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The Legumes Expert Forum

Expanding the area of legume cultivation by intercropping

A research strategy of the German Agricultural Research Alliance

Imprint

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The most important points at a glance

The present research strategy on intercropping with legumes by DAFA (German Agricultural Research Alliance) expands their research strategy "Science, economy and society – making ecosystem services from legumes competitive" published in 2012.

The production of domestic legumes (e.g. beans, peas, lentils, vetches, clovers, alfalfa) supports sustainable agriculture and reduces dependency on imported protein feed whose production can have significant negative impacts on the environment in the exporting countries. When legumes and other crops (primarily cereals) are mixed to a greater or lesser extent and cultivated together in a field, almost like in a partnership (Fig. I), it is called legume intercropping (also known as mixed cropping). As legumes can fix atmospheric nitrogen, less fertiliser is generally needed in intercropping than with sole-crop cultivation without legumes. Intercropping can be designed to reduce the impact of pests and weeds relative to production of sole crops. Flowering legumes grown in intercropping support pollinators and so have a favourable impact on the ecology of the surrounding area. However, cultivating legumes with or without other crops in intercropping is currently far more difficult than sole-crop cultivation. Farmers often do not have the right equipment to cultivate, process and market domestic legumes, so from a purely economic point of view on legume cultivation it is often not worth it under current conditions.

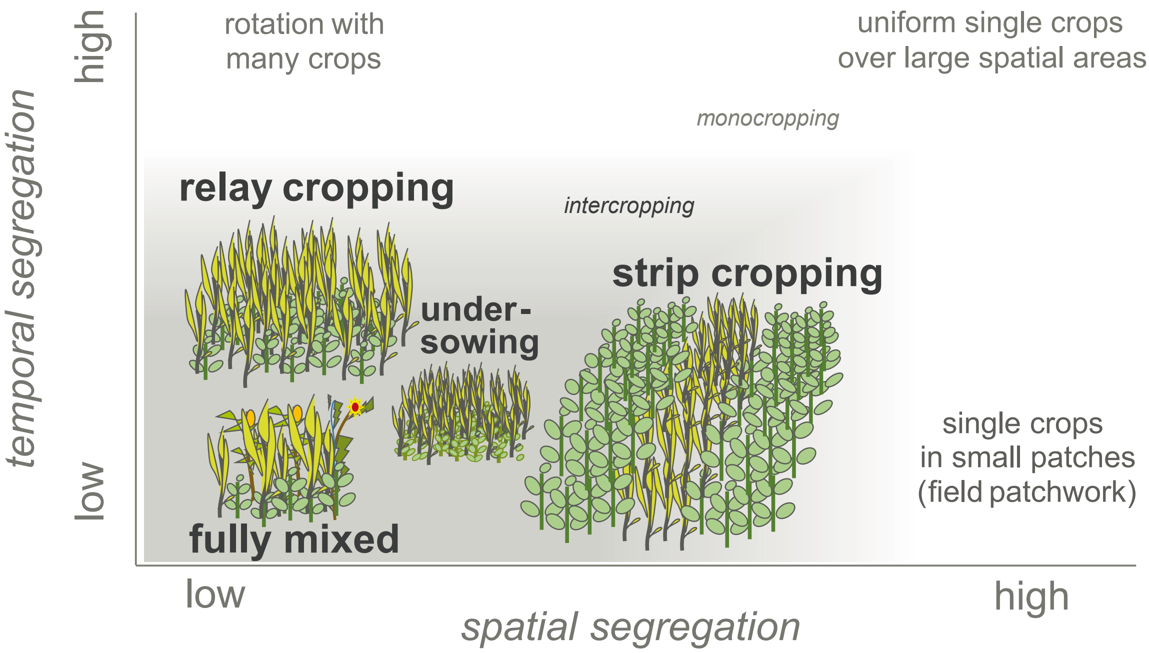


Figure I. Various forms of intercropping in the grey area; the distinction between intercropping and sole-crop cultivation (in the white area) is unclear. (Acc. to Brooker et al. 2015, DOI: 10.1111/nph.13132, P. 107-117)

For the benefits of legumes to materialise on a larger scale, the varieties used, the cultivation methods, the processing, the sale, and the legal framework for the entire value chain must be improved though research and development. This research strategy outlines how research to increase intercropping with legumes should be best organised from the DAFA (German Agricultural Research Alliance) point of view. It builds upon the research strategy published by DAFA on the expansion of legume cultivation which was incorporated into the BMEL's (German Federal Ministry of Food and Agriculture) Protein Crop Strategy and so contributed to an expansion of legume cultivation in Germany.

Starting with a fundamental feasibility study, the research to support intercropping with legumes could be split into three levels of increasing specialisation (Fig. II):

A "Classical intercropping" with existing equipment and varieties, harvesting of just one crop or separation of the crops after harvesting

B "Adapted intercropping" with adapted equipment and varieties, separation of the crops during or immediately after the harvest

C "Adapted intercropping with use of mixtures" with adapted equipment and varieties, joint harvesting and utilisation of both crops (no separation).

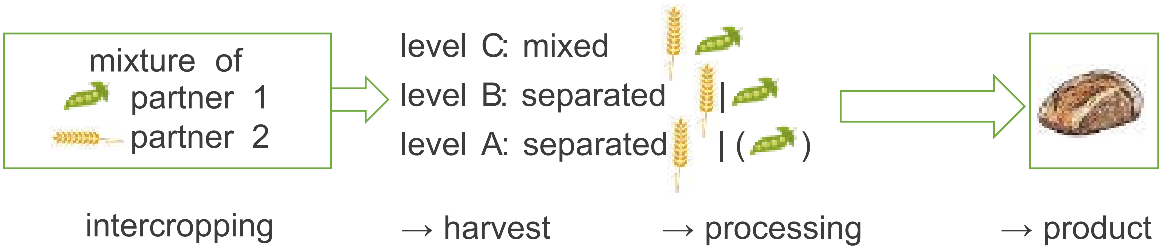


Figure II. From cultivation to product in Levels A, B and C: overview of the terms used in this research strategy.

As intercropping systems become more specialised, the challenges related to their practical implementation also increase, as do the requirements in terms of technical innovation, applied research and basic research, as well as the need for (agro-)political and demand-based support (Fig. III).

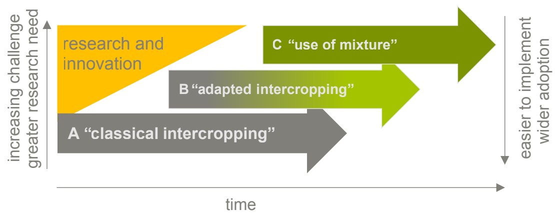
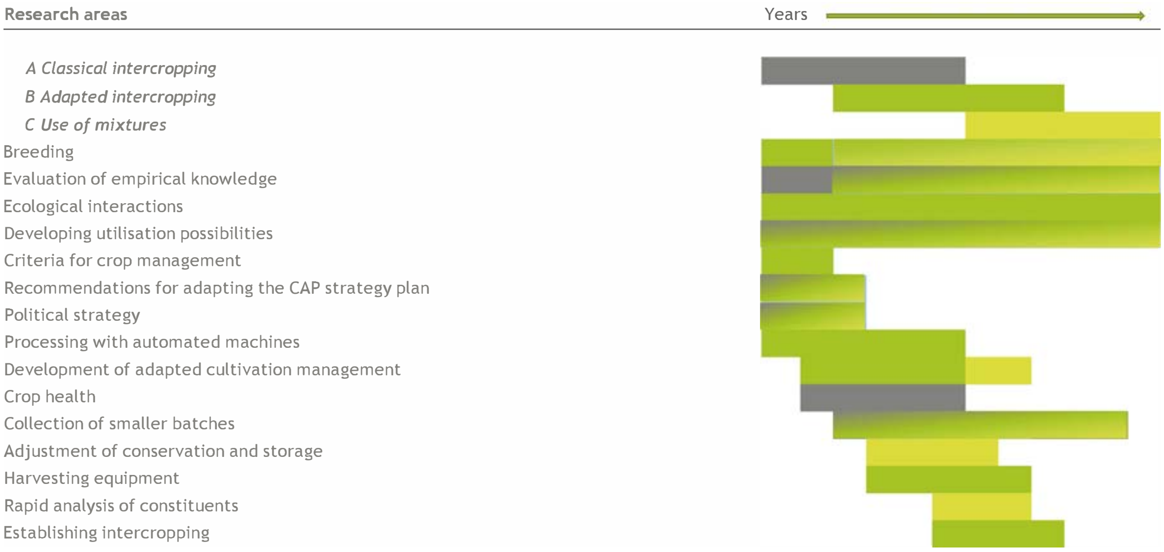


Figure III. Three levels of specialisation in intercropping

At all three levels, the aim is to collect, process, evaluate and make available existing experiences. This information should then be used to determine the most promising intercropping system that should be improved first. To accelerate the time-consuming breeding of new varieties, the process must be supported from the start. Increased demand for legumes that are produced through intercropping for animal feed and for human consumption improves opportunities for farms and processing companies to make a profit from these types of crops. Here, too, research must be commissioned early on to find and develop ways to encourage this demand. To help the organisations providing funding to plan funding programmes, the strategy also provides estimates for the minimum duration of research tasks – provided that conditions are optimal. These and other considerations result in a useful sequence of research areas (Tab. I) for production and the value chain.

Experiences both in Germany and abroad have shown that intercropping with legumes can, in many cases and under the right conditions, offer a range of ecological and economic advantages over sole-crop cultivation. Well-designed research funding can help to achieve these advantages on a much larger area than so far.

Table I. Areas with significant research needs in terms of time and in relation to the different levels of intercropping specialisation A (grey), B (green) and C (light green); Figure III. The indication of duration serves as a rough guide for research and development under optimal conditions.



1 Growing demand for plant proteins from sustainable agriculture

Agriculture has become increasingly specialised and efficient over the past few decades. The high demand for meat and dairy products into the 2010s also resulted in an increase in demand for animal feed. With reduced global trade barriers, the production of protein feed for animals has largely been supplied by countries outside of Germany[1]. Around 70% of the protein feed concentrates are imported in Germany. Due to the high demands of legume cultivation and the low profitability in comparison to imports, growing them as a source of protein for animals and humans was often no longer worth it and so the area used to cultivate these crops in Germany dropped to just three per cent in 2008 – the lowest level since the German reunification (Figure 1). At the same time, crop rotations in Germany were simplified to just a few crops (mainly winter cereals, maize, rapeseed).

Since the 1950s, instead of biological nitrogen fixation with legumes, increasing amounts of mineral fertiliser and manure from livestock farming have been used[2]. Simplified crop rotations also required an increased use of chemical-synthetic plant protection products. In parallel to this development, agricultural ecosystems and agricultural landscapes have become functionally, structurally, and aesthetically poorer over the years. Global demand for animal feed has resulted in an expansion of cultivation areas, a particularly striking example of this is with the cultivation of soybeans in South America, and has contributed to the extensive destruction of primary forests and grassland. This unsustainable production of food and animal feed has been (and still is) widely criticised by the scientific community and society as a whole.

