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REVIEW ARTICLE

Current research on the ecosystem service potential of legume inclusive cropping systems in Europe. A review

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Abstract

Legume crops hold promise to diversify the currently simplified rotations that dominate Europe and to increase the sustainability of European farming systems. Nevertheless, most legumes have been ignored by farmers, advisors, and value chain agents in the EU, where legumes are estimated to occupy only ~2% of arable land. Recent surveys find that farmers see a lack of knowledge on the agroecological impacts of (re)introducing legumes as a key barrier to legume adoption. A review of current research on the agroecological potential of legume-inclusive cropping systems would help in assessing whether research targeting sufficiently supports farmers in overcoming this barrier. We have systematically reviewed and synthesized published literature reporting on agricultural ecosystem service delivery in European cropping systems with legumes included compared to those without legumes. Our analysis of 163 published articles revealed: (1) the bulk of published research addresses production-related services delivered by few legume species (pea, clover, faba bean, and vetch, 70% of reviewed studies) comparatively assessed in cereal-based rotations; (2) substantial knowledge gaps also exist, encompassing ecosystem services with less direct relevance to economic outcomes (e.g., biodiversity) and with potential for high variability (e.g., pest and disease suppression); (3) studies at plot-level and within-season scales dominate (92% and 75% of reviewed studies, respectively). Assessed in the context of recent complementary studies, we find that a limited research focus is both counter to knowledge demands from farmers and likely the result of self-reinforcing socio-technical regimes which prioritize production over non- or indirectly-marketable ecosystem services. We conclude that scientists in Europe should diversify research to include legume species, ecosystem services, contexts, and scales not yet well studied, in order to provide the agroecological knowledge base farmers need to amplify the potential benefits of crop diversity.

Keywords Crop diversification · Research targeting · Technological regime · Socio-technical lock-in · Knowledge development

Contents

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1 Introduction

Diversification in industrialized arable farming is increasingly recognized as necessary to mitigate the negative externalities caused by low-diversity cropping systems (IPES-FOOD 2016). In the European Union (EU), cereals, maize (grain and silage), oilseed rape, and sunflower together cover 92% of the arable land area, resulting in short rotations (3–4 years on conventional farms) dominated by cereals, maize, and rapeseed in the north, and maize and sunflower in the south (Eurostat 2019; Mudgal et al. 2010). Introducing legumes into sole-crop stands and simplified rotations is one of the most commonly used diversification measures researched in cropping systems experiments globally (Hufnagel et al. 2020), as legumes are considered to afford many social and ecological benefits (Voisin et al. 2014; Zander et al. 2016). In Europe, societal interest in the potential of legumes has grown amidst discussion of the so-called 'protein transition' (Aiking and de Boer 2018) and the rise of sustainability-based legislative initiatives which seek to reduce reliance on agrochemical inputs and increase agrobiodiversity (e.g., the EU Green Deal's "Farm to Fork strategy") (European Commission 2020).

The potential benefits of increasing legume production in the EU by (re)introducing them to current cropping systems span from field to consumer. These benefits can be summarily described as ecosystem services (ES), defined as services people obtain from the functioning of ecosystems which support life on Earth (MEA 2005). ES provided by production ecosystems (agro-ecosystem services) (Zhang et al. 2007) are related to both biological and agronomic aspects. At the field level, including legumes in cropping systems (grown as food, feed/fodder, forage, or service crops) is beneficial from an agronomic perspective because they bring nitrogen (N) into the soil through symbiotic N fixation, thereby reducing the need for N fertilizers in companion or following crops (Peoples et al. 2009), improving the use of soil N resources (Jensen et al. 2020), and in some cases improving the yields of following crops (Angus et al. 2015). Aggregated at farm and landscape levels, increased presence of legumes in European cropping systems would cascade benefits through regulating ES such as nutrient cycling, potentially reduced greenhouse gas emissions, and biodiversity conservation (Watson et al. 2017). In mixed crop-livestock systems, production of legumes as feed and forage has been shown to reduce mineral N fertilizer use and nitrous oxide emissions (Reckling et al. 2016), and feed and forage self-sufficiency through on-farm legume production would improve the circularity of farming systems (Koppelmäki et al. 2021). Increasing production and consumption of legumes is also beneficial from a consumer perspective, as legumes provide high quality proteins, which are an important component of a healthy diet (Willett et al. 2019; Weindl et al. 2020). Fulfilling a larger portion of human dietary protein needs with legumes in place of meat would contribute to more sustainable diets by reducing the demand for livestock production and its associated environmental impacts (Springmann et al. 2018; Willett et al. 2019).

Despite these apparent benefits, the area of farmland under legume production in the EU is currently estimated at only ~ 2% of total arable land (Pelzer et al. 2017; Kezeya Sepngang et al. 2020). After a steady decline for several decades, the area started to increase marginally after 2014 when greening measures were introduced in the EU's Common Agricultural Policy; however, gains are regionally variable and can be largely attributed to an increase in the production of soybean (Schreuder and de Visser 2014; FAOSTAT 2018; Kezeya Sepngang et al. 2020). These trends appear to indicate that various interacting factors, referred to as socio-technical lock-ins, are dissuading farmers from including legumes in cropping systems (Magrini et al. 2016; Meynard et al. 2018). A review on the topic pointed to the dominance of economic systems that favor specialization over diversification, and the failure of markets to promote legumes, as the main barriers to legume adoption in Europe (Zander et al. 2016). Moreover, grain legumes often present more unstable yields compared to autumn-sown cereals (Reckling et al. 2018), and how (or whether) they fit into current systems is context dependent (Reckling et al. 2020).

In spite of these challenges, a recent study in France found that some farms are transitioning towards including more legumes (Mawois et al. 2019). Importantly, this study showed that in addition to market opportunities and supportive policies, a key factor driving the stable introduction of legumes on farms was increased knowledge and awareness of their multiple and long-term agroecological benefits, i.e., the ES that they can deliver. Similarly, a comprehensive study on barriers to crop diversification in general found that "convincing" conventional farmers in Europe to adopt more agroecological practices, such as including legumes in rotations, would require providing them with more evidence of the positive relationship between crop diversification and the sustainability of their farms (Morel et al. 2020). Additionally, Zimmer et al. (2016) surveyed Luxembourgish farmers and found the majority to be under-informed about legume cultivation. These findings highlight the importance of directing research priorities to effectively contribute agroecological knowledge in support of crop diversification in general and of legume uptake specifically.

