Fostering sustainable legume-based farming systems and agri-feed and food chains in the EU

Deliverable D1.1

Agroecosystem services provided by legume-based systems

Planned delivery date: M18

Actual submission date: M22

Start date of the project: June 1st, 2017 **Duration:** 48 months

Workpackage: WP1

Workpackage leader: INRA **Deliverable leader:** WU

Partners contributing to the deliverable: INRA, WU, SSSA, UNIPI

Version: V1

Dissemination Level	
Public	
Classified, as referred to Commission Decision 2001/844/EC	
Confidential, only for members of the consortium (including the Commission Services)	x

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°727672

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Summary

In this report (Deliverable D1.1), we present findings from a systematic literature review on the ecosystem services delivered by legume crops and legume-based cropping systems in the EU. The objectives of this review were to 1) describe the (agro)ecosystem services (ES) delivered by legume crops and legume-based cropping systems in the European context, and 2) to identify and characterize drivers of variability in the delivery of these ES. Findings of this review will support the WP1 on-farm and on-station research to quantify ES from legumes by providing a backdrop of what is already known, and by identifying what knowledge gaps still exist so that field measurements (and collaborations with other WPs) can be even more effectively directed.

Systematically reviewing the literature following the Prisma method resulted in a literature database containing 132 documents reporting on ES delivered by legume crops and legume-based cropping systems in the EU. Analysis of this database revealed that much of the literature is concentrated around a relatively small combination of possible ES, crops, management practices, and experiment locations. Papers on production-related services were the most prevalent in the reviewed database, and these primarily reported on cereal—grain legume intercrop systems, with experiments located in five main countries (France, Denmark, United Kingdom, Switzerland, and Italy). These combinations are also well represented in the LegValue WP1 network. Furthermore, it was found that the services for which there is an apparent knowledge gap in the literature (namely pest, weed, and disease suppression) mirror the services that farmers indicated they need information on in order to more successfully incorporate legumes into their cropping systems. A preliminary analysis of sources of variability in ES delivery showed that climate/environment, legume species and cultivar, and nitrogen fertilization (source, timing, and quantity) were all key drivers. Better understanding of sources of variability in ES delivery from legumes can be obtained through a more rigorous qualitative analysis of the literature database or a quantitative meta-analysis.

Overall, the results of this review point to two urgent needs in the context of the LegValue project: 1) to connect the knowledge gaps highlighted by this review with the topics farmers are interested in, and then use this information to direct the activities of WP1; and 2) the importance of fostering intra- and cross-WP linkages in revealing synergies that can augment the success of each WP and LegValue as a whole.

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1. Introduction

LegValue aims to support the development of sustainable, legume-based farming systems and agri-feed and food chains in the EU through a multifaceted approach including identifying agroecosystem services delivered by legumes in the cropping system, highlighting opportunities and constraints to legume adoption at the farm and value chain levels, multi-actor co-design platforms, and market and policy development. Work Package 1 (WP1) supports the LegValue objectives by describing and quantifying the delivery of agroecosystem services from legumes through a triangulation of literature review, crop-model simulations, and empirical data collected on-farm. Collecting, synthesizing, and describing the scope of scientific literature already available on the subject of ecosystem service (ES) delivery from legumes can both augment understanding of the role of legumes in sustainable farm management and direct future research on ES delivery to fill gaps in the current reported knowledge.

A growing body of scientific literature has documented the ES delivered by legume crops and legume-based cropping systems. However, to date, a comprehensive and systematic review of the literature on this subject is lacking. Watson et al. (2017) provide a relevant and general overview of the ES provided by legumes, but do not review the literature systematically. Systematic reviews have been conducted for certain legume species (e.g. faba, 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 not for multiple ES nor legume-based systems as a whole. Additionally, a systematic identification and assessment of the factors driving variability in the delivery of ES from legumes is missing from the literature.

Here, we systematically review the literature to address two primary research questions:

- *What are the ecosystem services provided by legume crops and legume-based systems?*
- *What are the drivers of variability in ecosystem service delivery by legume crops and legume-based systems?*

With this review, we build an understanding of what the available literature landscape looks like. In doing so, we identify areas that should be focused on further, for instance via the LegValue on-farm research network measuring ES in WP1.

2. Materials and methods

2.1. Literature search

We conducted a literature search on 21 August 2018 using the Scopus database and following the Prisma method for systematic literature review (Moher et al., 2009). All terms used in the search are listed in the Supplementary Information, SI.1. The set of returned documents was first refined in Scopus using the “limit to” feature for subject area (agricultural and biological sciences), document type (article, review, article in press), country (EU countries), and language (English). Manual additions were made to the document database by cross-checking the reference lists of “benchmark” papers, i.e. the most recently published reviews and meta-analyses on related topics. Next, documents were screened for inclusion on the basis of record title, abstract, and keywords using the following criteria: i) the research was conducted in the EU, and ii) the research involved one (or more) of the nine legume species grown in the

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LegValue network (see SI.1 for the species list). In the next screening phase, full-text documents were assessed for inclusion following the additional criteria that iii) the research involved a field experiment (on-station or on-farm, no pot trials), iv) an ecosystem service, other than or in addition to yield, was measured, and v) a non-legume reference system was used as a control. Criteria iii, iv, and v were assessed at the full reading stage because this information was sometimes difficult to obtain from the title, abstract, and keywords alone. Literature sorting and screening were done using EndNote software (version X8, Clarivate Analytics, 2018).