It is against this backdrop that the former German Federal Ministry of Food, Agriculture and Consumer-Protection (BMELV) adopted its Protein Crop Strategy[3] in 2012. Measures were introduced that – under consideration of the international context – aimed to reduce the competitive disadvantages of domestic protein crops (legumes like field bean, pea and lupins, as well as different species of clover, alfalfa and vetch), close up gaps in research and try to implement the required changes in practice. The Protein Crop Strategy incorporated suggestions for research topics and concepts from DAFA's research strategy on legumes[4]. The latter proposed that coordinated solutions could be achieved through research along the entire value chain – from prebreeding, through to new food concepts.

Due to the increased cultivation of grain legumes in particular, in 2022 feed and grain legumes cultivation including intercropping accounted for 5.1 per cent of arable land (594 280 ha out of 11 664 000 ha, Figure 1). Higher market demand, increasingly coming from the food processing sector, and payments issued as part of the European Common Agricultural Policy (CAP) are probably the main reasons behind this increase. This development has been supported by the demonstration networks for different types of legumes funded by the BMEL. To work out the current state of knowledge, DAFA put together a workshop on the topic "Doubling the legume cultivation area by 2030" in March 2022 and brought together over one hundred scientists, researchers and farmers for two days of intensive collaboration. It became clear that so far there have been few systematic approaches that have made the added value of legumes so attractive in Germany that the cultivation of legumes would

[1] Zander, Peter; Amjath-Babu, T. S.; Preissel, Sara; Reckling, Moritz; Bues, Andrea; Schläfke, Nicole et al. (2016): Grain legume decline and potential recovery in European agriculture: a review. In: Agronomy for Sustainable Development 36 (2), article 26, 20 pages. DOI: 10.1007/s13593-016-0365-y.
[2] Voisin, Anne-Sophie; Gueguen, Jacques; Huyghe, Christian; Jeuffroy, Marie-Helene; Magrini, Marie-Benoit; Meynard, Jean-Marc et al. (2014): Legumes for feed, food, biomaterials and bioenergy in Europe: a review. In: Agronomy for Sustainable Development 34 (2), p. 361–380. DOI: 10.1007/s13593-013-0189-y.
[3] Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (2012): Eiweißpflanzenstrategie des BMELV. 14 pages. Berlin. Updated, English version: Federal Ministry of Food and Agriculture (2020): Beans, Peas & Co. The Federal Ministry of Food and Agriculture's Protein Crop Strategy for promoting the cultivation of pulses in Germany. 16 pages. Berlin. Available online at https://www.bmel.de/SharedDocs/Downloads/EN/Publications/beans-peas.pdf, checked on 3/4/2025.
[4] Wiggering, Hubert; Finckh, Maria; Heß, Jürgen; Wehling, Peter; Michaelis, Thorsten; Bachinger, Johann et al. (2012): The Legumes Expert Forum : Science, economy and society – making ecosystem services from legumes competitive : A research strategy of the German Agricultural Research Alliance. Available online at http://d-nb.info/102543644X.

be widely adopted in practice. To date, there is still no recognition of the ecosystem services provided by legumes, among others. One of the biggest sticking points when it comes to legume cultivation, is the scarcer and more uncertain sales opportunities due to insufficiently developed sales structures. In addition, the production of grain legumes fluctuates far more than the cultivation of other crops, like winter cereals for example[5], which means that many farms usually prefer working with other crops.

The decline in milk and meat consumption seen at the beginning of the 2020s[6], is linked with a growing demand for alternative sources of protein. Even though domestic legume cultivation in Germany has increased again since 2014 (Figure 1), the majority of the demand for plant protein for animal feed and human consumption is still covered by imported crops[7]. The importance of increasing legume production in Germany is becoming even more apparent in view of current developments. The climate and biodiversity crisis means that the use of plant protection products and fertilisers needs to be reduced[8,9]. The war in Ukraine, the energy crisis and the related fertiliser shortages have led to extreme price increases with fertilisers, particularly mineral N fertilisers, and, as a result, food. Producers of legume products expect demand for plant-based diets to continue growing over the coming years. In order to determine whether this growing demand for legumes should be covered more by domestic crops, the following questions must be answered: How can crop cultivation in Germany

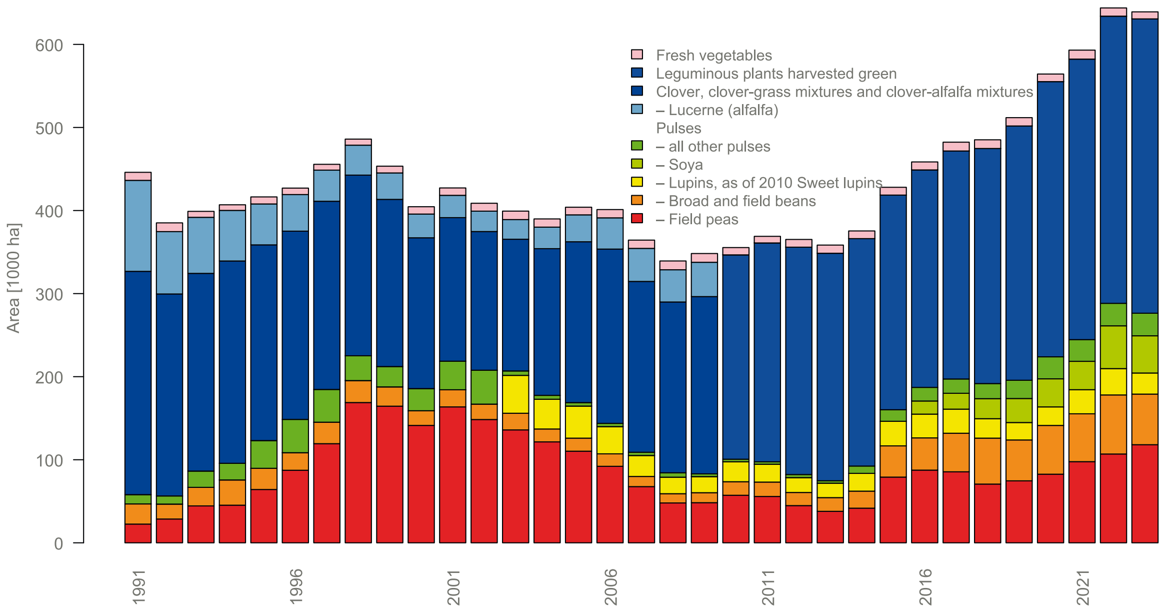


Figure 1. Cultivation area of different legume crops 1991-2023 in Germany according to eurostat.

[5] Reckling, Moritz; Döring, Thomas F.; Bergkvist, Göran; Stoddard, Frederick L.; Watson, Christine A.; Seddig, Sylvia et al. (2018): Grain legume yields are as stable as other spring crops in long-term experiments across northern Europe. In: Agronomy for Sustainable Development 38 (6), article 63, 10 pages. DOI: 10.1007/s13593-018-0541-3.
[6] Bundesanstalt für Landwirtschaft und Ernährung (ed.) (2023): Fleischverzehr 2022 auf Tiefstand. Available online https://www.ble.de/SharedDocs/Pressemitteilungen/DE/2023/230403_Fleischverzehr.html, updated on 03.04.2023, accessed on 13.04.2023.
[7] Bundesministerium für Ernährung und Landwirtschaft (2024): Versorgungsbilanz Hülsenfrüchte. Available online https://www.bmel-statistik.de/ernaehrung/versorgungsbilanzen/huelsenfruechte, accessed on 28.02.2024.
[8] Möckel, Stefan; Gawel, Erik; Liess, Matthias; Neumeister, Lars (2021): Wirkung verschiedener Abgabenkonzepte zur Reduktion des Pestizideinsatzes in Deutschland – eine Simulationsanalyse. Ed. by GLS Bank and GLS Bank Stiftung. Available online https://www.gls.de/media/PDF/Presse/Studie_Pestizid-Abgabe_in_Deutschland_2021.pdf, accessed on 03.05.2023.
[9] IPCC (2022): Summary for Policymakers. With assistance of Hans-O. Pörtner, Debra C. Roberts, Elvira S. Poloczanska, Katja Mintenbeck, M. Tignor, A. Alegría et al. In: IPCC (ed.): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, U.K. and New York, NY, U.S.A.: Cambridge University Press, pp. 3–33.

meet this higher demand? How can the cultivation of legumes be made more attractive? How can agricultural research best support this?

One of the most important agroecological findings from the last decade is that yield stability and increases in productivity can be achieved through intercropping, i.e., through growing several different arable crops (arable crop varieties) in a field at the same time (also known as mixed cultivation or companion planting, Chapter 2). A global meta study showed an overall positive effect on yields of 1.5 t ha^{-1} and significant savings in the amount of land (16-29%) and fertiliser (19-36%) used for intercropping compared to when cultivating a single crop on its own[10] In this international study, 934 pairs of crops grown either through intercropping or on their own using organic and conventional methods were compared. There are currently no meta studies available for Germany specifically. In practice, the effects on yields vary greatly and must be evaluated differently according to the location and combination of crops planted. With intercropping, the microbiome evidently plays an important intermediary function[11]. There are, however, still many other important processes that have not yet been sufficiently researched. Furthermore, when intercropping is used in conventional agriculture, it can help to reduce the use of fertilisers and plant protection products, as well as their negative effects on the environment[12]. Legumes are almost predestined for intercropping. Through their symbiosis with rhizobia, they can almost entirely supply themselves with nitrogen and, in some cases, can even add extra nitrogen to the soil. As such, resource-use complementarity is an important goal when intercropping legumes with non-legumes. Legumes increase the diversity of crops on an arable field and in the landscape. They can also help to increase resistance to biotic and abiotic stress, which means that the use of plant protection products and mineral fertilisers can be reduced. Intercropping with legumes offers additional ecological and operational advantages compared to single-crop cultivation, but it does pose additional challenges particularly when it comes to the cultivation, processing, and sale of the crops. This discovery has reinforced efforts at both an EU and federal state level to encourage intercropping. However, many farmers are hesitant to start intercropping while the purchase and processing of products from these systems cannot be satisfactorily ensured and an increase in added value cannot be achieved for the farms. It is therefore in the interests of society as a whole that research and innovation in this area contributes both to an increase in production and diversity and to the improved economic utilisation of the products of intercropping.

Based on the results from the workshop held in March 2022 and from further discussions, DAFA has expanded upon their research strategy for legumes by including the topic of intercropping. The aim of the present strategy is to use the proposed research on intercropping with legumes to make it a more attractive option for farmers to use in practice. This way, agriculture can have a positive impact on ecosystem functions in a landscape and make a significant contribution to stabilising and diversifying our agricultural and food systems to the benefit of society as a whole.