Mutually reinforcing feedback loops between research trends and technology adoption in agricultural systems have been identified in previous studies (Vanloqueren and Baret 2009), implying that research on ES delivery conducted at field and farm levels (as part of a multifactorial approach that includes market and policy foci) has an important role to play in un-locking barriers to legume adoption. Currently, a cluster of research projects focusing on crop diversification in the EU's Horizon 2020 funding scheme (www.cropdiversification.eu) is working to put a spotlight on legume research and fortify the knowledge base needed to support EU farmers in expanding the area of legume-inclusive cropping systems. Among market-based and socio-technical themes, several partners in these projects investigate the ecosystem (dis)services gained by introducing legumes in rotations as food, feed/fodder, forage, and service crops (Fig. 1). As is often the case in such projects, the topics chosen for study (e.g., which ES, from which legume species, and through which inclusion method(s)) may have been influenced by existing lines of research and prevailing analytical capabilities. The concentration of resources in projects like those in the crop diversification cluster constitutes a major opportunity for research on ES delivery to support legume adoption in practice (Mawois et al. 2019; Morel et al. 2020). However, it is important to critically reflect on whether studies like these will actually provide the agroecological knowledge needed for the development of on-farm practices or if a re-focusing of research agendas may be necessary.

Essential for developing pertinent research agendas would be a comprehensive overview of what ES have already been studied, for which legume species, in which cropping systems, and where. Such an overview would provide a lens through which to sharpen current research efforts to ensure that relevant and timely knowledge is being pursued. While a growing body of scientific literature has documented the ES delivered by legume species in cropping systems, no systematic reviews of the research subjects, i.e., the systems and ES studied, have yet been conducted. Stagnari et al. (2017) and Watson et al. (2017) both provided relevant and general qualitative overviews, but in the form of narrative reviews. Systematic reviews have been conducted for certain legume species (e.g., faba bean (*Vicia faba* L.), Köpke and Nemecek 2010) and for certain ES (e.g., biocontrol of pests, Iverson et al. 2014; and soil microbial activity, Duchene et al. 2017), but neither address multiple ES nor comprehensively inventory legume-inclusion systems to reveal the areas afforded attention by the research community.

In this study, we aimed to systematically identify the current areas of knowledge abundance and scarcity, as related to ES research in European legume-inclusive cropping systems. We addressed this aim by conducting a synthetic review of peer-reviewed scientific literature reporting on ES delivered by the inclusion of legumes in existing European agro-ecosystems. Based on the results, we sought to identify the most consequential knowledge gaps that should inform current and future legume-based research initiatives. Given the present spotlight on legumes in EU research and agricultural policy, we focused the review on studies conducted in Europe (EU28 countries, Norway, and Switzerland). Observing a general rise of ES research in agro-ecosystems around the globe, we expect that the highlighted trends and knowledge gaps will inspire reflection on research agendas even beyond Europe.

2 Review framework

This review was designed to illuminate trends in published, peer-reviewed research on the practices and functioning of legume agro-ecosystems, as we considered this knowledge an important contributor to breaking down barriers to legume adoption in the EU (Fig. 2). We looked specifically at studies in which ES delivery in systems with legumes included was compared to ES delivery in reference systems without legumes. We posit that such comparisons, which indicate the performance of comparable systems with and without

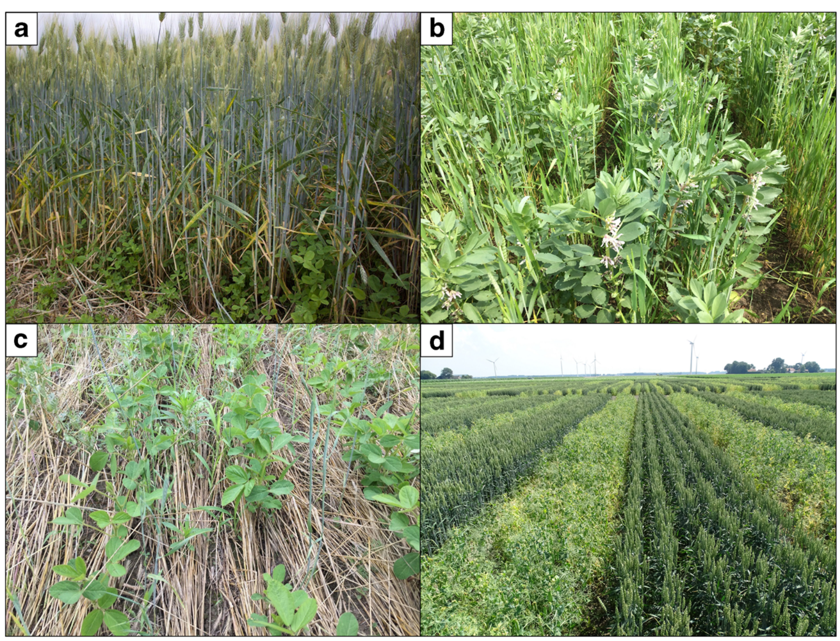

Fig. 1 Some options to include legumes in European arable cropping systems being studied in the Horizon 2020 crop diversification cluster: **a** durum wheat under-sown with clover in the SSSA-IWMPRAISE experiment at CiRAA, Pisa, IT; **b** winter wheat and faba bean mixed cropping in the DiverIMPACTS/LegValue field experiment at Wageningen, NL; **c** soybean sod-seeded on rye dead mulch in the LegValue experiment at CiRAA, Pisa, IT; **d** strip intercropping of pea with wheat in the REMIX experiment at Wageningen, NL. Photos **a** and **c** by Daniele Antichi, photo **b** by Lenora Ditzler, photo **d** by Dirk van Apeldoorn

legumes and show the effects of various options for diversifying current rotations, are highly relevant for farmers enacting incremental changes as part of a transition towards greater sustainability (Hill and MacRae 1996). Our review involved (i) a systematic search for peer-reviewed published articles examining ES delivery in legume-inclusive European cropping systems compared to reference systems without legumes; (ii) extracting meta-data from these articles to create a database and subsequent synthesis of the current research landscape showing what has been studied, where, and for which legume species, crop combinations, and management practices; and (iii) confronting results with those from inventories of farmer needs for including legumes in their farming systems.

