related to pest and weed control, resilience to weather variability, and, when a legume is included in the mix, a reduction in synthetic N fertilisation. Barriers to the employment of plant teams include the need for adapted machinery, the need for knowledge about using different crop management strategies, and the higher costs for harvest and grain separation. Other problems include lack of market for farmers' produce.

This report is framed by the known barriers to adopting plant teams identified in previous work in the project, and specifically in Deliverable 1.1, *The Synthesis Report on National Stakeholder Meetings* (Pearce et al. 2018), and Deliverable 4.5, *Report on Practical Restrictions Imposed by Plant Teams* (Tippin et al. 2019). These two reports provided insights into main practical barriers to adoption of intercropping identified by project stakeholders and participants. The value proposition of this present report is that it tests that framework against the experiences of 21 of the projects'

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participatory farmers (PFs) who evaluated intercrops in their own farm conditions. Vignettes of their experience with barriers and solutions are provided in Annex 1 of this report.

The objective of this report is to present information provided by farmers in this project on (a) motivations for testing intercropping, (b) challenges to using intercrops, and (c) suggested solutions to the challenges. We provide some emphasis on the qualitative aspects of the socio-economic dimensions of employing plant teams or intercrops. While one goal of the project was to produce a quantitative economic analysis of the trials, we believe that the extremely adverse weather during two trial years curtailed farmer's ability (or willingness) to provide a cost/benefit accounting of the trial operation. Thus, our discussion of economic aspects of using plant teams is qualitative and to some degree theoretical.

2. Report methodology

Thirty-three farmers in seven countries participated in 41 on-farm trials of plant teams as part of the DIVERSify project. Of these, ca. two-thirds employed organic production systems while the rest were following EU Integrated Production with no certification. Thirteen farmers responded to questionnaires and interview requests in detail and their farms were located in Denmark (ID number: PF1909; PF1910; PF2005), the United Kingdom (PF1820; PF1824 who also conducted a trial in 2020 (PF2001); PF1826; PF2007), Portugal and Spain (two IDs for same farmer but different trials: PF1831 and PF1832; PF1838; PF1841; PF1842; PF1846) and Italy (two IDs for same farmer but different years and trials: PF1811; PF1901), in two pedoclimatic zones: Atlantic/Nemoral and Mediterranean. Farms were of different sizes and types, ranging from a subsistence experimental farm, to a sheep farm with oak trees, and with more traditional arable cropping systems in between. Motivations of the PFs for using specific plant teams varied from specific, like using cereals for providing physical support to lentil plants, to the very general.

Plant teams used by PFs were mainly cereal-legume and grass-forage legume mixtures, but there were some trials with cereal mixtures and oilseed crop-grain legume mixtures. The specific plant teams tried in this project were defined during early stakeholder workshops (Task 1.1) or had previously been tested by farmers' own initiative. Information on the farms and trials was primarily gathered in "Completed Trial Scientific Summary" as well as "Trial Feedback Questionnaire" documents organised by WP4, a summary of which will be available on the DIVERSify legacy website (www.plant-teams.org). Elements of those summaries were used to inform this report. Collaboration with WP4 has greatly facilitated our interactions with farmers and has been essential for producing this current report.

The participating farmers were early adopters; most had already tested several plant teams. The sample of farmers is neither statistically robust nor unbiased; rather, they provide valuable experiential and empirical knowledge of intercropping that can serve to guide and inform both farming peers and researchers. Some encountered but overcame barriers even prior to joining the project, and others discovered barriers during their participation. Thus, while the findings on barriers

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to using plant teams we report here are not necessarily generalisable, they do represent many of the common challenges and concerns. We present qualitative results and case-based information to share knowledge that might be useful to other farmers.

Farmers collaborated with project partners during the growing seasons from 2018 to 2020, some for one year and others for multiple seasons. Results of agricultural trials of just one or two years are not generalisable, given significant interannual variations in weather, prices, and markets. Therefore, these results should be taken with some caution. In 2018 some of the trials of participating farmers were affected by a severe drought and high temperatures (Beillouin et al. 2020), in some cases resulting in total failure of the crops.

The results reported here are based on survey instruments designed to solicit feedback on intercrop system performance during the farmer's participation in the project as well as to solicit their informed opinions based on experience and future foresight.

Data sources include interviews, surveys and evaluations undertaken by WP1 and WP4. A first survey on ranking of their production costs was carried out after the first two years of on-farm trials and results are included as part of the Summary Table in Annex 1. Because of the short duration of the farmer participation, and the limited numbers of participating farmers, this report is based on a qualitative analysis. The interviews undertaken were designed to assess the interest of farmers in intercropping and their attitude towards future inclusion of intercropping in their production systems. We treat them as case studies to drill down into their own experience with intercropping.

Each participatory farmer engaged in the project was 'buddied' with an in-country scientific partner to support agronomic and socio-economic data collection (Banfield-Zanin et al. 2018, Deliverable 4.3/D28). Of the 33 participating farmers, we have data from 9 (43%) through post-trial questionnaires filled out either by the farmer or the buddy, 18 (81%) trial scientific summaries written by the buddies, and 14 (67%) 'interviews', which were a mix of actual live interviews of the farmer and farmers filling out the interview guide themselves. The 2018 post-trial questionnaires provide information related to the farmers' motivations for using plant teams, trial outcomes, challenges for the trial, and future interest in intercropping. The scientific summaries provide details on trial objectives and protocol, production outcomes, and challenges faced. The adverse weather (drought) in the 2017-2018 cropping season in the northern European trials and in the 2018-2019 season in the southern European trials may have overshadowed other challenges the farmers have faced in their plant team trials. Nevertheless, several farmers had taken their own initiative in the 2019-2020 cropping season to employ the plant teams again, or some variation of the initial trial.