[10] Li, Chunjie; Hoffland, Ellis; Kuyper, Thomas W.; Yu, Yang; Zhang, Chaochun; Li, Haigang et al. (2020): Syndromes of production in intercropping impact yield gains. In: Nat. Plants 6 (6), pp. 653–660. DOI: 10.1038/s41477-020-0680-9.
[11] Stefan, Laura; Hartmann, Martin; Engbersen, Nadine; Six, Johan; Schöb, Christian (2021): Positive effects of crop diversity on productivity driven by changes in soil microbial composition. In: Frontiers in Microbiology 12, article 660749, 16 pages. DOI: 10.3389/fmicb.2021.660749.
[12] Jensen, Erik Steen; Carlsson, Georg; Hauggaard-Nielsen, Henrik (2020): Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. In: Agronomy for Sustainable Development 40 (1) article 5, 9 pages. DOI: 10.1007/s13593-020-0607-x.

2 Intercropping to expand legume cultivation



With intercropping, more than one variety of crop (hereinafter referred to as “intercropping partners”) is grown on a field at the same time (Figure 2). Typical forms of intercropping include: the cultivation of annual, biennial and perennial mixtures (e.g. grasses with clover in grassland or arable forage crops), the cultivation of mixtures with (almost) identical sowing and harvesting times (e.g. peas-barley, wheat-field beans, lentils-barley), the planting of companion crops (e.g. frost-sensitive legumes in winter canola), the planting of undersown crops (e.g. clover and grasses in rye), relay cropping (planting a second crop into a first crop prior to its harvest, e.g. soybeans being planted between winter wheat) and strip cultivation with separate harvests (particularly common on large areas in China with, for example, wheat-field beans[13]). Intercropping can also be done with shrubs and woody plants.

Intercropping results in comparable or higher overall biomass yields per area unit and a reduction in weeds, harmful insects and crop diseases when compared to single-crop cultivation and is less risky if one of the crops grown produces a lower yield[14,15,16]. On the other hand, it is often far easier to grow a single crop on its own rather than a mix of different crops. Until now, our agricultural systems have been mainly oriented towards ensuring high productivity with a single crop and not at all focused on other ecosystem services. Over the years, cultivation methods, processing and breeding have all been focused on single-crop cultivation and have been improved accordingly, while experiences and competences for intercropping and its products have barely been developed further or have even been lost over time. At the moment, the mixes produced through intercropping are very difficult to sell, and producers must cover the costs for the separation and the cleaning. As such, for now, crops grown on their own are in general far more profitable for farmers than mixes grown through intercropping.

[13] Li, Long; van der Werf, Wopke; Zhang, Fusuo (2021): Crop diversity and sustainable agriculture: mechanisms, designs and applications. In: Frontiers of Agricultural Science and Engineering 8 (3), pp. 359–361. DOI: 10.15302/j-fase-2021417.
[14] Böhm, Herwart; Dauber, Jens; Dehler, Marcel; Amthauer Gallardo, Daniel A.; de Witte, Thomas; Fuß, Roland et al. (2020): Fruchtfolgen mit und ohne Leguminosen: ein Review. In: Journal für Kulturpflanzen 72 (10-11), pp. 489–509. DOI: 10.5073/JfK.2020.10-11.01.
[15] Alarcón-Segura, Viviana; Grass, Ingo; Breustedt, Gunnar; Rohlfs, Marko; Tscharntke, Teja (2022): Strip intercropping of wheat and oilseed rape enhances biodiversity and biological pest control in a conventionally managed farm scenario. In: Journal of Applied Ecology, 59 (6), pp. 1513–1523. DOI: 10.1111/1365-2664.14161.
[16] Li, Xiao-Fei; Wang, Zhi-Gang; Bao, Xing-Guo; Sun, Jian-Hao; Yang, Si-Cun; Wang, Ping et al. (2021): Long-term increased grain yield and soil fertility from intercropping. In: Nature Sustainability 4 (11), pp. 943–950. DOI: 10.1038/s41893-021-00767-7.

When it comes to choosing species for intercropping and the intercropping partners, it all comes down to the goal of the farm: higher yields, more secure yields, improved quality, phytosanitary measures, avoidance of lodging (prostrate growth) or investments in soil health. Location, climate, and variety availability all limit the selection of intercropping partners because they have to be coordinated in terms of size, ecology, and phenology to produce the best results. Ultimately, the technical possibilities for joint or separate sowing, joint or separate harvesting, as well as the processing and selling opportunities must all be taken into consideration.

Research funding geared towards intercropping requires additional financial investments from federal and state funds due to the wide range of possible crop combinations, particularly if new technology has to be designed and breeding programmes for a range of different crops have to be set up. To justify this financial outlay, the potential of intercropping combinations, taking into account suitable cultivation regions, cultivation breaks and crop rotations, should be examined early on (feasibility study). This means working out how much land will probably be needed to produce what quantities of plant protein and what reduction in cereals or other crops would this entail. Something that is decisive when it comes to the acceptance of intercropping in practice, is ensuring that the added value of intercropping is not just ecological but economic, too.

The range of possible combinations and cultivation methods in intercropping poses a challenge for research and practice as adequate recommendation must be given for the specific conditions and decisions must be made.

To help farmers overcome these challenges, there are five key areas of research that must be covered:

- Improving the understanding of the agricultural and ecological interactions between the intercropping partners – also for the development of models
- Adapting the breeding of the different intercropping partners to the different types of intercropping
- Further developing cultivation methods with new technical procedures (sowing, plant protection, fertilising, harvesting)
- Adjusting processing methods for joint harvesting
- Improving the processing and sale opportunities of the individual intercropping partners or the mixed harvested crops to improve quality and increase the added value

The required research is covered in more detail in the following sections and must be carried out in addition to the research into legume cultivation itself.

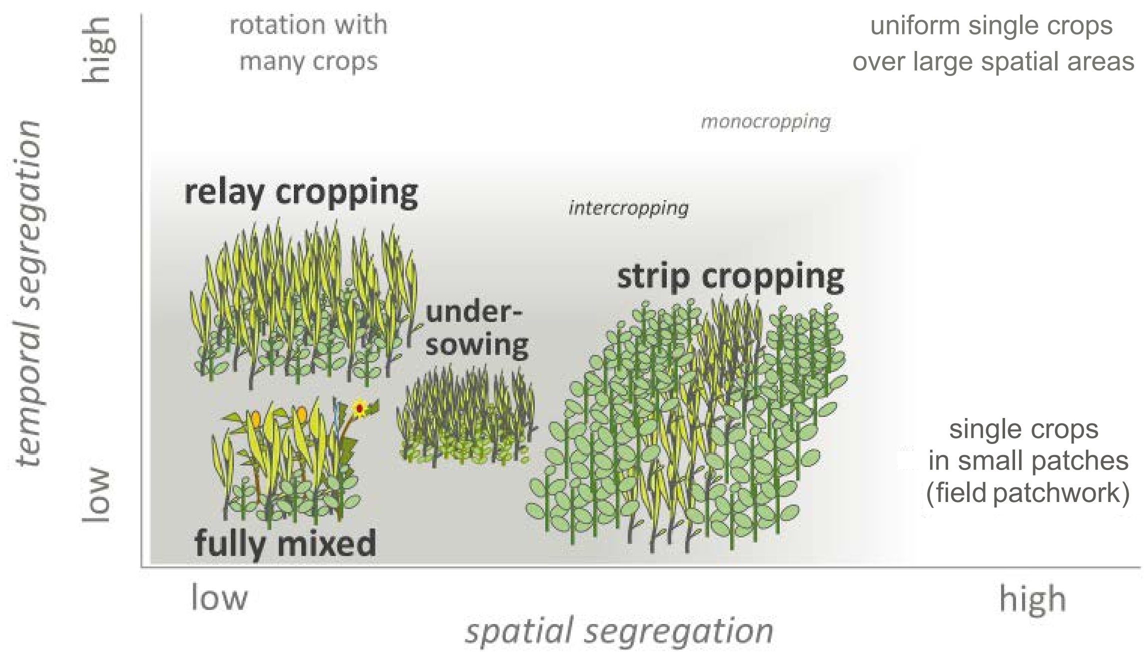


Figure 2. Various forms of intercropping in the grey area; the distinction between intercropping and single-crop (monocrop) cultivation (in the white area) is unclear. (Acc. to Brooker et al. 2015[17])

[17] Brooker, Rob W.; Bennett, Alison E.; Cong, Wen-Feng; Daniell, Tim J.; George, Timothy S.; Hallett, Paul D. et al. (2015): Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. In: The New Phytologist 206 (1), pp. 107–117. DOI: 10.1111/nph.13132.

3 Research needs for intercropping with legumes

The research needs for supporting intercropping with legumes must be forward-looking and oriented towards the intended development of intercropping and the utilisation of the harvested products. In this regard, it makes sense to split intercropping endeavours into three levels of increasing specialisation (Figure 3):

A “Classical intercropping” with existing equipment and varieties, harvesting of just one crop or separation of the crops after harvesting

B “Adapted intercropping” with adapted equipment and varieties, separation of the crops during or immediately after the harvest

C “Adapted intercropping with use of mixtures” with adapted equipment and varieties, joint harvesting and utilisation of both crops (no separation).

As intercropping systems become more specialised, the challenges related to their practical implementation also increase, as do the requirements in terms of technical innovation, applied research and basic research, as well as the need for (agro-)political and demand-based support. The development of intercropping systems must be driven and supported along the entire value chain by specific and more general findings from research for each level (A, B and C). Below, we will characterise the individual levels of intercropping specialisation and then will go into more detail about the research needs in the subsequent sections.

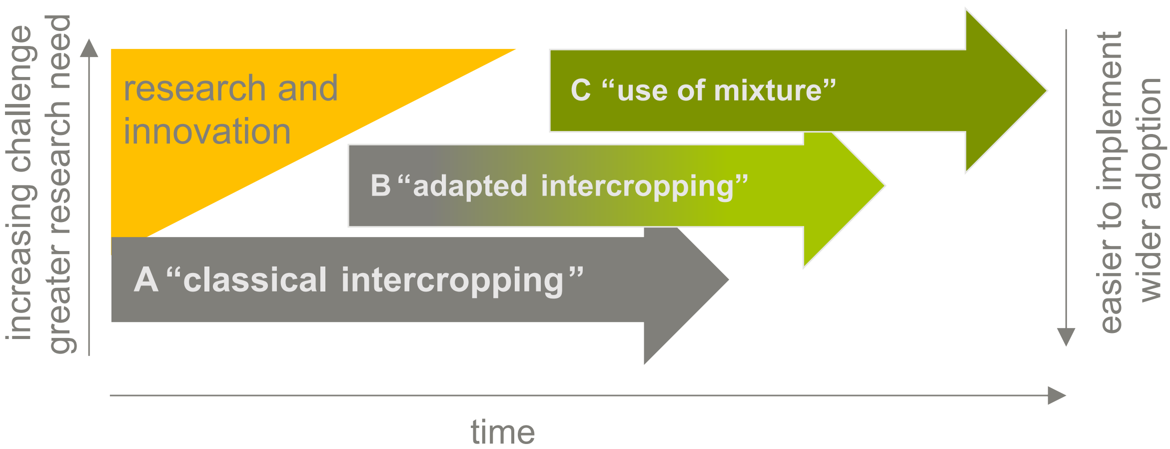


Figure 3. Three levels of specialisation in intercropping

A *Classical intercropping with existing equipment and varieties*

While the proportion of all arable land in Germany used for intercropping remains small, the low prevalence of intercropping makes it difficult to process and sell the harvested crops in a way that is economically competitive with other cultivation systems. There is also a lack of immediate business incentives for farmers to use intercropping. Intercropping can be done in a variety of different ways. The focus should initially be on the advantages of intercropping with legumes for the farm itself – expansion of crop rotations, reduced fertiliser use, reduced use of plant protection products[15], improvements in soil quality[16] – particularly for conventional farms that have not really grown legumes before, and on making these advantages more quantifiable, more transparent and more widely known.