We conducted a systematic literature search in Scopus and tracked the results following the Prisma reporting method (Moher et al. 2009). We combined four search term clauses using Boolean operators arranged in the following Scopus-compatible structure: TITLE-ABS-KEY ((general agriculture terms) AND (legume inclusion method terms) AND (ecosystem service terms) AND (legume terms)). A complete list of the search terms included in each clause is provided in the Supplemental Information, SI.1. For the purpose of the search, we defined ES following Duru et al. (2015) as services (agronomic, ecological, economic, or cultural) which contribute to (input services, relevant to the farmer) or are generated by (output services, relevant to society) agricultural production practices. We considered ES to encompass disservices as well as beneficial services (Zhang et al. 2007). Drawing on existing reviews of ES derived from crop diversification practices (e.g., Kremen and Miles 2012), we inserted search terms in the clause “ecosystem service terms” to cover the scope of ES expected to be associated with the inclusion of legumes in European cropping systems (Fig. 2). The search encompassed literature published up to and including December 31, 2019.

The full set of returned documents (>10,000) was first refined in Scopus using the “limit to” feature for subject area (agricultural and biological sciences), document type (article, article in press), country (EU28 plus Norway and Switzerland), and language (English). Manual additions were made to the document database by cross-checking the reference lists of the most recently published reviews and meta-analyses on related topics. Next, documents were screened for inclusion by reviewing titles, keywords, and abstracts using the EndNote software (version X8, Clarivate Analytics, 2018) on the basis of four inclusion criteria: (i) the research was conducted in the EU28 or Norway or Switzerland, (ii) the research involved a field experiment (on-station or on-farm,

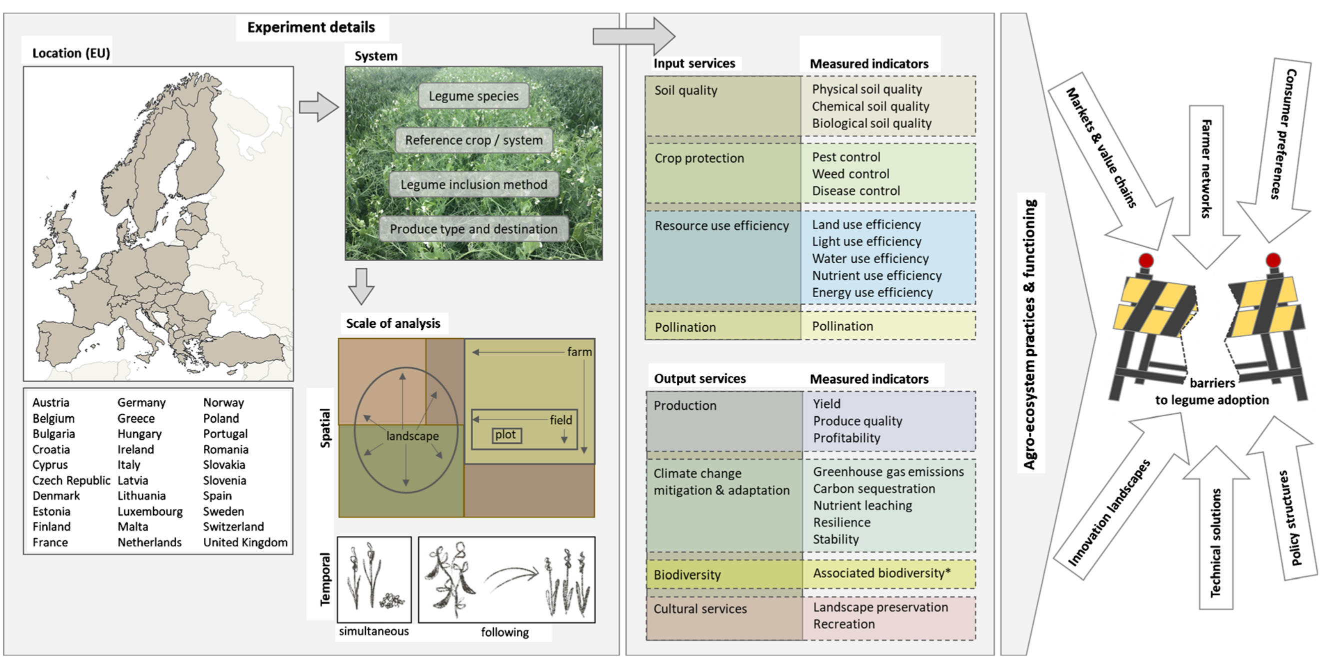

Fig. 2 The subject of the research covered in this literature review comprises knowledge about the practices and functioning of agro-ecosystems including legumes compared to reference agro-ecosystems without legumes (content within the grey boxes). This agroecological knowledge is one factor contributing to a larger body of research topics and knowledge-generation activities needed to break down the barriers inhibiting European farmers from adopting legume crops specifically and diversifying cropping systems generally (white arrows at far right of the diagram, based on the findings of Magrini et al. (2016), Meynard et al. (2018), Mawois et al. (2019), and Morel et al. (2020)). *Associated biodiversity refers to unplanned biodiversity that is an outcome of the system and not implemented by the farmer; we thus consider it here as an output service, although others have classified it as an input service (Duru et al. 2015)

no pot trials), (iii) an ES other than or in addition to yield was measured, and (iv) the research compared a cropping system with legumes included to a reference system without legumes. Modelling studies (including lifecycle assessments), reviews, and meta-analyses were excluded.