3. Motivations for using plant teams

Although organic farmers may use intercropping more frequently than conventional farmers, both organic and non-organic farmers seem to adopt similar approaches to intercropping, although they may do it for different reasons. For organic farmers, the use of plant teams is attractive for providing

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a rich source of nitrogen (N) since they rely solely on organic manure inputs and biological N_2 fixation by legumes. Conventional farmers provide N using inorganic fertilisers, the price of which is increasing. Thus, intercropping with legumes offers an attractive option for increasing productivity and profit for both types of farms: for organic, intercropping improves availability of N, and for conventional, intercropping reduces costs of N. Intercropping was also adopted by PFs for a range of other motivating factors including weed control and support/scaffolding for a legume crop.

For commercial farmers – at any scale – the main motivation for adopting on-farm innovation is to improve profits in the present and for the long term. A survey of project PFs supported this notion. Farmer answers to the "Trial Feedback Questionnaire" indicate that their main objective was to increase profit through increasing yields and/or decreasing costs. Cost reduction was expected to occur through fewer N inputs and shortening the supply chain for feed when providing on-farm production of high protein animal feed. Weed control (specified as pest, disease, weed control) was the other important issue and was pointed out by farmers in our visits.

The post-trial questionnaires were established to further specify ways to reach the main goals of the farmer in terms of increasing profits or gains. Depending on the farm type, farmer motivations included: (a) reduce inputs, mainly N, i.e. reduce production costs; (b) produce good quality feed *in situ* for sale, or for their dairy or animal production farm enterprise; (c) weed control (specified as pest, disease, weed control); (d) increase soil organic matter, reflecting a desired environmental outcome, such as increasing soil carbon and water holding capacity; and (e) increased knowledge for future improved management and profit.

A weighted ranking of the motivations (**Figure 1**) clearly shows that for most farmers, improving the economic outcomes of farming is the most important motivator.

Using those data and other discussions, the DIVERSify project aims to provide guidance and information to farmers related to using plant teams in five motivation areas:

1. Input reduction
2. Increased production of home-grown proteins
3. Reducing biodiversity losses
4. Resilience to climate change
5. Rural innovation.

These areas will be revisited in Section 5 of this report.

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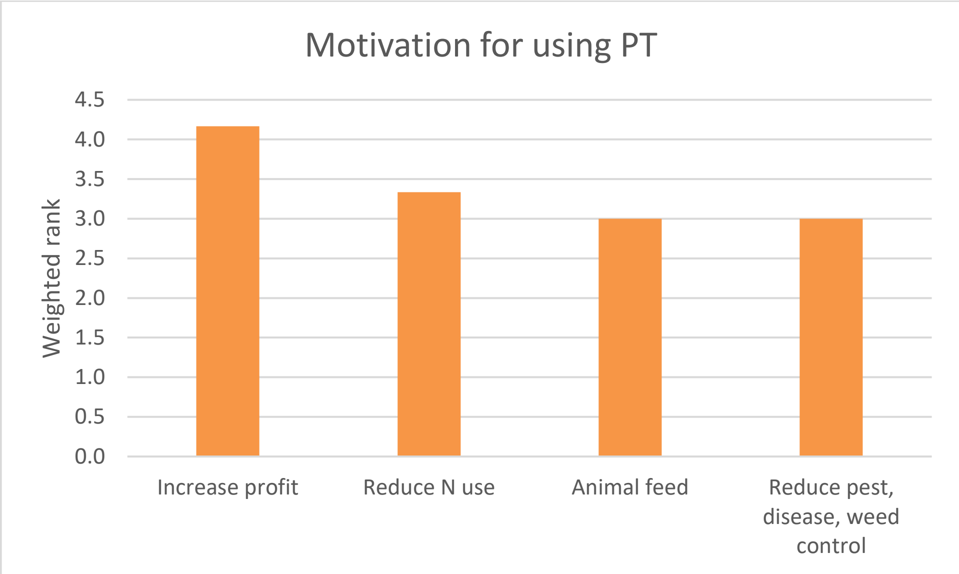

Figure 1. A weighed ranking of the responses by participants about their motivations for choosing and using plant teams (weighted total rank = sum[rank frequency/rank]). Note, however, that these categories all conflate with increasing profit by reducing costs.

4. Barriers and constraints to using plant teams

DIVERSify project Deliverable 1.1 (Pearce et al. 2018) identified 25 specific barriers to plant team adoption through project discussions and a series of multi-stakeholder workshops. Further analysis presented in Deliverable 4.5, *Report on perceived or realised practical restrictions imposed by plant teams* (Tippin et al. 2019), revisits the Deliverable 1.1 (Pearce et al. 2018) barriers and includes new information from barriers identified in other Horizon 2020 projects and from field trials. For the present report, a new list of barriers was gleaned from the different data collection methods performed with PFs during and after their trials (**Table 1**). These, together with barriers identified previously, are summarised in **Figure 2**. In this section, we present the barriers and constraints identified by PFs.