For organic farms, intercropping can supplement the cultivation of grain legumes grown alone and feed legumes. The effects on crop rotations in organic cultivation cannot yet be estimated. Intercropping should act as an introduction to or an expansion of existing legume cultivation.

It would therefore be a good idea to start by discussing with growers and identifying systems that seem to be the most promising and then start researching these as a priority. Likewise, the characteristics of different locations where intercropping would be better than single-crop cultivation must be identified ⇒ 3.1.2.1 *Comparison of cultivation methods*. Farms just starting out with intercropping could choose one main crop and one accompanying crop with the aim of harvesting just the main crop and selecting the accompanying crop as a "supportive" intercropping partner depending on the situation (e.g., a nurse crop to suppress weeds or increase nitrogen levels; Figure 4). As such, at this level the most urgent research task is to systematically evaluate experiences from practical applications and scientific studies, make these experiences known and then render the results usable. ⇒ 3.1.2 *Adapting cultivation methods*.

It is often not possible to achieve an optimal crop cultivation in intercropping with existing varieties and existing sowing and harvesting equipment. This results in lower yields being achieved than with adapted varieties and cultivation methods. For example, crops with high nitrogen needs like maize, mixed with beans require a precise fertilisation with regards to the time and location. Likewise, many species and varieties are not suited for the competitive relationships that occur during intercropping. Chemical plant protection may also be needed in intercropping, but the corresponding products are frequently not authorised for use on all crops in the planted mix. ⇒ *3.1.4 Crop health*

B *Adapted intercropping with adapted equipment and varieties*

The more that the crop management is geared towards intercropping, the more the advantages of intercropping become tangible. Experiences from research and practice should be compiled into recommendations for the crops most frequently used in intercropping and should cover the following topics: seedbed preparation, seeding rate, seeding depth, time and layout of the sowing (single-row, multi-row, mixed, staggered, row spacing), crop health and harvesting methods (with multi-row intercropping e.g.

staggered harvesting and resulting impact of vehicles passing over the crop to be harvested later) and preparation.

While ideally the crops for intercropping would be sown at the same time and at the same depth, they can be sown at different times and in different locations and using sowing techniques adapted to the physiology of the species. ⇒ 3.1.3 *Establishing*

The intercropping partners can be used cost-effectively either on their own or as a mix. There is still a lack of established processing and sales structures for mixtures to be sold as animal feed, human food or as a raw material. Taking this into account, it is therefore initially more promising to harvest the crops separately (only possible if they have been sown at different times and in different places; Figure 4) or to harvest them together and then separate them immediately after harvesting. The technical solution needed for the individual and separate harvesting of the crops depends on the form of intercropping. Standard harvesting equipment can only be used to a certain point here, the separating method must be optimised or redeveloped for the possible combinations of intercropping partners. ⇒ 3.1.5 *Harvesting equipment*

The greater heterogeneity of the harvested crops also affects its moisture content and therefore its suitability to be stored for prolonged periods of time. If the intercropping partners are only separated after the harvest (Levels A and B) or not separated at all (Level C), the methods for drying, ventilation and protection against storage pests must be improved. ⇒ 3.1.6 *Processing and utilisation*

The lack of utilisation and sales opportunities for potential intercropping partners, if they cannot be completely separated or if new crops are used, means that they are cultivated far less frequently. To get out of this self-defeating cycle, it is important to combine harvested goods from smaller, scattered batches into larger units for more economic selling and to set up processing and sales structures, even for new or previously insignificant intercropping partners. In Switzerland, a similar system resulted in intercropping increasing more than tenfold between 2009 and 2020 [18]. ⇒ 3.1.6 *Processing and utilisation*

For breeding varieties that are better adapted to the requirements of intercropping and selling the harvested crops, it is important to start early due to the long development time of over ten years. ⇒ 3.1.1 *Breeding*

At the same time, the utilisation of products of intercropping needs to increase, as intercropping will only be able to expand if demand for it rises. Social and scientific research can recommend ways to design favourable food environments to policymakers. ⇒ 3.2 *Supporting demand for products of intercropping with legumes*, ⇒ 3.3 *Supporting policymaking*

C *Adapted intercropping and use of mixtures*

As farmers gain experience and intercropping becomes more widespread, it will become more attractive for manufacturers to develop equip-ment for the simultaneous harvesting of two or more crops and the adapted varieties. Sub-sequent further processing of the mixtures re-quires either large capacities for separating the mixed crops or – as described here – an option for processing the mixed crops further without prior separation (Figure 4). At the moment, this form of utilisa-

[18] FiBL Film (2020): Mit Mischkulturen die einheimische Eiweiss-Versorgung erhöhen – Erfolgsgeschichte (Diverimpacts). Video. Available online https://youtu.be/pnVUBqmgyLc?t=375, accessed on 22.05.2023.

tion is seen as more of a niche, but it could significantly increase the expansion of intercropping in the future.

Farms already use crops from intercropping in the feed for their animals. At the same time, however, methods for processing mixtures outside of farms in food production facilities must be developed. There have already been some attempts to make mixed flour using wheat and peas or wheat and field beans[19]. Here researchers and industrial players must work together to further develop the foundations for utilisation options at different steps during food processing in practice. Quick and inexpensive analyses of the heterogeneous raw materials upon harvest or during the subsequent processing, as well as an efficient rough separation and remixing or admixing are all possible ways for industrial players to obtain their preferred homogeneous (intermediate) products with known properties.
⇒ *3.1.6 Processing and utilisation*

The use of mixtures in food processing can really help to encourage intercropping. A perfect example of this is the production of bread made using field beans. At the moment, the different types of flour are mixed in the bakery. But two pure types of flour could actually be premixed in the mill before being delivered to the bakery. Or the flour could be made in the mill using a directly harvested ground wheat-field bean mixture, adding wheat flour or field bean flour as necessary depending on the composition.

As only a few farms have experience in processing mixtures produced through intercropping and to find suitable processors nearby can often be difficult for them, systems for the collection and processing of small batches should be developed and tested in practice to begin with. It would be sensible to plan this type of system together with the utilisation of the intercropping partners mentioned under B (adapted intercropping). It would also be sensible to examine under which economic and regulatory framework conditions and with help from which possible funding opportunities could these systems be established.

Research needs over time

The necessary research described below requires different durations. This results in a chronological sequence of research (Table 1) that is adapted to the levels of specialisation of intercropping and that should be taken into account in research funding.

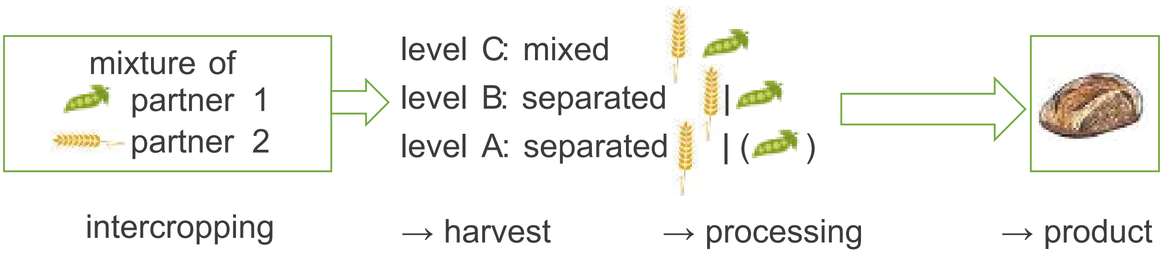


Figure 4. From cultivation to product in Levels A, B and C: overview of the terms used in this research strategy.

[19] Brotbüro; Naturland; Demonetzwerk Erbse–Bohne (2019): Leitfaden für Bäckereien zum Backen mit heimischen Ackerbohnen und Körnererbsen. Available online https://ltz.landwirtschaft-bw.de/pb/site/pbs-bw-mlr/get/documents_E-1915284073/MLR.LEL/PB5Documents/ltz_ka/Arbeitsfelder/Eiwei%C3%9Fpflanzen/Eiwei%C3%9Finitiative/Aktion%20Eiwei%C3%9Fbrot/Leitfaden_Baeckereien_DemoNetErBo_brotbuero190426.pdf, accessed on 22.09.2023.

Table 1. Areas with significant research needs in terms of time and in relation to the different levels of intercropping specialisation A (grey), B (green) and C (light green); Figure 4. The indication of duration serves as a rough guide for research and development under optimal conditions.

Research areas	Chapter	Years
A Classical intercropping		
B Adapted intercropping		
C Use of mixtures		
Breeding	3.1.1	
Evaluation of empirical knowledge	3.1.2.2	
Ecological interactions	3.1.2.3	
Developing utilisation possibilities	3.2.1	
Criteria for crop management	3.1.2.1	
Recommendations for adapting the CAP strategy plan	3.3.2	
Political strategy	3.3.2	
Processing with automated machines	3.1.5	
Development of adapted cultivation management	3.1.2.2	
Crop health	3.1.4	
Collection of smaller batches	3.1.6.1	
Adjustment of conservation and storage	3.1.6.3	
Harvesting equipment	3.1.5	
Rapid analysis of constituents	3.1.6.2	
Establishing intercropping	3.1.3	

3.1 Improving production and utilisation

Research can contribute to achieving the goals mentioned above by providing solution-oriented recommendations for practice and politics. This includes interdisciplinary preliminary investigations to identify, on the one hand, the overall interests of society that need to be supported by policy instruments and public innovation funding. It must also consider, on the other hand, the task of classic entrepreneurial market research and development.

The biggest advances in agriculture in the past few decades are the result of technological developments and have been encouraged by business initiatives. Over the next decade, machines and systems will be developed further in view of the intended use, digitalisation, and the use of artificial intelligence. Here, public research funding must take care to ensure that field robots and AI procedures are not solely developed for single-crop cultivation, but that they are also developed to deal with the heterogeneity of crops grown with intercropping. Intercropping has massive environmental and often operational advantages and should therefore receive independent research funding.

To encourage the spread of Level B and C intercropping across Germany, there is a need for innovations that support intercropping with legumes in the areas of breeding, crop management (planting, sowing, fertilising, plant protection, harvesting), processing (including utilisation), business management, selling and political support. A close coordination and feedback between breeding, cultivation, equipment manufacturers, processing, selling, and political support is necessary.