Each article deemed eligible for inclusion was read in full, and meta-data were entered into a database. These meta-data, extracted per article, included year of publication, location of study, experimental factors (including crop(s) studied and management practice employed (Table 1)), reference crop or system, produce destination, spatial and temporal scales of analysis, and which ES were measured. If multiple studies (sites or experiments) were reported in a single article, each study was entered into the database separately. During the full reading phase, articles found to not meet the inclusion criteria were dropped from the database. The final database contained 163 articles (Supplemental Information, SI.2) and consisted of 468 discrete entries. Since the appearance of the first single document in 1988, the number of articles in the database steadily increased to a peak of 25 in 2018, and then dropped to 12 in 2019 (the last year reviewed).

We analyzed the meta-data using descriptive statistics (counts, frequencies, and associations between study locations, crop combinations, management practices, and ES measured) to illuminate trends and gaps in the literature. For the analysis, we combined the meta-data categories "management practice" and "produce destination" to create an aggregated classification describing the legume crop functional type: food/feed (for human consumption or fed to animals, representing a general market orientation), forage (grazed in situ), or service (returned to the soil). Food and feed were combined because it was often difficult to discern for whose consumption the legume was being grown (humans or animals), given the experimental setting.

3 Areas of research abundance: reflection of the productivist paradigm?

Our review revealed that much of the published literature on ES from legumes introduced in EU cropping systems is concentrated around combinations of a relatively small number of legume species, management practices, and measured ES (Fig. 3). A large cluster of studies (70% of the total) is centered on four main legume species (pea (*Pisum sativum* L.), clovers (*Trifolium* spp.), faba bean (including broad bean and pigeon bean, *Vicia faba* L.), and common vetch (*Vicia sativa* L.)) and their delivery of production-related services primarily in cereal-based mixed and row intercrop systems, with experiments located in five main countries (France, Denmark, the United Kingdom, Switzerland, and Italy; data not shown). Several grain legume species potentially important for sustainable human diets (lentil (*Lens culinaris* Medik.), chickpea (*Cicer arietinum* L.), lupin (*Lupinus* spp.), and soybean (*Glycine max* (L.) Merr.)) are notably not as well represented; together these comprise just over 7% of all studies in the database. We found only one study that used strip intercropping, suggesting that despite being a once-popular way to incorporate legumes into cropping systems in the USA (Francis et al. 1986), it apparently never gained popularity in the EU. The most commonly studied production-related services include productivity measures (yield, produce quality, land use efficiency), as well as ES linked to the N-fixation capacity of legumes (chemical soil quality and nutrient use efficiency), and weed suppression.

These findings suggest that there is only a limited formal scientific basis for understanding the effect of legumes on ES delivery across the variety of locations, crops, and management practices possible in the EU. While more knowledge likely exists in other realms (e.g., grey literature, advisory service pamphlets, local-language reporting), the lack of

Table 1 Management practices (i.e., methods through which legumes are included in cropping systems) as classified for the literature database and their definitions

Method	Definition
Cover crop	A crop grown between seasons to provide soil cover and/or catch nutrients
Green manure	A crop grown between or during cash crop seasons, the residues of which are incorporated into the soil with the purpose of improving soil quality
Mixed cropping	Sowing multiple species or cultivars in the same field at the same time, as a broadcast mixture with a given seeding ratio but random spatial arrangement
Rotation	Growing different crop species in the same field over the course of seasons or years in a deliberate sequence*
Row intercrop	Sowing two (or more) crop species in the same field at the same time in alternate rows
Strip intercrop	Sowing two (or more) crop species in the same field at the same time in multi-row strips wide enough to allow independent cultivation
Relay cropping	Intercropping of two crop species in which the second species is under-sown in the first at a later point in the growing season

*Rotation here includes "multiple cropping" (multiple crops grown in the same field one after another in the same season)