2.2. Data collection and synthesis

Each paper deemed eligible for inclusion in the review was read in full, and basic meta-data was entered into a common database. These data included year of publication, location(s) of study, soil type, experimental factors (including crop(s) studied and management practice(s) employed, scale of analysis, and which ES were measured). The categories used to structure the database (with definitions for how categories were delimited or defined) are reported in the Supplementary Information, SI.2. Meta-data were then cleaned and analyzed to build an overview of the currently available literature. Exploration of the database was conducted using R (version 3.4.3, R Core Team, 2017). Additionally, a subset of papers was screened manually a final time to develop a finer-resolution understanding of which services specifically (within ES macro-categories), and the accompanying drivers of variability, were reported in the literature. This subset was generated by randomly selecting, for each ES, three to five papers (if available) from the database which were marked as having reported on the service.

3. Results

3.1. Overview of literature database

The literature search and screening resulted in 132 eligible documents reporting on ecosystem services delivered by legume crops and legume-based cropping systems in the EU. The Prisma flow-chart of the total documents returned, screened, assessed for eligibility, and included in this review is reported in the Supplementary Information, SI.3. There is a clear trend in the scientific literature of increasing reporting on ES from legumes, demonstrated by the rising number of articles published since the first document in the database appeared in 1988 (Figure 1). Based on the total number of database entries per country, it is evident that France is leading the study of ES from legumes in cropping systems (Figure 1).

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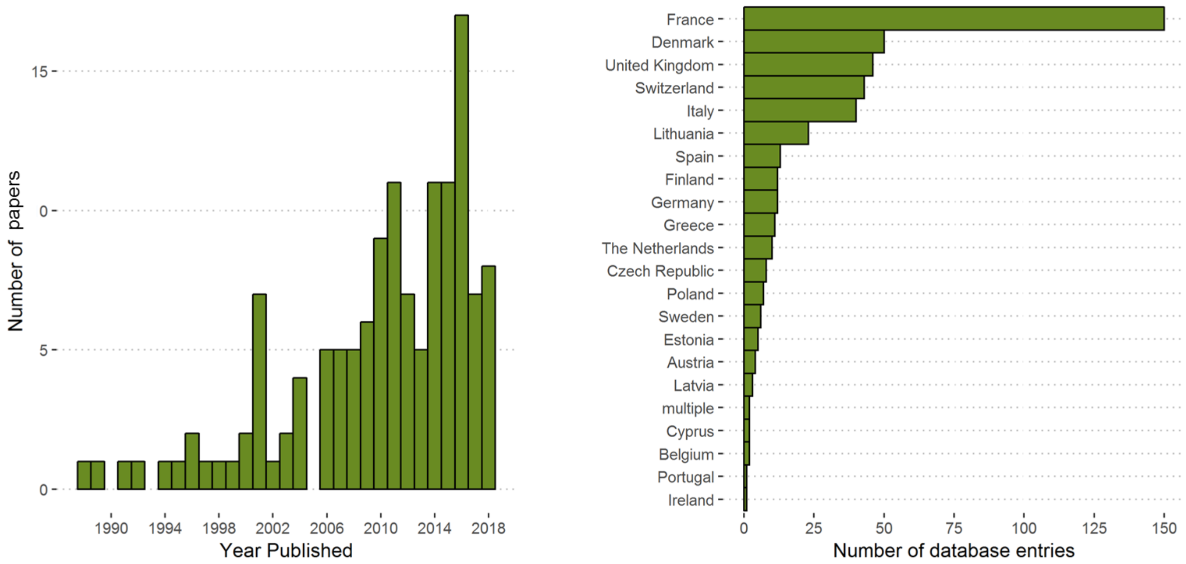

Figure 1. Number of papers included in the review by year published (***left***) and number of individual experiments entered into the literature database by country (***right***).

Based on a simple y/n (the service was measured (y) or not (n)) count of which ES macro-categories were reported on in the literature, we found that the most commonly reported-on services were those that are production-related (yield, produce quality, and land use efficiency) and linked to the nitrogen (N) fixation capacity of legumes (chemical soil quality and nutrient use efficiency) (Figure 2). Weed suppression was the sixth most reported ES. All other ES in the database were reported infrequently, with disease suppression having the lowest number of reports. It is particularly interesting to note that ES likely functioning at the farm and/or landscape scale (e.g. pollination) are not represented in the literature. This is probably linked to the fact that 92% of studies entered in the database reported on measurements taken and analyzed at the plot level. The most commonly experimented methods of incorporating legumes into cropping systems were green manuring and intercropping in mixtures and rows (Figure 2). The least studied management system was strip intercropping, for which there was only one entry in the database.