The machines, systems, and technology for crop management and for processing the harvested crops that are currently available for Level A have been developed for classic cultivation systems and single crops. In these cases, the uniformity of the crop material and location allow for an economically efficient processing with large machines on large areas. These machines and technologies are less suitable for intercropping, which is characterised by spatial variation. On an interim basis, technical solutions are helpful that can be used to convert existing equipment. The significant costs of replacing existing, functioning equipment are a massive barrier for many farms today. In the long term, agricultural equipment should be development for intercropping and not just single-crop cultivation.

Sowing, mechanical weed treatment and grain separation after harvesting were all mentioned by the German Parliament's Committee for Education, Research and Technology Assessment as major obstacles for intercropping[20]. While there are indeed machines that can place different types of seeds at different depths, there is still a lack of equipment like separation modules for combines. For a greater expansion of Level B and C intercropping, it is not enough to simply adapt existing technologies in small steps. For example, swarms of lighter, electrically powered, and autonomous agricultural machines could perhaps better deal with the spatially heterogeneous cultivation procedures and better protect the soil. For intercropping, a new optimum of economic and ecological efficiency should be developed from a contest of ideas on crop management, technology, and utilisation. Technologies for intercropping may have to be completely redesigned and rebuilt to make them more practical to use.

[20] Ausschuss für Bildung, Forschung und Technikfolgenabschätzung [des deutschen Bundestages] (2006): Moderne Agrartechniken und Produktionsmethoden – ökonomische und ökologische Potenziale : 1. Bericht: Alternative Kulturpflanzen und Anbauverfahren. Available online https://dserver.bundestag.de/btd/16/032/1603217.pdf.

The following sections outline the necessary research tasks for an expansion of intercropping with legumes. At the end of each section, the estimated duration for the tasks (under optimal conditions) and up to which technology readiness level (TRL, Figure 5) research should be supported by public funds is stated. With social issues (Section 3.3), the TRL should be understood as a degree of maturity in the sense of an increasing concretisation of overarching political strategies through to implementation regulations.

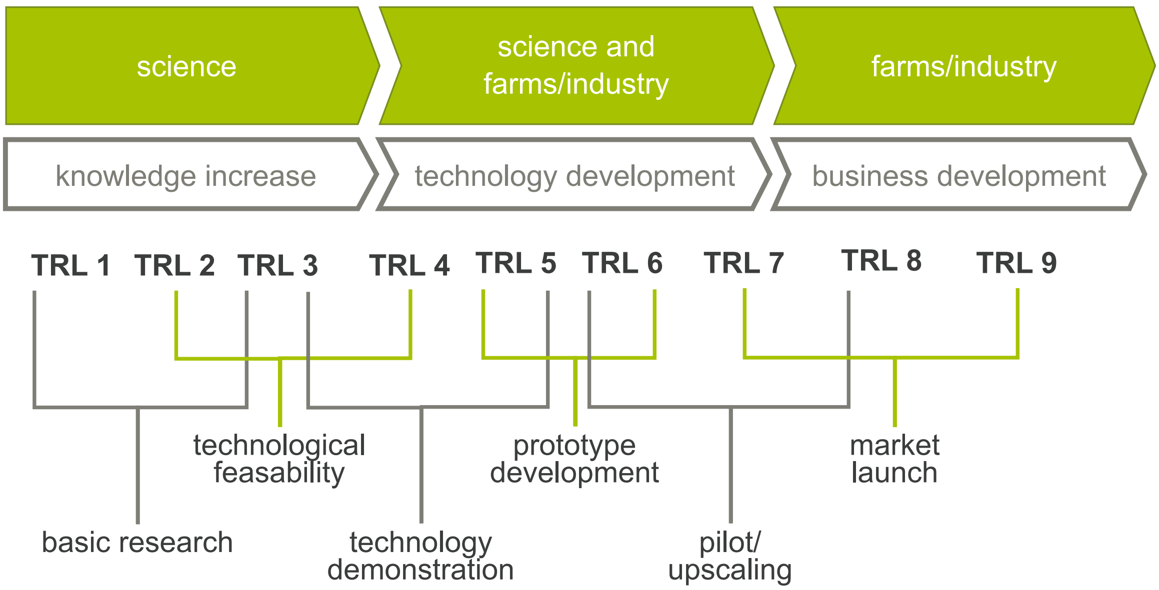


Figure 5. Technology Readiness Levels (TRL); simplified representation acc. to Projektträger Jülich (https://www.ptj.de/hymat)

3.1.1 Breeding

Varieties that are bred to be grown as a single crop are primarily defined by their uniform growth under intraspecific competitive conditions. Crops often struggle to compete with weeds and react strongly to a lack of water, nutrients, and light. In intercropping, the intercropping partners should have their own properties, such as resistance to diseases and pests, and should complement each other as best possible when it comes to their resource use (water, nutrients, light). For example, shade-tolerant varieties could be grown under varieties that need lots of light; legumes being capable of symbiotic N_2-fixation provide more nitrogen for other crops. These complementary properties can be adapted to intercropping even more through the breeding of already used but also little used varieties in prebreeding (see box).

So that there is enough genetically varied material for the breeding, preparatory work with a significant amount of effort is required (prebreeding). Wild material, regionally propagated varieties or closely related species must be procured from gene banks, checked for the desired properties, genetically stabilised, and propagated in order for these properties to be incorporated into productive varieties through breeding techniques. In the future, this fundamental task should have the same high importance for intercropping as for single-crop cultivation. However, additional properties oriented more towards intercropping should also be investigated and the existing prebreeding system expanded upon. The amount of work and time for prebreeding for intercropping with legumes is not currently covered by private

Breeding focuses for intercropping

1. Architecture (length, leaf position, shoot branching, roots)
2. Growth phase (sowing time, harvesting time, climate, staggered/simultaneous)
3. Physiology (tolerance to shade, tolerance to heat and drought, tolerance to weeds and intercropping partners, resistance to pests)
4. Utilisation (animal feed, food for human consumption, raw materials, energy, use of residues, use of whole crops, mulch: rich in valuable but low in invaluable constituents)
5. Harvestability (time of maturity, poor suitability for storage, burst-proof husks)
6. Seed properties (colour, breaking resistance, hullability, even weight)
7. Ecosystem services (N_2-fixation, soil health, erosion protection)

sector breeding programmes. As such, public funding for pre-competitive prebreeding is essential here.

In addition, suitable rhizobia strains must be selected to increase nitrogen fixation and therefore the contribution to greater resource efficiency. Interactions with mycorrhizae (symbiotic root-soil fungi) for new mix combinations and under low-nitrogen conditions should be investigated as this could help to strengthen symbioses and reduce fertiliser use in practice.

For legume cultivation in grassland, there are currently breeding programmes for pasture, cut- and walk-over resistant varieties. Mixes should be designed in combination with grasses and forbs to reduce methane emissions from cattle as much as possible, e.g., by ensuring that they have an adequate tannin content. Crop breeding goals that are more adapted to the animal that will be consuming the crops are necessary.

BREEDING – research tasks (by urgency)	**Research duration**	**Goal TRL**
Breeding of constituents	5–9 years	6–7
Adjustment of species for intercropping	10–20 years	6–7
Matching and adjustment of rhizobia strainss	3–9 years	5–6
Breeding of grassland species	9 years	5

3.1.2 Adapting cultivation methods

Thanks to its diversity, intercropping can vary significantly and be adapted to different locations. However, recommendations for certain locations are often based on experiences with only a few different types of crops used for intercropping. Approaches to disseminating this empirical knowledge, like those established within the framework of the EU CAP Network ("EIP-Agri" until 2022), the Legume Hub[21] or the Agrodiversity Toolbox[22], should be researched and developed further. It requires the recording, systematisation and imparting of already available empirical knowledge and research oriented towards this (see Section 3.1.2.2). At the same time, models for intercropping that can help with things like the location-suitable selection of intercropping partners and seeding rates, for example, must be developed (see Yu et al. 2024, for example)[23].

As such, (1) the different cultivation methods must be systematically compared and evaluated, (2) the cultivation methods must be adapted to intercropping, and (3) the interactions between the species (legumes and non-legumes) in intercropping must be investigated and quantified in order to improve cultivation processes in a targeted way.

This way, questions that are relevant for practical application[24] like (a) the integration of intercropping into crop rotations and the preceding crop effect of intercropping, (b) the influence of intercropping on the development of diseases in subsequent crops and the cultivation phases of the individual intercropping partners to be observed and (c) infestations of pests and fungi in comparison to single-crop cultivation, can be answered.

Over 19500 varieties of legumes have been identified worldwide. But only a few are of economic significance in Germany or other countries with a similar climate. The large diversity could be used for intercropping if both historically used[25] and new varieties with interesting properties (e.g. certain constituents, tolerance to certain weather conditions) are integrated into research programmes.

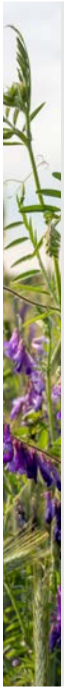
3.1.2.1 Comparison of cultivation methods

Intercropping should meet several different requirements (productivity, ecological contribution, resilience to environmental variations) and be adapted to the location and climate where the crops are being grown. In order to choose the right system for a certain location, intercropping must be compared with other forms of cultivation[26]. For the comparative assessment, criteria, measurement methods or indicators that describe parameters that are important for the value chain[27] and that take into account and evaluate ecosystem services must be selected. The assessment must be conducted for different cultivation variants, harvesting methods, soil and climate conditions and must therefore cover a sufficient number of environmental conditions to enable a well-founded assessment. The results from the assessment should then be compiled into models for location-specific ecological and agricultural consulting.

[21] Donau Soja (2021): Legume Hub. Europas Wissensplattform für Hülsenfrüchte. Available online https://www.legumehub.eu/de/, accessed on 28.08.2023.
[22] AgroDiversity Toolbox. Toolbox on Agricultural Diversification. Available online http://www.agrodiversity.eu, accessed on 28.08.2023.
[23] Yu, Jing; Rezaei, Ehsan Eyshi; Thompson, Jennifer B.; Reckling, Moritz; Nendel, Claas (2024): Modelling crop yield in a wheat–soybean relay intercropping system: A simple routine in capturing competition for light. In: European Journal of Agronomy 153, article 127067. DOI: 10.1016/j.eja.2023.127067.
[24] Fischl, Martin; Dierauer, Hansueli (2020): Anbau von Körnerleguminosen in Mischkultur im Trockengebiet. Ed. by Ländliches Fortbildungsinstitut Österreich. Wien. Available online https://www.fibl.org/fileadmin/documents/de/news/2020/bionet_mischkulturen_2020.pdf.
[25] Fruwith, Carl (1921): Handbuch des Hülsenfruchterbaues. 3. ed. Berlin: Parey. Available online https://nbn-resolving.org/urn:nbn:de:hbz:38m:1-61037.
[26] Bybee-Finley, K.; Ryan, Matthew (2018): Advancing Intercropping Research and Practices in Industrialized Agricultural Landscapes. In: Agriculture 8 (6), article 80. DOI: 10.3390/agriculture8060080.
[27] Khanal, Uttam; Stott, Kerry J.; Armstrong, Roger; Nuttall, James G.; Henry, Frank; Christy, Brendan P. et al. (2021): Intercropping – Evaluating the Advantages to Broadacre Systems. In: Agriculture 11 (5), article 453. DOI: 10.3390/agriculture11050453.