The barriers listed in **Table 1** are partly due to the technological and economic lock-ins that many farmers face today in the environment of mechanised conventional agriculture. The technological lock-ins are mainly based around the fact that the machineries for planting, fertilisation, harvesting, threshing etc. are designed for monocultures, which can present a significant hindrance to adoption of intercropping. Economic lock-ins can be another significant factor where the farmers are assured a minimum price for their sole crop produce by their buyers, whereas plant team produce does not have an assured price for the farmer, hindering the confidence of the farmer to adopt plant teams. Hence, the barriers listed here should be considered within the socio-economic contexts of economic and technological lock-ins that the farmers face more widely today.

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Table 1. Barriers cited by Participatory Farmers to implementing plant teams.

Category	Barriers that farmers faced to adopt intercropping
Agronomic	Information: finding optimal sowing density and timing for both crops.
	Sowing: machinery to sow mixture of seeds.
	Suppression of autumn grass under barley.
	Cover crop reduced maize yield.
	Intercropping threatens "rotational hygiene" (weed proliferation, pests associated with certain crops).
	Intercropping lowered yield of target crop (pea) but did help provide physical support.
	Processing, no huller for micro-scale oats.
	Lack of knowledge and data on best varieties, other aspects.
	Processing separation of grains: timing is too slow for market.
	Separation of grains: machinery.
	Need at least 3 years results before uptake.
Economic	Sowing: high labour requirement to sow twice.
	Limited market for mixed grains as product for sale.
	Limited market for legumes.
	Cost, generally.
	Market: low demand for intercropping or organic. Local cattle production no demand for IP products.
	Market value increases only if seeds can be separated.
Institutional	CAP: no premium for intercropping, general.
Social	Contractor mismanagement of implementation.
	Cultural: minimise risk and apply management they know.

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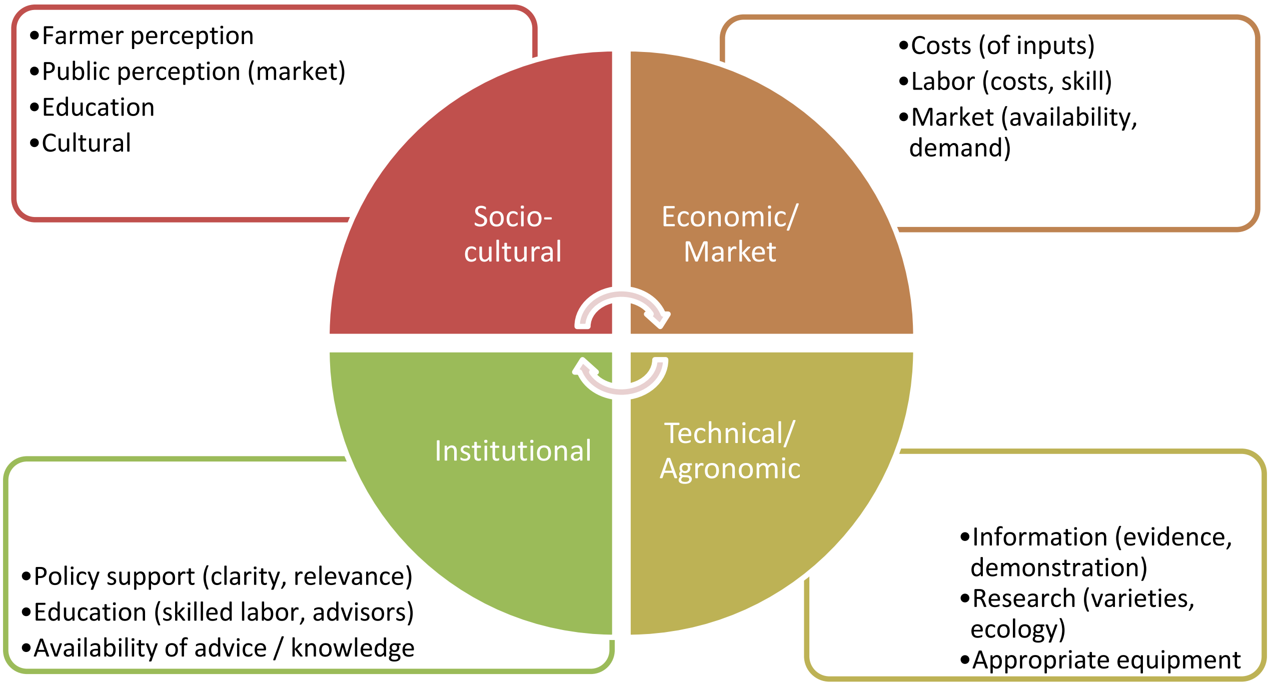

Figure 2. Four categories of barriers (and, eventually, of solutions), with specific examples found in this project.

4.1. Institutional

Institutional barriers come in the form of policy and regulations, lack of appropriate knowledge and technology, educational services, training, and advice.

4.1.1. Policy

Several PFs identified a lack of policy support for using plant teams. Farmers in the interviews mentioned that there is no premium for products grown in plant teams, nor is there specific policy support through the Common Agricultural Policy (CAP) for intercropping systems. Because the current CAP does not consider intercropping, there is confusion about how to apply for support through this policy. For example, the system is set up for listed single crops in a system. Farmers do not know what to claim when they have two (or more) crops in one system, or if one of the crops used in the intercropping system should not be listed.