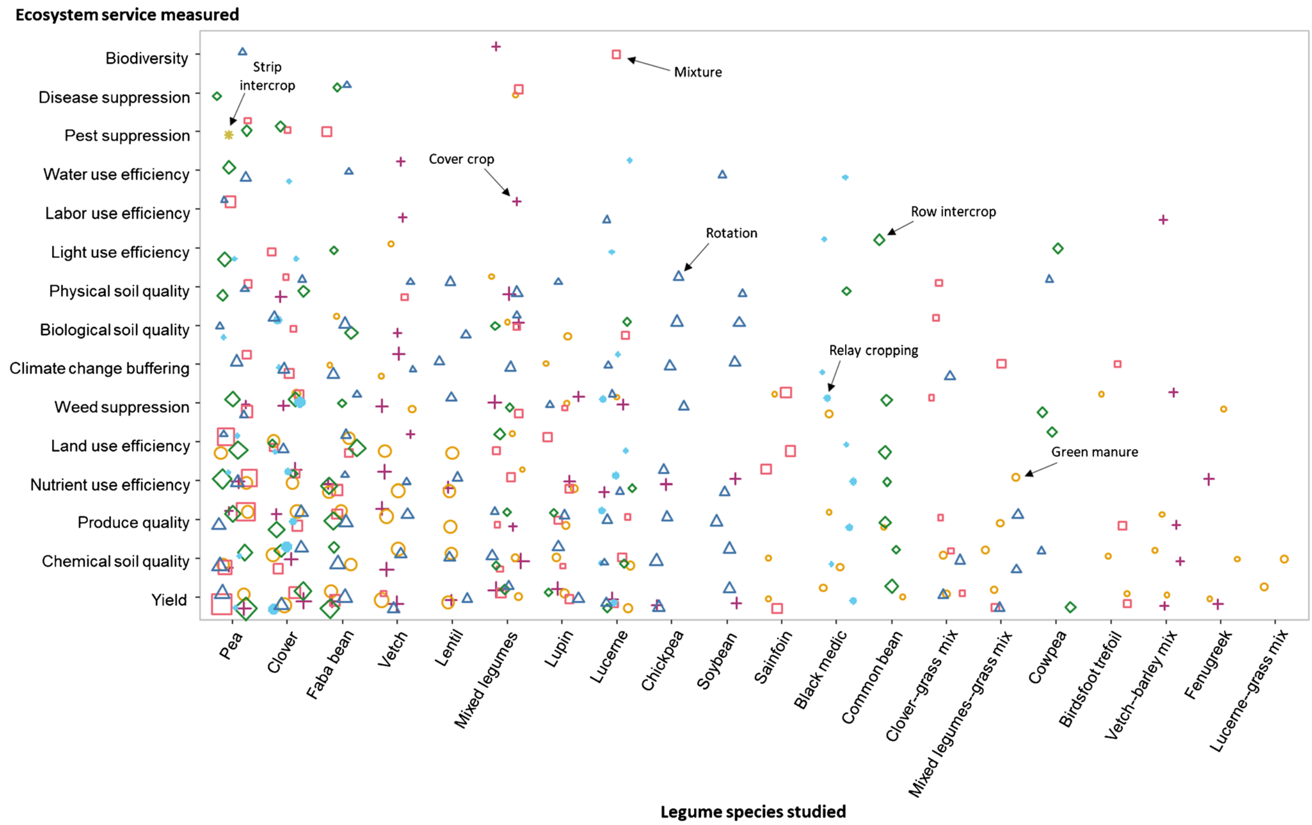

Fig. 3 Matrix showing the number of synthesized peer-reviewed studies reporting on ecosystem services (*y* axis) delivered in cropping systems with different legume species included (*x* axis) compared to reference systems without legumes. Symbols and colors correspond to the legume inclusion method employed in the study. The larger the symbol, the more studies on that species–service combination; the largest symbol in the plot (*x* = pea, *y* = yield, inclusion method = mixture) denotes 60 studies, and the smallest symbol (*x* = pea, *y* = pest suppression, inclusion method = strip intercrop) denotes one study. Legume species and ecosystem services are ordered according to the frequency with which they appear in the literature review database

peer-reviewed literature imposes an inherent limitation on efforts to support expansion of legume-inclusive cropping systems in Europe for policy makers and advisors relying on peer-reviewed scientific analyses. The focus we observe in the literature on production-related ES is logical: yield and produce quality have the most direct impacts on farmers' ability to market and make immediate revenue from the inclusion of legumes in cropping systems, so production-related ES gain high priority on research agendas aiming to provide support for farmers in adopting legume crops. This focus, however, is also likely reflective of the dominant productivist paradigm, which prioritizes market demands and thereby directs research to support such demands (Magrini et al. 2016; Zander et al. 2016), while deemphasizing other less-easily monetized benefits of legumes for farmers and society.

The influence of the productivist paradigm is further reflected in the fact that cereals are the companion or following reference crop against which the addition of legumes was studied in 69% of the total database entries. These studies are relatively equally distributed between those incorporating legumes as a service crop (often for facilitating a cash crop) and as a marketable food or feed crop. Studies using legumes as a service crop are dominated by those incorporating legumes as green manures or cover crops in a rotation with cereals, while those using legumes as a food or feed crop predominantly refer to systems where legumes and cereals were combined in rotations or intercropped by row or as mixtures (Fig. 4).

Within the legume–cereal studies subset, three combinations make up 25% of the total: pea–barley (*Hordeum vulgare* L.), pea–wheat (*Triticum* spp.), and clover–wheat. Within these three groups, there appears to be specialization based on experiment location. Studies on pea–barley combinations are most frequent in Denmark, while pea–wheat and clover–wheat studies are more common in France (Fig. 5). Again, these studies focus primarily on production-related ES. Although many fewer legume–cereal studies report on the remaining range of ES, each ES is covered by at least one study in the reviewed database, with the exception of biodiversity for which there are no studies in this subset of the literature. For pea–wheat, we saw that the two crops were integrated into experimental systems most often as mixtures, and that yield, resource use efficiency (nutrients, land, and labor), produce quality, and chemical soil quality were the most commonly studied ES. Pea–barley was more often