Variables for comparing intercropping

- Intercropping partners
- Cultivation methods (strip, relay, undersowing, community, second crop × row and temporal spacing, sequence)
- Harvesting method (simultaneous, separate)
- Soil and climate types



Criteria, measurement methods and indicators

- Effort (equipment, fertiliser requirements, crop health)
- Yields, yield variability
- Preceding crop value
- Utilisation possibilities (single and multiple utilisation)
- Value: feed, nutrition, energy, raw material
- Ecosystem functions and the resulting services (incl. soil fertility, substance retention, influence on the microbiome)
- Contribution to biodiversity

3.1.2.2 Development of adapted cultivation methods

As the number of possible combinations for cultivation is massive and subject to additional variability due to weather influences, a very high number of multi-location and repeated trials are necessary. This requires a participative research approach that allows farmers to optimise intercropping on farms using simple experimental setups, taking into account the interactions between the intercropping partners (Section 3.1.2.3). Living labs are good options here. It is important to provide suitable scientific support for practical issues being investigated here. The farms taking part in this approach must receive expense allowances that cover the costs for data collection and for processing the harvested crops. This practical research must be supplemented with commissioned research if there are certain important combinations that will not be covered otherwise.

Experiments with intercropping have been and will be conducted also in neighbouring countries and further afield in regions with a similar climate. These experiments and a systematic evaluation of intercropping combinations that have already been tried out in Germany can help narrow down the variables to investigate. Therefore, one urgent research task is to systematically evaluate and depict experiences from practical applications and scientific studies. The top priority should be the evaluation of different variants for intercropping that farms can carry out with existing varieties, existing equipment, and sales channels for the main crop (Level A). The depiction of the advantages and disadvantages should be supplemented by demonstration plots on farms that already successfully implement intercropping, and by professional exchanges. Instructions and models, for example demonstrations of how good intercropping systems for specific locations can be developed, should be worked up in collaboration with practitioners.

3.1.2.3 Understanding the interactions between the intercropping partners

Not a lot is known about the ecological interactions in intercropping that are impacted by resource use, environmental influences, microbiomes, and other species in the ecosystem and that are closely intertwined by control loops. It is therefore difficult to estimate how well new intercropping partners will go together. In addition to an evaluation of cultivation methods, a deeper understanding of how two or more species interact when mixed and what environmental influences are decisive here is necessary. Growth models can be expanded based on this information and then used to simulate more combinations under different location and climate conditions. The calibration and validation of models adapted for intercropping requires additional data on growth trends for certain model parameters to be collected in field trials.

In order to improve understanding of interactions between intercropping partners, surveys on the following topics must be conducted during field trials (ordered according to importance based on the opinion of the steering committee):

1. Water needs of the crops and competition for water between the crops
2. Competition between shoots (light requirements/shade tolerance)
3. Competition in the rhizosphere
4. Nutrient needs of the species and synergies (e.g., phosphorous mobilisation)
5. Variety-dependent nitrogen assimilation depending on nutrient availability and intensity of the nodule form and performance
6. Biotic interactions in the rhizosphere (between crops and/or microorganisms) and above ground (between insects and other animals, amongst other things)
7. Legume-specific diseases
8. Disease, especially fungal diseases that affect the non-legume intercropping partners due to the altered microclimate
9. Optimisation of combinations with rhizobia strains
10. Crop rotation design

3.1.3 Establishing intercropping

In Level A (Figure 3), existing machines can be adapted to intercropping with suitable settings or implements. Chambers of agriculture, state offices and machine manufacturers have developed recommendations or new products for this. In Levels B and C, more flexible cultivation methods with precise data recording with the sowing and a corresponding control with the harvest is likely to make the variability of intercropping more economically viable. This can be done through: (1) more efficient equipment for the simultaneous or relay sowing of different-sized seeds – even to match small-scale spatial variation[28, 29] (2) improved equipment for reseeding in grassland and for sowing legumes in existing cereal stands (e.g. with drones), (3) autonomous robotics systems for farming at a single-plant level and (4) technologies that

[28] Ditzler, Lenora; van Apeldoorn, Dirk F.; Schulte, Rogier P.O.; Tittonell, Pablo; Rossing, Walter A.H. (2021): Redefining the field to mobilize three-dimensional diversity and ecosystem services on the arable farm. In: European Journal of Agronomy 122, article 126197. DOI: 10.1016/j.eja.2020.126197.
[29] Wegener, Jens Karl; Urso, Lisa-Marie; Hörsten, Dieter von; Hegewald, Hannes; Minßen, Till-Fabian; Schattenberg, Jan et al. (2019): Spot farming – an alternative for future plant production. Themenheft Neue Pflanzenbausysteme. In: Journal of Cultivated Plants 71 (4), pp. 70–89. DOI: 10.5073/JfK.2019.04.02.
[30] Donat, Marco; Geistert, Jonas; Grahmann, Kathrin; Bloch, Ralf; Bellingrath-Kimura, Sonoko D. (2022): Patch cropping- a new methodological approach to determine new field arrangements that increase the multifunctionality of agricultural landscapes. In: Computers and Electronics in Agriculture 197, article 106894. DOI: 10.1016/j.compag.2022.106894.

evaluate agricultural land according to different sub-area-specific characteristics and, based on this, reorganise it into different small areas (spot farming[24,25] or patch cropping[30]).

When establishing intercropping, it can be efficient to combine several work steps into one (soil loosening, sowing, ground cover, mulching, fertilising, and sowing) and to treat the intercropping partners differently depending on their germination ability, sowing depth and fertiliser needs. The separation of work steps can also produce successful results if they are automated, apply light machinery and are overall gentler on the ground. Machinery like this can facilitate small-scale differentiated intercropping, flexibly take care of the individual process steps – from sowing and care to harvesting – for the different crops and separately harvest undersown crops, like white clover, for example.

The impacts of climate change require further research and innovation. We expect to see increasingly frequent periods of drought during springtime, which will have an effect on the interactions between crops used for intercropping (Section 3.1.2.3) but which can be countered with a range of agricultural techniques (e.g., with mulching, ridging up, drill channels).

3.1.4 Crop health and nutrition

In intercropping, choosing suitable intercropping partners can result in a reduction in the amount of synthetic-chemical plant protection products used in conventional agriculture[15,31]. Nevertheless, regulation methods for pests and weeds will be required in this complex system. For conventional agriculture, particularly in Level A, herbicide recommendations for intercropping with legumes must be developed, ideally for spot or strip application in combination with physical techniques. To further reduce the effects of synthetic-chemical plant protection products on the environment and to ensure that concerns about a lack of plant protection do not hinder the expansion of intercropping, proven biological and physical techniques for pest and weed control are needed as quickly as possible. Successful experiences with intercropping and weed control from organic farms must also be collected as they play an important role in consulting and in the transfer of knowledge. Practical, scientific-based recording of this type of empirical knowledge, systematised summaries and knowledge transfer should be established as research results on new physical and biological techniques, particularly to combat pests[32], are only expected to come in 3-5 years' time. As research progresses and to reach Level B, the expected changes in the spectrum of pests and diseases must also be taken into account in order to develop plant protection measures for mixes to improve self-regulation. The risks of the physical and biological techniques should also be investigated.

To ensure a healthy development of the crops, it is important that there is a sufficient to good supply of crop-available nutrients in the soil. This can be ensured by means of a system-adapted fertilisation. Although mixed cultures can be chosen to complement each other in their needs, the essential nutrient requirements should still be secured as far as possible. For these types of situations, techniques must be improved to ensure that fertiliser can be applied in a targeted way to support the growth of the crops, and that the application is economically viable.

[31] Beillouin, Damien; Ben-Ari, Tamara; Malézieux, Eric; Seufert, Verena; Makowski, David (2021): Positive but variable effects of crop diversification on biodiversity and ecosystem services. In: Global Change Biology 27 (19), pp. 4697–4710. DOI: 10.1111/gcb.15747.
[32] Stukenbrock, Eva; Gurr, Sarah (2023): Address the growing urgency of fungal disease in crops. In: Nature 617 (7959), pp. 31–34. DOI: 10.1038/d41586-023-01465-4.

3.1.5 Harvesting equipment

Depending on the types of crops and type of intercropping, harvesting can represent a greater or smaller challenge and must be looked at in a different way. For example, crops grown together during intercropping are already being harvested together as green forage, silage or hay. The joint threshing of cereals is also common in practice; a subsequent rough separation of the intercropping partners can usually be done with existing, stationary equipment (often with little extra work required)[33]. A clean harvest and a precise separation of the crops for sale remains one of the biggest challenges that is preventing intercropping from becoming more widespread[34].

During threshing, grain breakage must be prevented but all grains must still be removed from their ears and husks. The combine harvester settings, such as the speed and the winding, must be set and regulated very carefully. For very different intercropping partners, new threshing units may have to be developed. In the future, methods for a separation step during threshing with separate grain tanks is a possibility and the physical principles and individual technical solutions are known, however their application in a combined use on farms must still be developed further.

Other harvesting techniques that need to be adapted to intercropping conditions and that must be made ready to be put on the market include high cutting methods for the separate harvesting of intercropping partners or separation methods for leaves and stems of one or both intercropping partners, similar to those that are already being developed for pure stands of alfalfa[35]. This means that leaves with higher protein contents can be used in a targeted way as feed for monogastric animals (pigs, poultry) or as a starting product for food, and that the stems can be used as structure hay for ruminant feed or for use as a sustainable raw material.

A simultaneous separate recovery of the intercropping partners in the form they are collected in the cutting unit requires separate, parallel treatment in the following process steps. While this is technically a lot of work, it will allow two vastly different intercropping partners (even grains and forage) to be harvested at the same time. Robotics systems could offer an alternative here (see above, 3.1.3).

3.1.6 Processing and utilisation

3.1.6.1 Creating market-relevant volumes

Overall, also processing companies look at market supply and demand. If farms in a region produce less mixed crops – a situation that exists at the start of the expansion of intercropping to Level C – the processing of these smaller quantities is usually not economically viable. As such, the possibilities for mobile processing units or cooperative, cross-farm collection and processing routes should be developed and analysed. Agglomeration effects should be investigated and encouraging factors identified. It needs to be analysed whether the establishment of a collection system would be worthwhile because such a collection system would also promote the cultivation and utilisation of other “small” crops that contribute to landscape diversity.

[33] Saathoff, Georg; Siegmeier, Torsten; Timaeus, Johannes; Finckh, Maria R. (2022): Mischkultur-Weizen in der Lebensmittelverarbeitung. In: Innovation Food 9, pp. 20–22. Available online https://www.food-innovation.ch/forschung/mischkultur-weizen-in-der-lebensmittelverarbeitung.
[34] Bedoussac, Laurent; Deschamps, Elina; Albouy, Lisa; Bourrachot, Patrick; Morrison, Alastair; Justes, Eric (2021): Harvesting and separating crop mixtures: yes we can! Intercropping to boost agroecology in European. Virtual Conference, France, March 2021. Available online https://hal.inrae.fr/hal-03342750.
[35] Maxa, Jan; Thurner, Stefan (2023): Luzerne: Wie lassen sich Blätter und Stängel trennen. Hg. v. Bayerisches Landwirtschaftliches Wochenblatt. Available online https://www.wochenblatt-dlv.de/feld-stall/landtechnik/luzerne-lassen-blaetter-staengel-trennen-571786, updated on 12.01.2023, accessed on 14.06.2023.