Some farmers expressed a belief that policy does not recognise the ecosystem services from agricultural systems, which is one of the key non-consumptive, 'public good', and non-monetised benefits of using plant teams. Ecosystem services remain as externalities, but they should be receiving policy and market support.

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4.1.2. Advisory services

As Bybee-Finley and Ryan (2018) suggest, “intercropping can be knowledge intensive” and requires “a greater understanding of ecology and the interconnectedness between crops and their environment to fully realize the potential benefits” (Section 3). PFs from the UK and Denmark indicated that a barrier was the lack of knowledge on the optimal plant combinations for a given objective and field conditions, and on planting details – sowing density, sowing timing, and fertiliser needs. Furthermore, they reported a lack of relevant information and support from advisors. This is an institutional problem of limited extension or advisory services available. A related issue is the lack of independent advice. Too often, farmers report, information is pushed on them by private companies that are promoting their own products for profit. Finally, at least one farmer indicated that their farm workers lacked the knowledge and expertise to implement plant teams.

Advisory services are dependent on the availability of information, and the relevance of that information to specific pedoclimatic, market and policy conditions. Just about all farmers in one way or another indicated that the lack of precise agronomic information specific to their pedoclimatic zone or their objectives was a challenge. As mentioned in Deliverable 1.1, the challenge is that “the unique nature of each farm and system could end up dissuading farmers from trying to use plant teams.” Access to knowledge and information is an institutional barrier in as much as institutions support both the generation of knowledge and the dissemination of information.

Older, more conservative and small-scale farmers are more resistant to adopting new practices related to sustainable land management in general (Mills et al. 2020). One farmer indicated that they refrain from adopting new crops or management activities until results from three years of trials were available to minimise risk.

4.2. Agronomic

Since intercropping for grain production is relatively new to many farmers, effort (i.e., thought, time, money, space) must be put into discovering the best crop combinations and cultivar selection. Multiple farmers expressed a desire to have better information on which cultivars work well together and in their pedoclimatic zone. They expressed concern that appropriate cultivars may not be available for these systems. Variety trials to ascertain performance in low-input and organic systems are often lacking. Similarly, farmers felt that information on the efficacy of intercropping for weed control and reduction of pest and disease is lacking, though research suggests that it is effective for weed control (Corre-Hellou et al. 2011, Verret et al. 2017, Radicetti et al. 2018) and pest control (see references cited in Bybee-Finley and Ryan 2018, and in Weih et al. 2021)

4.3. Technical

Challenges of separating grains after harvest is high on the list of problems for PFs. The difficulties with this node in the supply chain relegates much of the intercropped production to animal feed, effectively cutting off additional optionality for the system. But even there, the proportion of pulse

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to cereal that might be ideal from an agronomic standpoint, for example, might not provide the ideal nutritional mix for livestock.

Several farmers had this challenge solved mechanically, by adapting their own machinery to the challenge, or developed alternative routes to market. Other farmers stated their wishes for commercial solutions.

4.4. Economic

The economic aspects of using plant teams are also little known. It can be difficult to obtain financial data from farmers in general, either because they do not want to share, or do not keep sufficient records for the required analyses, or do not feel confident in costing their time. Furthermore, because some of the trials for this project were adversely affected by the severe weather, few farmers reported the costs and revenues from the trials. Generally, organic farmers and forage producers indicate that the inclusion of legumes in the plant team is essential to achieve cost savings in N inputs on an area basis, as well as weed control.

There are additional costs to using plant teams. The cost of seed increases on a per area basis where the intercropping is an additive design (>50:50), where there is an additional crop added, or where the more appropriate variety might be more expensive than the usual cultivar. Farmers also mentioned the higher cost of labour required for using plant teams related to double sowing, and time required to adjust sowing and grain sorting machines.

Intercropping did allow farmers to diversify their rotations and income streams. In some cases, they were growing niche crops (e.g., linseed) that they were able to generate higher returns from than commodity crops. Intercropping a structural cereal component with a grain legume cash crop by farmers in the UK did improve the quality of the grain yield (if not the quantity), thus increasing revenue.

Cost savings can mainly be found in a reduction of N inputs (either chemical or natural fertilisers), and reduction in weeding or herbicide use.

4.5. Market

Considerable concern was expressed by PFs about the market for crops originating in intercropping systems. The grain legume markets are equally not well developed across Europe, especially outside of the southern Mediterranean region. There is little demand for grain blends aside from animal feed, resulting in the need to separate intercropped grains. One farmer expressed concern about the low supply volume of harvested product from new crops or crop mixtures, which hinders value chain development efforts.

A related question raised by interviewed farmers is whether there is enough consumer awareness and consumer demand to support a market for plant team products.

Accessing markets with the products from the plant team depends on (a) there being a market for mixed grains, or (b) the cost viability of grain separation. It may also be difficult to control the quality

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of grains produced in intercropping systems, simply due to the introduction of increased interaction effects in a more diverse cropping system, and production may not meet the standards set by supermarkets. Overcoming this quality barrier is related to consumer awareness and consciousness, as reported in Deliverable 1.1: "Frequently, farmer stakeholders felt that consumers wanted environmental responsibility while still demanding flawless produce, as encouraged by the supermarkets" (Pearce et al. 2018).