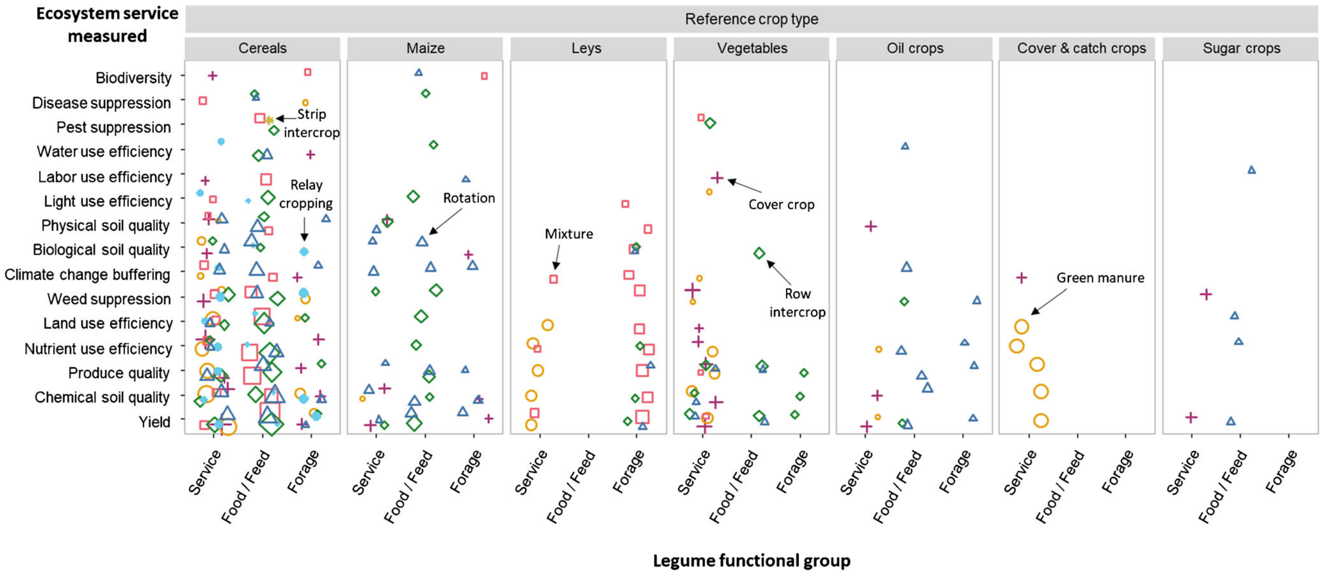

Fig. 4 Matrix of associations studied in the reviewed literature between legume crop functional groups (service (returned to the soil), food/feed (for human consumption or fed to animals), forage (grazed in situ), *x* axis), and ecosystem services (*y* axis) delivered when introduced to systems with non-legume companion or following reference crop types. Symbols and colors correspond to the legume inclusion method employed in the study. The larger the symbol, the more studies on that combination; the largest symbol in the plot (group = cereals, *x* = food, *y* = yield, inclusion method = mixture) denotes 60 studies, and the smallest symbol (group = cereals, *x* = food, *y* = pest suppression, inclusion method = strip intercrop) denotes one study. Ecosystem services and reference crop type are ordered according to the frequency with which they appear in the literature review database

studied in row intercropped systems. Differing from pea–wheat, additional ES reported on for pea–barley include water and light use efficiency. Clover was commonly incorporated into wheat systems through temporal diversification, either as an under-sown relay crop (to establish a winter cover crop or a forage crop) or as a service crop in a wheat-based rotation.

The concentration of research around production-related services in wheat- and pea-based cropping systems signals not

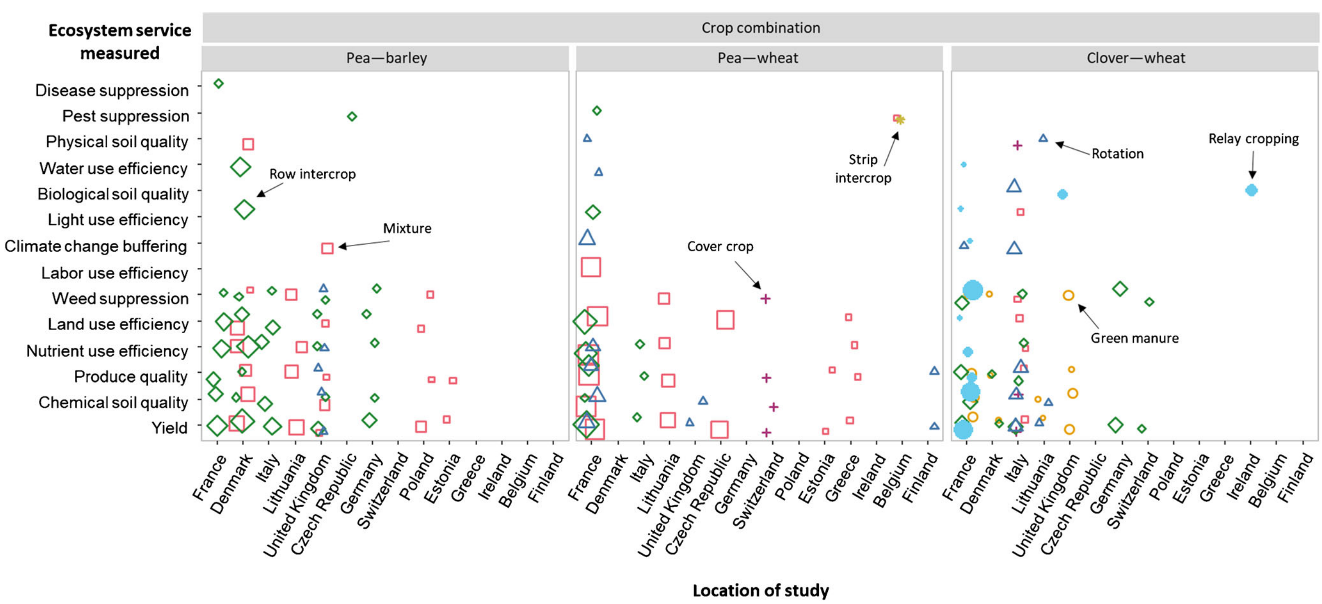

Fig. 5 Frequency of studies measuring ecosystem services in the three most commonly researched legume–non-legume reference crop combinations (pea–barley, pea–wheat, and clover–wheat) in different locations in the EU, as reported in the reviewed literature. Symbols and colors correspond to the legume inclusion method employed in the study. The larger the symbol, the more studies on that combination; the largest symbol in the plot (crop combination = pea–wheat, *x* = France, *y* = yield, inclusion method = mixture) denotes 12 studies, and the smallest symbol (crop combination = pea–wheat, *x* = Belgium, *y* = pest suppression, inclusion method = strip intercrop) denotes one study. Location of study and ecosystem services are ordered according to the frequency with which they appear in the literature review database

only a well-known agronomic synergy (Jensen et al. 2020), but is also likely reflective of a long history of co-evolution towards specialization at all levels of the agri-food chain. Magrini et al. (2016) presented a comprehensive analysis of how this co-evolution occurred and led to what they call the "marginalization" of legume crops in France specifically and in the EU more generally. They described how current economic structures, built upon choices made decades prior, re-enforce lock-ins by rewarding the adoption of major crops (in Europe, cereals), rather than minor crops (like legumes). In their analysis of grain legumes in France, Magrini et al. (2016) found these initial choices to be rooted in historical European-wide preferences for fertilized cereals and imported soybean, which led to increasing returns to adoption of these practices, reinforcing the initial choices and hammering in the socio-technical lock-in. Examples from outside Europe may provide useful insights into how historical trends can alternatively be redirected towards including legume crops, e.g., through breeding, state policy, and farmers' networks, as in Brazil (de Sowa and Busch 1998; Cattelan and Amélio 2018).