CULTIVATION METHOD – research tasks (by urgency)	Research duration	Goal TRL
Determining evaluation criteria for cultivation methods	3 years	–
Mechanical control of pests and weeds	3–5 years	7
Improving techniques for cleaning harvested crops	3–5 years	8
Testing and evaluating cultivation methods	5–9 years	7
Improving techniques for separate (in terms of time or area) harvests	3(–9) years	7
Improving techniques for sowing or resowing	3–5 years	7
Reducing pests through intercropping	3–5 years	8
Plant protection recommendations for intercropping	5–9 years	5
Adjustments to cultivation for spring drought	5(–9) years	6
Improving techniques for fertiliser spreading	3(–5) years	6
Learning more about the interactions between species	(5–)9 years	5–6
Techniques for separating leaves and stems with feed legumes	3–9 years	6
Influence on pests when legumes are added to the crop rotation through intercropping	10 years	7

3.1.6.2 Determining the composition for a better utilisation

Mixtures can be separated according to their constituent (Levels A and B, Section 3.1.5) or potentially (in Level C) utilised as a mixture. Mixtures can be used for both animal and human food and are sometimes even preferred. When evaluating a mixture, it is important to know the proportions and the qualities of the crops in the mix at the start of the processing. There is a lack of cost-effective, automated methods for determining the proportions in the mixture during the processing if the proportion determination has not already been done at the time of harvest. The proportion of broken grain is also critical but this can be reduced through crop breeding (Section 3.1.1) and through technical improvements in the harvesting and grain separation (Section 3.1.5). If the composition of a mixture is known, constituents can be added to achieve standardised mixing ratios or to adapt the formula. In particular, the determination of proteins and protein fractions of legumes must be adapted for mixtures, made more practical and less expensive in order to optimise their protein quality and composition for food and animal feed (silage, dry material). Likewise, the levels of unwanted constituents in mixtures must be able to be determined quickly. It is also necessary to investigate what is special about processing plants that can better handle changing batch proportions (e.g., plant size).

3.1.6.3 Storage and conservation

Mixed crops cannot always be optimally harvested as one of the intercropping partners may be less ripe (wetter) then the other. In addition, the cultivation and harvesting can result in greater heterogeneity in the harvest crops. When it comes to storage, good ventilation and temperature control is important to prevent crop spoilage and ensure better protection against storage pests. The moisture content of legume grains should be 14% or lower, like with cereals. As such, the storage and conservation techniques must be adapted to the type of mix and for what it will ultimately be used. The more important thing here is to improve methods for identifying zones with high humidity and to control the ventilation of storage units.

When using (whole crop) mixtures as animal feed, the two main conservation methods, drying and ensilaging, present different challenges, and therefore different research needs. With drying, it is important to (1) avoid crumble losses and an undesired selection of the individual intercropping partners or of crop parts during the harvesting and other handling steps, (2) quickly reduce moisture contents and (3) keep drying damage, particularly that caused by Maillard reactions, to a minimum. Pre-drying in the field (withering) should be kept to a minimum. Harvested crop that has only been dried a little in advance subsequently needs a significant amount of drying energy or long drying times. As such, it is best that the heat used for the drying comes from renewable sources. Too low temperatures and an intermittent supply of energy (e.g., direct use of solar energy) inhibit throughput in order to really assert themselves economically, with the exception of high-priced speciality crops. In addition, the influence that technical drying methods currently available on the market have on nutrient quality is less standardised and defined. Solutions are being sought for quick, energy-efficient plants that dry relatively wet dry goods economically, i.e., with sufficient throughput, with renewable sources of energy without having a negative impact on nutrient quality.

Ensilaging is cost-effective but difficult and with an uncertain success rate when used with different intercropping partners. As legumes are generally difficult to ensile (high buffer effect against lactic acids), intercropping partners should complement each other, especially in terms of ensilability (low buffer capacity, sufficient fermentable carbohydrates). This is necessary for both an optimal adjustment of the pre-drying (wilting) and for a potential necessary addition of silage additives. Control methods for determining the ensilability, and subsequently the ensilaging process and potential success, which are practical, applicable on farms and quickly available are decisive when it comes to control biological fermentation processes with mixtures. Innovative solutions for minimising protein and amino acid breakdown during ensilaging are in particularly high demand. This can be achieved through the use of special additives, targeted intercropping partners with specific secondary constituents (e.g. condensed tannins) or through so-called dry ensilaging, a process that combines drying and ensilaging (“haylage”). Here, recommendations for optimal methods for the different mixtures must be worked up and machines for an efficient pre-drying and dry ensilaging must be developed.

3.1.6.4 Processing intercropping partner crops as mixtures

Methods must be developed for the manufacturing of food using mixtures that are suitable for decentralised and centralised processing (see Section 3.1.6.2). If mixtures containing legumes cannot be processed in a cost-efficient way, they can perhaps be separated at a later point in time. As such,

- separating, hulling, and sorting technologies must be developed further to enable the processing of mixtures with different compositions and
- wet and dry fractionation methods that are designed for processing mixtures must also be developed.

PROCESSING – research tasks (by urgency)	**Research duration**	**Goal TRL**
Improving the determination of protein contents of mixed harvested crops	3–5 years	5
Techniques for separating the intercropping partners once harvested	3–5 years	7
Analysis of secondary constituents in the harvested crops	3–5 years	4–6
Automated determination of proportions or constituents in the harvested crops and adjustments during the preparation	3–5 years	5
Dealing with changing mix ratios on the farm and during processing	3–5 years	7
Adjusting conservation and storage	3–5 years	6
Developing mobile processing units or cross-farm processing routes	3–5 years	7

3.2 Supporting demand for products of intercropping with legumes

High consumer demand for products of intercropping is a decisive incentive for farms to get started with and invest in intercropping, and for processing, trade, and distribution companies to add products of intercropping to their portfolio. In addition to technical issues with the processing, storage and utilisation, institutional issues along the value chain must be addressed, addressing the specific challenges of mixtures in Level C in order to guarantee a high availability of attractive prices for consumers. This also includes the unsolved question of the simple quality determination of mixtures under market conditions. Simplified methods for quality determination open up options when it comes to packaging and pricing throughout the value chain that are worth investigating and developing (see Section 3.1.6.2).

3.2.1 Developing utilisation possibilities for animal feed and human food

Products of intercropping with legumes, e.g., maize-bean silage, or alfalfa-clover-grass hay, have been used for feed. Farms that do not have livestock can cultivate these mixtures as part of their crop rotation and then contribute or sell them in feed-manure co-operations with farms that have livestock.

Support of the demand and research on its implementation should firstly be oriented to animal nutrition and the direct utilisation of products of intercropping on farms and potentially in the feed industry as (1) the consumption of protein-rich animal feed (and the cultivation area needed) is still high compared to consumption in human food, (2) concentrated feed for livestock is mostly mixed feed (starch- and protein-rich components from cereals, soya and/or rapeseed) that could also come from intercropping, (3) the requirements in terms of the purity of products (from intercropping) is significantly lower for animal feed than it is for human food.

The necessary cultivation area for animal feed will probably remain at a relevant level even during the shift towards more plant-based diets. In the introduction, we briefly mentioned the issue of imports of soya from South America, most of which go into animal feed. In Germany, the cultivation area of soya grew from 1 000 ha in 2008 to 51 000 ha in 2022 (128 000 tonnes of soybeans). In terms of feed consumption (2.8 million t), the amount of soya harvested domestically barely makes an impact, accounting for just 4.6 per cent of all soya consumed in Germany[36].

Cultivation-specific experiences with intercropping for feed production can also be used for the production of human food, this means that there is already a lot of information about this subject available. As a general rule, however, products for human consumption require a higher degree of purity. This means that a stricter differentiation of the harvested material must be made for crops for human consumption than for crops harvested for animals. In addition, the crops harvested for human consumption are often subject to special quality criteria that are necessary for technical utilisation of the raw material (e.g., flour).

However, the promotion of intercropping for feed production should not lead to the production of animal feed competing with production for human consumption. Research into sup-

[36] Bundesinformationszentrum Landwirtschaft (2023): Soja - Nahrungsmittel für Tier und Mensch. Ed. by Bundesanstalt für Landwirtschaft und Ernährung (BLE). Available online https://www.landwirtschaft.de/diskussion-und-dialog/umwelt/soja-nahrungsmittel-fuer-tier-und-mensch, updated on 01.07.2023, accessed on 22.05.2024.

porting demand should therefore be oriented toward using intercropping to produce crops for human consumption, and potential competitive or synergy effects with livestock farming explicitly taken into account. For example, possibilities for the direct use of green crops from intercropping for human consumption by means of fermentation processes in bioreactors or other processes that take into account the specific potentials and requirements of crops harvested from intercropping could be developed. Likewise, cereal and legumes mixtures can be and already are being used to make bread. In this case, the proportions just have to be adjusted accordingly.

3.2.2 Shaping food environments

When it comes to consumer research, options that link to existing preferences or that develop these preferences further must be considered. There are large gaps in knowledge regarding the use of intercropping products or mixtures in food for human consumption, for example, the effect of different combination options on the design of meals. Research on shaping environments in which food is purchased or consumed (food environments)[37] is of central important when it comes to promoting demand for intercropping products. Here, empirical knowledge must be recorded, systemised, and scientifically examined. Transformation-oriented research that generates system, goal and transformation knowledge is needed to make changes to food environments. And when it comes to the development of new marketing and sales strategies, interdisciplinary collaborations between the different sub-disciplines of consumer sciences are needed.

In order to develop new sales channels, a deeper understanding of the effects of communication contents and instruments regarding products of intercropping is necessary. Corresponding research is needed to close up these gaps in knowledge. This approach should be supplemented with practical research in the area of communicative design options of food environments. Research in this area should be oriented towards the relevant recommendations of the Deutsche Gesellschaft für Ernährung (German Nutrition Society), and more particularly the specific requirements of vulnerable population groups. New design options for food environments should also be explored in transdisciplinary approaches with practical partners from the out-of-home-catering and food retail sectors.

Sensory research by trained panels and subjective evaluations by consumers (affective and hedonic tests) are important to promote the sale of processed products from intercropping and mixtures containing legumes. In addition to the nutritional effects, a greater focus should be placed on the nutritional-medicinal effects of products of legume mixtures. In particular, the contribution of foods based on domestic legumes to reduce malnutrition with micronutrients and to reinforce plant-based diets should be taken into consideration here. Interaction effects with allergens or anti-nutritive secondary crop constituents must be considered in research programmes.