4.6. Adaptation to climate change

Research does show that the use of intercropping can help mitigate climate change impacts on the farm and help farmers adapt to the climate change impacts (Beillouin et al. 2020).

The extreme weather (drought) in several experimental years of the project, i.e., one in the northern regions and the other in the southern ones, took a toll on the plant team trials. The poor performance of those trials could erode confidence in using plant teams. On the other hand, the poor performance in the very bad year(s) also provides information for what not to do next time. In the interview, we asked about whether using plant teams might be beneficial in general in the face of climate change. The answers were as variable as there are climatic zones, but the general feeling among farmers was that weather variability is part of the business, and they shall continue to adapt as best they can. Several farmers said they cannot comment on the relevance of intercropping to dealing with the impacts of climate change given the short time frame of evidence generated by using plant teams.

Farmers using intercropping as forage had the following to say to the question, 'Does using plant teams provide any advantage in the face of climate change?'

- Yes, using plant teams improves the quality of forage, and there are varieties [to use] that are more resilient with climate variability.
- Yes, there is no bad year because plant teams produce good forage.
- Yes, plant teams are viable in various markets, so depending on the year [and the production outcome], I can sell [either] grain or fodder.

Farmers producing food had mixed answers, according to their locale or the plant team employed:

- No, in a drought, one crop outcompetes the other, in the end reducing the yield by a high percentage.
- No, drought can damage the crops, and we need to develop varieties that are more tolerant to temperature and drought extremes.
- Yes, the plant team produces more stable yields due to the deep roots of at least one of the crops, which increases the area of exploitation of water and nutrients.
- No, using plant teams is a disadvantage in rainy years, since it requires entering the field twice to sow the different crops due to lack of adequate machinery for sowing mixtures.
- Not relevant, since climate extremes are less in their maritime region.

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5. Enabling adoption with sustainable solutions

In this section we look at how to mitigate the barriers to plant team adoption. **Table 2** links the main barriers identified by PFs to seven areas for innovation identified by the project team, which are explored in six subsections below. To ground these recommendations in the needs of farmers, we return to the five motivations that might draw farmers into using plant teams. **Table 3** lists these and highlights the opportunities they generate, barriers they may face and the general type of solution that can help.

Table 2. Barriers and enabler recommendations from the DIVERSify project.

Barrier (this report)	**Enabler**
High cost of adoption (labour, seed, land) and low revenue (no market, low price)	1. **Incentives/payment schemes,** developed in Deliverable 1.6. Policy Guide to plant teams (Mínguez et al. 2021).
Lack of access to appropriate (and independent) knowledge and information	2. **Extension services**, information/resources for practitioners and support.
Lack of evidence of benefits of plant teams	3. **Participatory research** and field demonstrations hosted by farmers.
Lack of information on specific plant team for specific objectives and under specific conditions	4. Increased understanding of **traits/mechanisms** that deliver optimal performance in plant teams. Develop a menu of plant teams with different seeding and mixing ratios to achieve different objectives e.g., local feed, food products, separation, and valorisation of each components.
Lack of access to cultivars optimized for use in plant team, and which are optimised for climate change resilience	5. **Breeding** for optimal varieties. There is a need to breed varieties suited for plant teams with high trait plasticity to complement and facilitate the resource use efficiency for enhanced productivity, environmental benefits, and quality production.
Difficulty in sowing, harvesting, and processing plant teams	6. Innovations in **machinery and technology and knowledge sharing.** This is part of the technological lock-ins and there is a need for support from policy to overcome this obstacle.
Lack of market for plant team products	7. Access to **processing and novel markets.** There is a need to valorise produce from plant teams for different food and feed products and add value for multiple uses.

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Table 3. Motivations and potential benefits or opportunities of using plant teams (PT), barriers identified by participating farmers, and solutions required.

Motivation	Benefits	Barriers identified by participating farmers	Solution
1. Input reduction	Reduce insecticides	PT can disrupt rotational hygiene.	Agronomic research
	Reduce fungicides		
	Reduce herbicides	Optimizing PT crops, sowing density for weed control.	
	Reduce synthetic fertilisers	Optimizing PT crops, sowing density for nutrient use efficiency.	
2. Increased production of home-grown proteins	Improved legume agronomy	Optimizing PT crops, sowing density for nutrient use efficiency.	
	Food market opportunities	No market for mixed PT grains.	Technological innovation
	Feed market opportunities	No market for green premium on feed, optimizing PT crop ratio for yield with required protein yield for feed.	Market, research
3. Reducing biodiversity losses	Attracting beneficial insects	Unless an economic incentive is provided, this will be relegated as co-benefit to increasing production.	Policy - market for ecosystem services
	Increase crop species and genetic diversity		
	Grassland diversification		
4. Resilience to climate change	Yield stability and bet-hedging	Availability of appropriate cultivars for PT that are also resilient.	Agronomic - breeding
	Resilience to environmental stress		
	Increase soil carbon storage	Unless an economic incentive is provided, this will be relegated as co-benefit to increasing production.	Policy - market for ecosystem services
5. Rural innovation	Diversify income streams	Market for other products.	Market development
	Informed advisory services	Lack of services, inadequate training of advisors, commercial biases of advisors.	Institutional development
	Peer-to-peer learning and knowledge exchange	Lack of organization.	
	Co-research opportunities	Lack of opportunity or incentive.	
	Equipment and PAT	Lack of machinery in the marketplace, high cost of adaptation.	Technological innovation
	Breeding opportunities	Lack of value chain coordination.	Market

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It should be noted that no enabling condition can be taken alone, as all are interconnected. Institutional support to promoting sustainable agriculture, such as using plant teams, can come from policymakers and regulators, outreach programmes, networking associations, educational centres, and research entities. Policy can influence markets; innovations and new knowledge can be generated through research; and outreach programmes, education and networking can influence farmer knowledge and decisions, and, ultimately, agronomic practices. Generating information and innovations through research requires public-private collaboration and investment. Sharing the information with decision makers, including policymakers, farmers, and consumers, requires educational programming, technical training, and stakeholder networking.