Currently, the drive to produce wheat in Europe is powered largely by dietary preferences and industrialized processing, which demand highly standardized bread-quality grains that depend on heavy N fertilization. Meanwhile, the economic competitiveness of soybean meal, coming into Europe through international trade as the dominant source of protein-rich animal feed supporting the demand for meat (Kezeya Sepngang et al. 2020), stimulates research institutes to focus on locally-adapted and cost-effective feed-protein replacements, of which grain pea is one. Societal demand in the EU further fuels the desire to find local and non-genetically modified alternatives to internationally produced soybean, with grain pea again appearing as a viable alternative (faba bean is gaining some attention in this regard as well (cf. Jensen et al. 2010)). Our review results suggest that together, these drivers make plausible a heavy focus on wheat (and in colder climates, barley) and pea intercropping systems where the value of the legume is in its dual ability to reduce the need for artificial N fertilizer supplied to the cereal and to provide a high quality and locally produced animal feed source. This kind of positive mutual reinforcement between market demand and research demand further reinforces a production, research, and market climate that is unaccommodating to novel, less productive, and diversified crops (Meynard et al. 2018).

4 Under-studied services: does research targeting address farmers' interests?

The large gaps in the legume–ES matrix (top right area of Fig. 3) highlight the services that have so far been infrequently studied in cropping systems with legumes compared to systems without. For ES with less direct relevance to marketability and profit (e.g., climate change buffering, water use efficiency), there are fewer studies in the database (45 and 13 studies, or 9.6% and 2.8% of the total, respectively), and those present are focused primarily on legumes included in cereal-based systems. We found only four studies which directly measured associated biodiversity as an effect of legume presence, representing less than 1% of total database entries. Very few studies addressed pest and disease suppression (11 and 6 studies, or 2.4% and 1.2% of the total, respectively), and among these we found contrasting reports, with both positive and negative effects of legumes on ES delivery described. In such cases, it might be that there are strong drivers of variability, for instance seeding ratios (e.g., Schoeny et al. 2010), intercropping methods (e.g., Lopes et al. 2015), or residue management techniques (e.g., Abou Chehade et al. 2019), which affect the service delivery for better or worse. The scarcity of published research exploring these interactions suggests that research has not sufficiently addressed ES with high potential for variability in delivery by legumes, and that further research is needed that connects variability in ES delivery to environment- and management-related variables (Stagnari et al. 2017). It may also be that studies on some topics, for example disease, are designed to make comparisons between legume species or cultivars rather than between systems with legumes and those without. In these cases, the structure of our review may not have allowed capturing the full range of current scientific knowledge.

Drawing on previous studies, there is evidence that farmers seeking support for the adoption of new methods may have interests that are not well reflected by the research foci dominant at institutional levels. In the LegValue project, one of those in the Horizon 2020 crop diversification cluster, a survey exploring legume adoption among European farmers (Pelzer et al. 2019) showed that in addition to the more widely assumed need for support in the development of market and value chains, the ES on which farmers indicated they needed more information in order to more successfully incorporate legumes into their cropping systems were closely aligned with the apparent knowledge gaps we found in the literature. Pelzer et al. (2019) found that among farmers' top interests was to have better support on crop management topics; in particular, farmers wanted information on pest, disease, and weed control in legume-inclusive systems. These findings reflect those of Mawois et al. (2019) who did a similar study in France and showed that this kind of crop management knowledge was pivotal in the success of farmers who had made a stable transition towards legume-inclusive systems. In their broader study on crop diversification, Morel et al. (2020) also found that evidence of farm-level sustainability benefits was a key factor in whether or not conventional farmers would try adding new crops to their rotations.

Despite farmers' apparent interests, our review suggests that institutional research specialization remains closely linked to production specialization and market demand. Historical cropping specialization away from legumes, as discussed in the previous section, appears to have led to a concurrent knowledge drain away from legume crops, translating into learning that enables higher yields of major crops (mostly cereals) rather than learning that facilitates the adoption of new crops previously considered minor and of low interest for economic actors and scientists. A clear example exists in France, where funding for research and development of major crops comes in part from a tax paid on the sale of these same crops, whereas lesser-grown but potentially interesting crops do not receive such funds (Magrini et al. 2016). Such a feedback mechanism leads to a reinforcement of selective knowledge development through the so-called learning economies (Callon and Bowker 1994) where rewards for scientific knowledge development are greater in domains populated by many scientists who can understand, refer to, and disseminate the new knowledge contributed (Pimbert 2017). In other words, specialization on the farm and in the market stimulates knowledge specialization among researchers (and vice versa), widening the learning differential between the already-dominant knowledge arenas and potential alternative practices (Vanloqueren and Baret 2009), in spite of farmers' expressed interests.

5 Small-scale and short-term: evidence of resource constraints?

Farmers in the LegValue survey also cited economic and cultural ES in their expectations of what legumes could provide (Pelzer et al. 2019), few of which are documented in this literature review. Services for which the benefit may be delayed (e.g., economic benefit of residual N provision to post-legume crops beyond a single season (Pelzer et al. 2012)), and for which the underlying processes operate at the farm or landscape scale (e.g., supporting beneficial insect populations with large ranges of movement (Schellhorn et al. 2014)), are generally not well represented in the literature returned by our search. Of the studies we entered in the database, 92% focused on measurements taken and analyzed at the plot level, and 75% measured the legume effect within the same season. Half of these also measured effects in the immediately following season, but it was not well indicated whether measurements were continued beyond the first season after legume inclusion.

The focus we saw on short-term plot-level experiments could be because studying processes that operate at wider spatial and temporal scales does not fit current research organization and resourcing. It may also be that these topics are studied in experimental designs that do not fit within the scope of our review. For example, Rundlöf et al. (2014) provide a valuable analysis of the role of late-flowering clover fields in habitat and resource provisioning for bumble bees which shows the importance of legumes for supporting pollinators at the landscape scale. The design of their study, however, did not meet our inclusion criteria so it was not considered in our analysis. Another consequence of the focus of our review on empirical field trials at cropping system level was the exclusion of the wide body of literature utilizing models. Models are often used to address questions of scale (especially temporal). However, Costa et al. (2020) also observed a focus on shorter-term effects in their review of life cycle assessments of legume-inclusive cropping systems, in line with our results for field trials.