[37] Scientific Advisory Board on Aricultural Policy, Food and Consumer Health Protection at the Federal Ministry of Food and Agriculture (2020): Promoting sustainability in food consumption. Developing an integrated food policy and creating fair food environments. Executive Summary and Synthesis Report. Berlin. Available online at https://www.bmel.de/SharedDocs/Downloads/EN/_Ministry/promoting-sustainability-in-food-consumption.pdf, accessed on 04.03.2025.
See also: Spiller, Achim: Politik für eine nachhaltigere Ernährung. Eine integrierte Ernährungspolitik entwickeln und faire Ernährungsumgebungen gestalten. Available online https://gutachtenw-bae.org/blog/die-ernahrungsumgebung-als-entscheidender-aber-unterschatzter-einflussfaktor/, accessed on 31.05.2023.

DEMAND-RELATED research tasks (by urgency)	**Research duration**	**Goal TRL**
Evaluating empirical knowledge regarding processing	3–6 years	6
Evaluating empirical knowledge of food environments	3–6 years	6
Researching transforming food environments	3–9 years	7
Consumer research on preferences	3–6 years	5
Communication content and instruments	3–6 years	5
Nutritional-medicinal effects	3–9 years	4

3.3 Supporting policymaking

The implementation of societal goals is better supported by the general public if target groups were involved in the policymaking and if their expectations are taken into consideration in the policy. Continuous research into and with target groups can therefore help to improve support for policies with economic incentives and tax and administrative regulations. Research that analyses the impact of implemented policy measures can also help policymakers to better shape future policies[38]. The DAFA research strategy for the development of the organic farming and food sector in Germany[39] has recommended well-performing structures for research and research funding. Their extension and use would also support the expansion of intercropping.

3.3.1 Assessment indicators

To promote legume-based value chains, political control instruments should be built up based on scientifically founded indicators like life cycle assessments and analyses (e.g., Saget et al.[40]). As the available approaches to the quantitative recording and evaluation of ecosystem services are not yet entirely convincing, existing methods and indicators must be adjusted, particularly when it comes to taking the cultivation of legumes and their community partners into account. From DAFA's point of view, expanded and more differentiated formats for the comprehensive participation of relevant stakeholders are necessary and must be developed immediately. The first step here is to conduct an evaluation of the different existing methods of life cycle assessments or analyses with regards to a specific application for intercropping and use of products of intercropping. With the separation of harvested crops in particular, critical questions of attribution and their implications must be clarified. In addition, different applications can be developed, validated, and tested in the policy. This should also include other interesting approaches like transferring the principles of the German Renewable Energy Sources Act to the agricultural value chain[41].

[38] Strand, Roger (2022): Indicator dashboards in governance of evidence informed policymaking: Thoughts on rationale and design criteria. Ed. by Kristian Krieger und Lorenzo Melchor. European Commission. Joint Research Centre. DOI: 10.2760/328204
[39] Hamm, Ulrich; Häring, Anna Maria; Hülsbergen, Kurt-Jürgen; Isermeyer, Folkhard; Lange, Stefan; Niggli, Urs et al. (2017): Research strategy of the German Agricultural Research Alliance (DAFA) for the development of the organic farming and food sector in Germany. In Organic Agriculture 7 (3), pp. 225–242. DOI: 10.1007/s13165-017-0187-5.
[40] Saget, Sophie; Porto Costa, Marcela; Black, Kirsty; Iannetta, Pietro P.M.; Reckling, Moritz; Styles, David; Williams, Michael (2022): Environmental impacts of Scottish faba bean-based beer in an integrated beer and animal feed value chain. In: Sustainable Production and Consumption 34, pp. 330–341. DOI: 10.1016/j.spc.2022.09.019.
[41] Project "Entwicklung eines Nachhaltigen Lebensmittelgesetzes (NLG) als Analogie zum Erneuerbare-Energien-Gesetz (EEG) der Energiewirtschaft" (FKZ 01UT2107A/BMBF). Available online https://www.feda.bio/de/blaupause-lws/, accessed on 15.06.2023.

For comprehensive sustainability evaluations, the evaluation indicators must be supplemented with methods for measuring the social and economic impacts of intercropping. This means that corresponding social science research is required. The potential influence of state or private sector measures and instruments on production, utilisation, use and purchasing behaviour should be investigated in terms of impact using a comprehensive evaluation indicator system. For this, a stronger collaboration between crop production and agricultural economics research is necessary.

3.3.2 Political governance

With regards to policymaking, the European Common Agricultural Policy (CAP) is an important tool. Many of the decisions made on farms are based on measures laid out in national CAP strategy plans, in federal state programmes and in conjunction with other European regulations. Agricultural policy impact research should therefore determine how measures introduced in Germany have promoted or inhibited intercropping and how (agricultural) policy strategy plans and measures can be shaped to promote intercropping. It is also vital that the effects of political control instruments with regards to different types of intercropping (strip, relay, companion, undersowing) in existing and future agricultural regulations at a state, national and EU level are investigated. In particular, it must be clarified whether and if specific regulations are restricting intercropping (e.g. fixed proportions of legumes in communities regardless of community type, upper limits for legume quantities) or whether intercropping falls through the grid of implementing regulations.

Intercropping is also influenced by other political fields. The availability of varieties is also influenced, for example, by research policy in the fields of breeding and prebreeding. Consumer demand for products from intercropping is influenced by consumer policy, and the trade and processing of intercropping products by trade and processing policies. Research is needed into the effectiveness of current and future policy instruments, which in addition to classic agricultural policy instruments, also takes into account food policy, trade and competition policy and, last but not least, science policy in order to consider the situation as a whole. Agricultural economics and agricultural policy research should work more interdisciplinary with other areas of political science.

3.3.3 Transdisciplinarity and multi-actor approaches

In order to disseminate existing experiences and the knowledge gained through research, DAFA recommends[39] involving farms in the planning and execution of research and publishing the results appropriately. A whole range of different formats and terms have been developed for these types of shared experiments (living labs, on-farm-research, multi-actor approach). From the authors' point of view, the "model demonstration network" developed as part of the BMEL protein crop strategy has made a significant contribution to the increase in legume cultivation in Germany. The multi-actor network of the EU ReMix project[42] provided valuable insights into the functionality and success factors for the development of participatory processes.

For a sustainable transfer of knowledge in the practical policy design to promote intercropping, political actors (politics, management, associations) must also be involved in transdisciplinary research approaches. Living labs offer the opportunity to conduct inter- and transdisciplinary research into the expansion of intercropping. It is crucial that the expansion of intercropping is continued with different types of joint experiments and that players from all levels of the value chain, from breeder to consumers, are involved[43]. As the planning and execution of participation can take a long time, project durations must be extended to at least 5 years accordingly.

POLICY – research tasks (by urgency)	**Research duration**	**Goal TRL**
Recommendations for updating the national CAP strategy	1–5 years	5
Policy field research	2–6 years	7
Expansion of indicators for sustainable intercropping	5–7 years	5
Expansion of life cycle analyses for intercropping	3–6 years	5
Concepts for shaping food environments	3–6 years	5

[42] Salembier, Chloé; Aare, Ane Kirstine; Bedoussac, Laurent; Chongtham, Iman Raj; de Buck, Abco; Dhamala, Nawa Raj et al. (2023): Exploring the inner workings of design-support experiments: Lessons from 11 multi-actor experimental networks for intercrop design. In: European Journal of Agronomy 144, pp. 126729. DOI: 10.1016/j.eja.2022.126729.
[43] Dühn, Theresa (2020): Erkenntnisse aus der Öko-Forschung - Wie es gelingt, sie im ostdeutschen Raum an die Praxis zu kommunizieren. Master of Science. Hochschule für Nachhaltige Entwicklung, Eberswalde, Fachbereich Landschaftsnutzung und Naturschutz, Studiengang: Öko-Agrarmanagement, accessed on 05.04.2023.

4 Conceptual recommendations



The quantities of imported protein feed (primarily soybeans) from South America should be reduced in order to protect the natural environment and climate in South America and to improve local production conditions. It should be replaced by domestic livestock production on permanent grassland and by forage production on mineral soils in order to protect organic soils (as a potential source of greenhouse gases) and biodiversity[31]. This will be possible if demand for animal feed drops, i.e., if less meat and dairy products are consumed and exported. Although a lower demand for feed and reduced production of animal products remains unlikely for a while, the promotion of intercropping with legumes should be oriented to the cultivation of mixed crops for human consumption in the long term and under consideration of climate protection measures, and it should be coordinated with the implementation of nutrition strategies.

Legal regulations can support or inhibit intercropping (see Section 3.3.2). Any political strategy for promoting intercropping should therefore include a possible adjustment to the legal situations and have an encouraging effect at all federal levels.

This new research strategy on intercropping with legumes supplements the existing DAFA strategy on legume cultivation in Germany[4]. This applies to both the direct recommendations for legume cultivation and the overarching conceptual recommendations that can be summarised as follows: "The empirical knowledge gained through long-term and transdisciplinary research oriented towards value chains, the implementation of results from research in practice with support from regional cultivation centres, and the creation of suitable political framework conditions form the foundations for a successful strategy for promoting legume cultivation." With the model demonstration networks promoted as part of the BMEL's Protein Crop Strategy, a good approach for promoting legume cultivation and utilisation was found that should be supplemented and expanded by the development of long-term living laboratories within value added systems[44]. Significantly more resources must be provided for the development of regional value chains, particularly if a market for products of intercropping is to be created.

The estimated durations for the research mentioned in this strategy apply provided that framework conditions are optimal. For example, making adjustments to the breeding of species for intercropping in just 5-10 years (⇒ 3.1.1 Breeding) would be very ambitious and impossible to implement in practice. The public institutions entrusted with conducting value tests and state variety tests are already under a lot of strain. Their financing must, to stay with the example, be taken into consideration and prioritised in terms of time in a political strategy to promote intercropping.

Even with intercropping, research funding must look at the value creation system as a whole and then proceed according to urgency. The tables ordered according to urgency in Chapter 3, provide some orientation here. The chronological sequence (Table 1) must also be considered here. The necessary systematic investigations – in particularly into crop rotations and cultivation breaks – must be inte-

[44] value added system: "network or system consisting of value-creation chains or value chains which can include not only cross-connections but also dependencies between them" (VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik [2017]: Industrie 4.0 - Begriffe/Terms. Available online https://www.vdi.de/ueber-uns/presse/publikationen/details/industrie-40-begriffeterms.)

grated into cultivation systems and long-term programmes involving agricultural practice and downstream companies. The feedback of research results to policymaking should be structured and transparent and political players should be involved in the research process by means of a transdisciplinary understanding.

Findings from research on intercropping with legumes can make things easier for farms that want to start intercropping. Research on the breeding, cultivation and utilisation of legumes mixtures can accelerate the spread of intercropping if this is supported by politicians in a targeted and coordinated way. This can also increase the temporal, structural and biological diversity of landscapes and reduce the use of chemical pesticides.

DAFA hopes that this research strategy on legumes and intercropping can continue to successfully support politicians and researchers.

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This strategy has been endorsed unanimously
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Thank you!

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