5.1. Policy

Intercropping is a practice with environmental benefits that represents a change in production systems. Policies can incentivise and support the use of plant teams through subsidies for intercropping practices and products. Potential mechanisms for this are outlined in Deliverable 1.6, *Policy guide to Plant Teams* (Mínguez et al. 2021).

Among the targets of the new Common Agricultural Policy (CAP) derived from the Farm to Fork Strategy, there are three that relate directly to intercropping:

- Reduction of fertilisers.
- Reduction of pesticides.
- Increasing agro-biodiversity, and pollinators in particular.

Farmers that are making a transition to meet the targets established in the Farm to Fork Strategy, partly through intercropping, by doing their on-farm trials to reach optimum mixtures and management, and adapting their machinery, will require some financial support. DIVERSify PFs highlighted this issue, i.e., they need to maintain profits.

However, within the framework of the new CAP, the Member States will be responsible for channelling financial support through either direct payments in the new conditionality requirements, which could recognise the role of intercropping in rotational diversification, or else as (a) an eco-scheme which supports longer term changes in crop management, the need for new or adapted machinery, income foregone or reduced profits, and/or (b) an agri-environmental measure that provides compensation for income foregone or smaller profit. Facilitating access to the 'Farm Advisory Service' is also within the ambition of the new CAP that will be implemented from January 2023. Similar approaches are also being followed in non-EU Member States, although specific mechanisms relating to how the strategic targets will be implemented and monitored remain to be seen.

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5.2. Agronomic innovation

More public and private research and development in intercropping is needed, and especially on the plant traits, mechanisms, and agronomic practices (sowing arrangements, sowing densities, input levels) that deliver optimal performance in plant teams. Together with this, plant breeding is needed to produce **optimal varieties** for specific cropping objectives, systems, and pedoclimatic zones.

Research and demonstration that highlight multiple benefits of plant teams is needed, and especially to hedge against failure in one area. The **use of multiple-purpose mixtures** can hedge against unexpected weather. In a drought, for example, water shortage can adversely affect a legume crop component more than, say, a cereal crop. The harvest can be sold for forage rather than food to mitigate profit decreases or losses. Using multi-purpose mixtures is a well-established agronomic practice than can be adopted more widely.

5.3. Technology innovations

One of the main barriers to adoption of plant teams is the lack of equipment suited to sowing, harvest, and grain processing of mixed crops. Several farmers reported having solved these mechanical problems, while others felt that appropriate machinery was unavailable in the market or that adjusting their own machinery was labour intensive. Networking among farmers related to the adaptation of existing equipment can help, as will commercial innovations. Some call on the private sector to develop new machinery and to make it available in the market. Within the DIVERSify project, a *Trouble Shooting Matrix of PAT practical solutions* has been developed (George et al. 2020, Deliverable 4.6/D32). Within this report, it is highlighted that a range of solutions to many of the technological barriers identified throughout the DIVERSify project may already exist without need for significant investment, through modification of existing options.

5.4. Participatory research

Participatory research can be an important contributor to overcoming barriers for adoption of plant teams. In participatory research, plant team trials are hosted by the farmers in close collaboration with the advisory services and researchers, and the joint evaluation of plant teams with farmers provides a common platform to address the field-level constraints for adoption of plant teams. Trialling plant teams themselves can help to overcome barriers associated with perceptions, lack of knowledge, and the tradition of using conventional agriculture practices. Agricultural trial research has an important role to play in providing validated information on crop varieties, crop mixtures, and sowing densities and timing, appropriate for local conditions. Participatory research is an effective way to target research questions to the real conditions of farming.

As a consequence of their participation in the DIVERSify project, on the agronomic side, farmers indicated that they met their expectations for a decrease in the use of N and the possibility for better weed control. They also valued the new knowledge acquired in the trials and in visits with other PFs via the demonstration events within the project. One said it was helpful to have weed scientists on hand to identify some of their weeds. They appreciated the low-risk opportunity exploring new forms of crop diversification with no financial outlay of their own. Despite the very

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extreme weather during some of the trial years, PFs do consider intercropping to be an interesting alternative practice to be included in their rotations and applied in the future, including testing new mixtures of plant teams.

5.5. Advisory services

Many farmers requested access to objective data, information, and recommendations about the use of plant teams. The project has also heard the same request directly from agricultural advisors. The provision of advisory services is dependent on structures for communication and other types of outreach. They only work if they can reach farmers, or if farmers can reach them. PFs in this project mentioned that a benefit from their participation was to have direct access to the advisory services the project provided. They also appreciated the information provided by the researchers, for example on trial design and data collection, which helped to validate their observations in the field.