In a field trial setting, large areas are needed for unravelling spatially explicit processes, and long-term studies are needed for examining temporally influenced (e.g., N-fixation, phosphorus mobilization, or weed, pest, and disease control) or building (e.g., soil organic matter increase or decrease, soil microbial and macro-fauna diversity, weed diversity, physical soil quality) services. Such spatial and temporal requirements go beyond current conventions on what constitutes an agronomic field trial as supported by short-duration research funding schemes, reinforcing gaps in this knowledge. Furthermore, research that takes multiple years to conduct has a lower turnover rate from inception to publication (Vanloqueren and Baret 2009). While these constraints are understandable, the strength of farmers' interests, as illustrated by both Mawois et al. (2019) and Pelzer et al. (2019), should provide motivation to overcome these challenges and direct new research toward understanding the effects of legume-inclusive cropping systems on ES provision at longer temporal and broader spatial scales. Morel et al. (2020) specifically call out a need for farm-level research on longer rotations and systemic long-term assessment of crop diversification benefits, while Voisin et al. (2014) argue for an even wider approach that includes processing and consumption. Recent studies which take a systems-level co-design approach to innovation in legume-inclusive systems (such as Reckling et al. 2020) provide good examples for how to do this and can complement reports looking at production and consumption dynamics (e.g., Kezeya Sepngang et al. 2020).

6 Ways forward for ecosystem service research in legume-inclusive systems

In agricultural research systems, multiple determinants can be identified which together shape and direct the technological regime, dictating the choice of which technologies are studied and developed, thus structuring the development of technological (and knowledge production) trajectories (Vanloqueren and Baret 2009). From the signals highlighted in this review (e.g., an abundance of research on production-related ES in pea–cereal systems), we infer that the narrow focus of legume research on particular ES in the EU is likely the result of multiple factors acting together at all levels of the science and technology landscape. A key factor may be the market-driven dominance of few legume species and management systems, which directs researchers to narrow in on production-related ES of particularly these species; investigating this possible causal relation would enhance existing insights on barriers to legume adoption in Europe. The area of land devoted to legume production in the EU overall is already small, and within this area, a relatively large portion is dedicated to the few crops we identified as being most studied (Kezeya Sepngang et al. 2020). These are also the legumes with the greatest market demands (with the exception of soybean, which is growing in area and market demand but for which there was less ES research (Kezeya Sepngang et al. 2020)), with pockets of variation in regional specialization that likely correspond with local market opportunities.

Knowledge on ES delivery is one piece of the larger puzzle of how to break down barriers to legume adoption and crop diversification in general in the EU. Our discussion here has shown the importance of reflecting on the role research on ES plays within that puzzle, particularly in regard to supporting farmers' knowledge needs. Beyond the farm level, it appears that the limited and productivist-oriented research that historically predominates the literature does not fully support the sustainability directions aspired to by the European Commission. Low-input, diversified, and biodiversity-based initiatives such as those included in the EU Green Deal could be better underpinned by agroecological systems research that examines a wider spectrum of ES delivery mechanisms, contexts, and systems, within a framework that incorporates other social and market concerns. This review reveals a need for projects that will follow the Horizon 2020 crop diversification cluster to take stock of current research and critically reflect on the potential lock-ins and their causes that may be influencing research agendas. It may be that reformulating research priorities is necessary in order to fill the most consequential knowledge gaps.

This study does not account for the likelihood of publication biases, nor does it quantify the effect of incorporating legumes on the delivery of the studied ES. Instead, the usefulness of this study lies in its potential to catalyze critical reflection, and to lead to general recommendations for how to add breadth to current and future research portfolios. Added breadth could be achieved by putting emphasis on minor and underutilized legume species for human consumption (e.g., chickpea, lentil) which may soon see a rise in consumer demand (Vasconcelos et al. 2020), and by exploring ES delivery in more diverse spatial and temporal arrangements that stimulate agrobiodiversity at both fine and course resolutions. Increasing the breadth of current agroecological research targets would add value to other efforts contributing to breaking down adoption barriers. To that end, a recommended next step would be to quantitatively review the ES effects of introducing legumes to current cropping systems, particularly for those ES with direct agroecological interest to farmers, although this may be challenging given the lack of research on certain ES. Furthermore, it would be useful to simultaneously examine the sources of variability in the delivery of those ES, so that cropping systems can be adapted to local preferences, practices, climates, and soils. Together, this information would support farmers in fitting legumes into existing systems, allowing legume inclusion to act as the stepping stone towards greater European crop diversification that proponents expect it to be.

7 Conclusion

With this review, we sought to systematically inventory the published research on ES delivery from legumes when introduced in current European cropping systems, and to subsequently identify areas of knowledge abundance and scarcity with potential relevance for un-locking barriers to legume adoption. Our findings suggest a need to extend and diversify research on ES from legumes to include multi-criteria and multi-scale approaches to ES not yet well explored, rather than reinforcing knowledge on known ES, crop combinations, and management systems which reflect a narrow market-driven paradigm. It is important to be critically reflective of the status quo of research trajectories, not only in Europe but also globally, because they can act as a selection device limiting future science and technology development. When it comes to socio-technical lock-ins in agriculture, such as the narrow focus we observed on few studied legume species, market uses, and ES delivered, choices made decades ago apparently still have effects that are self-reinforcing, leading to the co-evolution of specialized farms, narrowly focused research and knowledge-support agendas, and few dominant industry and market chains. The apparent misalignment between what farmers want to know and what is present in the peer-reviewed literature provides compelling stimulus to redirect research agendas and foster multi-actor engagement towards work that directly supports farmers in developing diverse, productive, and sustainable legume-inclusive cropping systems, particularly in countries currently underutilizing legumes. As long as research remains narrowly targeted, farmers and advisors will remain under-supported in efforts to fully exploit the potential benefits of crop diversity. Connecting research needs with the topics farmers are interested in, and using this information to direct research agendas, is imperative for keeping research timely and relevant, and for supporting the sustainability ambitions of the European Commission.

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