On-farm research might be most useful since it is based in real conditions that farmers face. Research outputs sometimes then need to be translated to be relevant to a wider group of farmers and for policymakers.

Useful information can come from the empirical experiences of farmers, farm labourers, equipment developers and suppliers, and it can come from trials run by researchers. Knowledge exchange among farmers is also critical. This project has motivated some PFs to continue to experiment, looking for optimum sowing densities, more suitable crop varieties, and different crop combinations. Some fed back that neighbouring farmers were now interested in trying intercropping. Not all farmers have the space, time, or financial resources to experiment, and thus rely on advisory services.

The data and information generated through research and knowledge sharing can be made visible and available to a broader audience through several channels:

1. Publications (print, electronic)
2. Advisory services (in person, remote consultation, workshops)
3. Demonstration sites (research trials, farmer plots)
4. Social media.

Developing long term (i.e., funded) communication channels will address this key barrier to the adoption of plant teams. Different institutions have a role to play, including research institutions, government extension services, non-governmental organisations, and private companies.

5.6. Private sector and markets

The market can drive increased interest in the use of plant teams. The market is influenced by consumer knowledge and preferences, and product availability and price. In as much as the private sector is a driver of the market, it can play a large role in encouraging the use of plant teams. Seed companies can support research and development of appropriate cultivars and provide multi-species mixtures; equipment companies can innovate and make available specialised equipment; and grain buyers can set purchasing standards. Food businesses have their part to play by providing consumers

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with motivational information on the health, environmental and social justice benefits of products emerging from the use of plant teams.

6. Conclusions

To some degree, all the barriers indicated by the PFs somehow impact the economic outcomes of farming, which, for most farmers, is their bottom line. Lack of advice and support from extension agencies, for example, on selecting the right crop combinations for their pedoclimatic conditions, can lead to poor system productivity, resulting, of course, in lower financial gain. Lack of policy clarity or absence of relevant policy can lead to real opportunity costs of employing a plant team. For example, one farmer reported that employing a cereal-based plant team in a rotational system with cereals can interrupt the "rotational hygiene" of the system. The cost will be in cleaning up the subsequent disease, or pest or weed outbreaks.

To be viable, the plant teams or intercropping system must be:

- flexible to interannual variation in weather, prices, markets
- adaptable to changing policy
- productive
- cost-effective
- supported, or at least not restricted, by policy
- market demand competitive – consumer acceptance
- beneficial to society – co-benefits and public goods.

To achieve these conditions, we need investments in experimental trials, on-farm trials, plant breeding on the agronomic side, technological innovations on farm machinery, market analysis and value chain development in the private sector, and farmer, advisor, and consumer education and outreach. Government policies can help, but sustainable solutions are likely to be rooted in the private sector of agriculture.

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Appendices

Summary table of the vignettes on barriers and benefits from participatory farmers.

Region	***Plant team objectives***	***Benefits***	***Barriers***
United Kingdom	• improve weed control • ↓ crop loss from lodging • ↓ need for inputs • ↑ crop quality • ↑ fun/experiment • hedge bet against bad weather • produce protein (food and feed) on the farm	• ↓ weeds • drought resilience • ↑ yields • ↑ soil structure • ↑ pollinator presence • on-farm protein food production • on-farm high-protein feed production • ↑ wheat protein content • sold surplus production • revival of a historic practice	• cost of sowing twice • cost of seed • intercropping options very limited in this environment (is not suitable) • lack of knowledge • interferes with rotational hygiene • lack of a policy incentive (not subsidy, but real incentive) • lack of equipment for grain separation • lack of market for mixed product
Denmark	• produce high protein feed on the farm • ↓ need for inputs (N)	• ↑ soil fertility • ↑ soil cover • ↑ water use efficiency • ↑ and stabilize yield • ↓ need for inputs (N) • ↓ weeds • on-farm production of high protein feed	• lack of equipment, cost and labour for double sowing, grain separation • cost of see • lack of knowledge
Italy, Iberian Peninsula	• ↑ forage production	• ↓ expense for feed	• lack of sowing equipment

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		• ↑ increase agro-biodiversity and ecosystem services • less soil compaction • ↓ weeds • ↓ erosion • ↑ soil fertility • ↑ soil water holding capacity • ↓ need for inputs	• high cost of labour for sowing and separating grains • no market for organic feed • no market for mixed grain • reporting to the CAP is unclear

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Vignettes of farmer objectives, barriers and benefits to adopting intercropping, with some requested support or their own solutions.

Farmer	PF1820
Plant team	oat + various

Objectives for plant team:

General

- decrease crop loss
- decrease need for inputs
- improve quality of crop
- is more fun to experiment
- serves as a risk management tool (in the event of crop failure)

Specific

- Oat + lentil, employed to prevent lentil lodging to improve grain quality
- Oat + linseed, employed to prevent pest damage to linseed
- Oat + bean, employed in beans to prevent weeds and disease in beans

Barriers:

- Equipment: grain separation challenge
- Market
- Knowledge: lack of practical information
- Policy: lack of incentive (not subsidy, but real incentive)

Benefits:

- Production: increased yields
- Project: research served to validate their observations

Support / Solutions

- Equipment: own machine innovation for separation allows farmer to clean and save own seed

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Farmer PF2007

Plant team oat + pea

Objectives for plant team:

- experiment with a technique of historical importance
- produce protein on the farm
- regenerative agriculture

Barriers:

- Equipment: no machines exist for very small quantity of oat hull separation
- Knowledge: lack of practical information and availability of appropriate cultivars, and this practice had fallen out of favour decades ago

Benefits:

- Cultural: reviving an historic practice
- Production: protein yield on farm for vegan lifestyle
- Project: stimulated farmers to continue to experiment with plant teams

Support / Solutions

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Farmer	PF1824
Plant team	winter beans + spring wheat

Objectives for plant team:

One single objective: Weed control in the bean fields to improve protein production for cattle feed

Barriers:

- Equipment: must bring in equipment to the field twice to sow two crops at different times and depths
- Equipment: time required to separate grains prevents marketing (must send grains within 3 days of harvest)

Benefits:

- Production: wheat had higher protein content, and farmer might "throw beans into other crops" to get the protein boost
- Production: sold surplus wheat, which was of higher quality than average
- Production: reduced weeds in beans
- Environmental: more pollinator insects were observed, attracted to the bean flower
- Agronomic: speculates that presence of wheat in the bean field may improve soil structure
- Project: participating in research provides empirical data to justify our practices economically
- Project: researchers helped with weed identification

Support / Solutions

- Policy: Subsidies for organic agriculture will be necessary if the green premium goes down (if many farms convert to organic)

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Farmer PF1826

Plant team peas + triticale

Objectives for plant team:

One single objective: reduce lodging in peas to reduce grain loss

Barriers:

- Knowledge: Need more data to optimise plant team sowing proportions and cultivars to optimise benefit
- Cost of companion plant seed
- General: use of plant teams is exceptionally rare in this region, and the farmer sees no obvious reason to try something else. The farmer does employ plant teams in forage fields and as cover crops, but it does not seem beneficial for harvestable crops.
- Production: Introducing a cereal with the pea disrupts the rotational hygiene (no break in cereal)
- Production: main crop (pea) yield is reduced, but increase proportion of usable grains

Benefits:

- Production: all crops did well despite the drought
- Production: fewer weeds

Support/ Solutions

- Market: would like to see more farmers growing organic peas

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Farmer PF1831/1832

Plant team vetch + oat, pea + wheat

Objectives for plant team: improve forage production

Barriers:

- Equipment: lack of appropriate equipment for sowing
- Policy: unclear how to report plant teams in the CAP
-

Benefits:

- Production: less input of fertilisers
- Environmental: reduces soil erosion, GHG emissions; improves soil water holding capacity
- Project: project provided finance to try something new

Support / Solutions

- Subsidy: assistance needed to acquire appropriate equipment
- Market: market could open to higher volume of forage crops to be able to commercialize faster

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Farmer	PF1838
Plant team	tritordeum + lucerne
Objectives for plant team:	Not specified

Barriers:

- Labour cost increase
- Market: there is little demand in the market for organic feed
- Market: organic feed has not reached economy of scale to influence the market: there is little demand for organic feed by meat producers; there is low production of organic feed, so supply is not large enough to create a market

Benefits:

- Agronomic: improves soil fertility
- Agronomic: improves water use efficiency
- Environmental: improves agro-biodiversity and associated ecosystem services

Support / Solutions

- Policy: rules for organic agriculture could be a little more relaxed or flexible
- Market: develop specific value chain for organic feed

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Farmer PF1811/1901

Plant team wheat + faba bean / wheat + pea

Objectives for plant team: Not specified

Barriers:

- Equipment: lack of specialised sowing equipment for mixed crops
- Labour: more labour is required to sow and to separate grains at harvest
- Market: no market for mixed grains

Benefits:

- Cost: reduced outlay for animal feed
- Soil: less Equipment required for mixed crop, thus less soil compaction
- Market: one company innovated new product using mixed grains for poultry feed
- Production: cereal controls weeds in the mixed crop field
- Environmental: mixed crop is perceived to lower soil erosion
- Agronomy: improved soil fertility (and less need for fertiliser) due to presence of legume

Support / Solutions

- Agronomic: make available cultivars appropriate to our environment
- Financial: payments to incentivise mixed crops
- Equipment: specialised equipment should be available in the market

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Farmer	PF1802
Plant team	spring barley + pea
Objectives for plant team:	reduce N fertiliser needs, produce on-farm feed

Barriers:

- Costs: labour for sowing is higher, cost of seed of additional crop
- Equipment: need to have the right equipment for simultaneous sowing

Benefits:

- Production: higher yield, more stable yield
- Production: lower weed pressure
- Production: increased soil fertility
- Production: produce high-quality feed for use on farm
- Cost: less need for N fertiliser

Support / Solutions

- Knowledge: need information relevant for the local context
- Market: need to develop local demand for mixed harvest

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Farmer	PF1909 [same as PFDK1803]
Plant team	faba bean + triticale (PFDK1803)
Objectives for plant team:	produce high-protein feed for use on the farm

Barriers:

- Cost: sowing is labour intensive
- Processing: high cost of dry and separation of grains
- Knowledge: not enough evidence available to fully embrace the practice

Benefits:

- Production: increased soil fertility
- Production: improved soil cover
- Production: improved water use efficiency
- Environment and cost: decrease need for fertiliser and herbicide

Support / Solutions

- Market: contract farming with a fixed price would be helpful
- Equipment: appropriate equipment for sowing

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