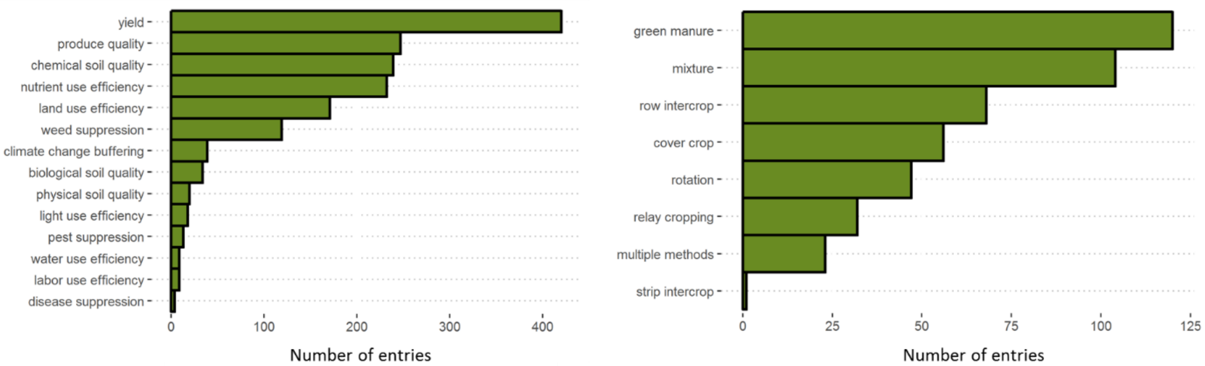

Figure 2. Tally of ecosystem services measured (***left***) and management practices experimented with (***right***) by total number of entries in the literature database.

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The legume species appearing in the literature database are shown in Figure 3. Here it is evident that pea (*Pisum sativum*) is the most commonly studied of the LegValue crops as related to ES, followed by clovers (*Trifolium* spp), faba bean (*Vicia faba*), and common vetch (*Vicia sativa*). Other grain legumes important to the LegValue network (lentil (*Lens culinaris*), chickpea (*Cicer arientinum*) and soy bean (*Glycine max*)) are not as well studied in relation to ES delivery. Of all the combinations of legumes with non-legume companion crops, cereals are the companion for 74% of the database entries, with six combinations making up 37% of the total entries, and these are dominated by grain legume–cereal combinations (Figure 3).

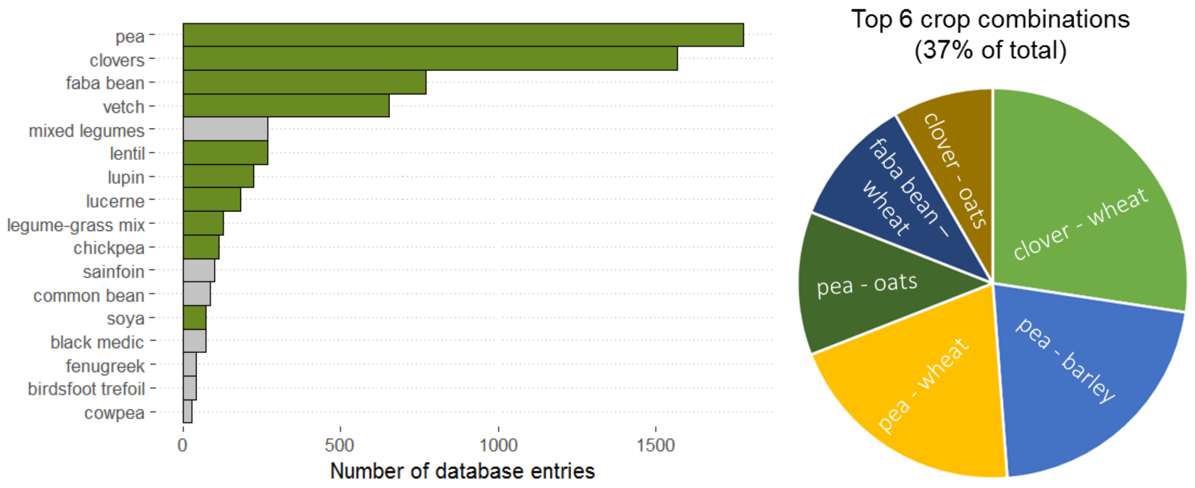

Figure 3. Legume species represented in the literature database (***left***, bars in green are the main legume species grown in the LegValue on-farm network), and the six most commonly studied legume—non-legume crop combinations present in the literature database (***right***).

Trends are also evident as to which countries specialize in studying certain legume crops (Figure 4). Among the top five countries reporting on ES from legumes, the majority of studies follow the aforementioned trend illustrated in Figure 3, reporting on pea, clovers, faba bean, and vetch. Switzerland and the UK appear to have the most diverse portfolios among the top five countries, both reporting on twelve different legume species.

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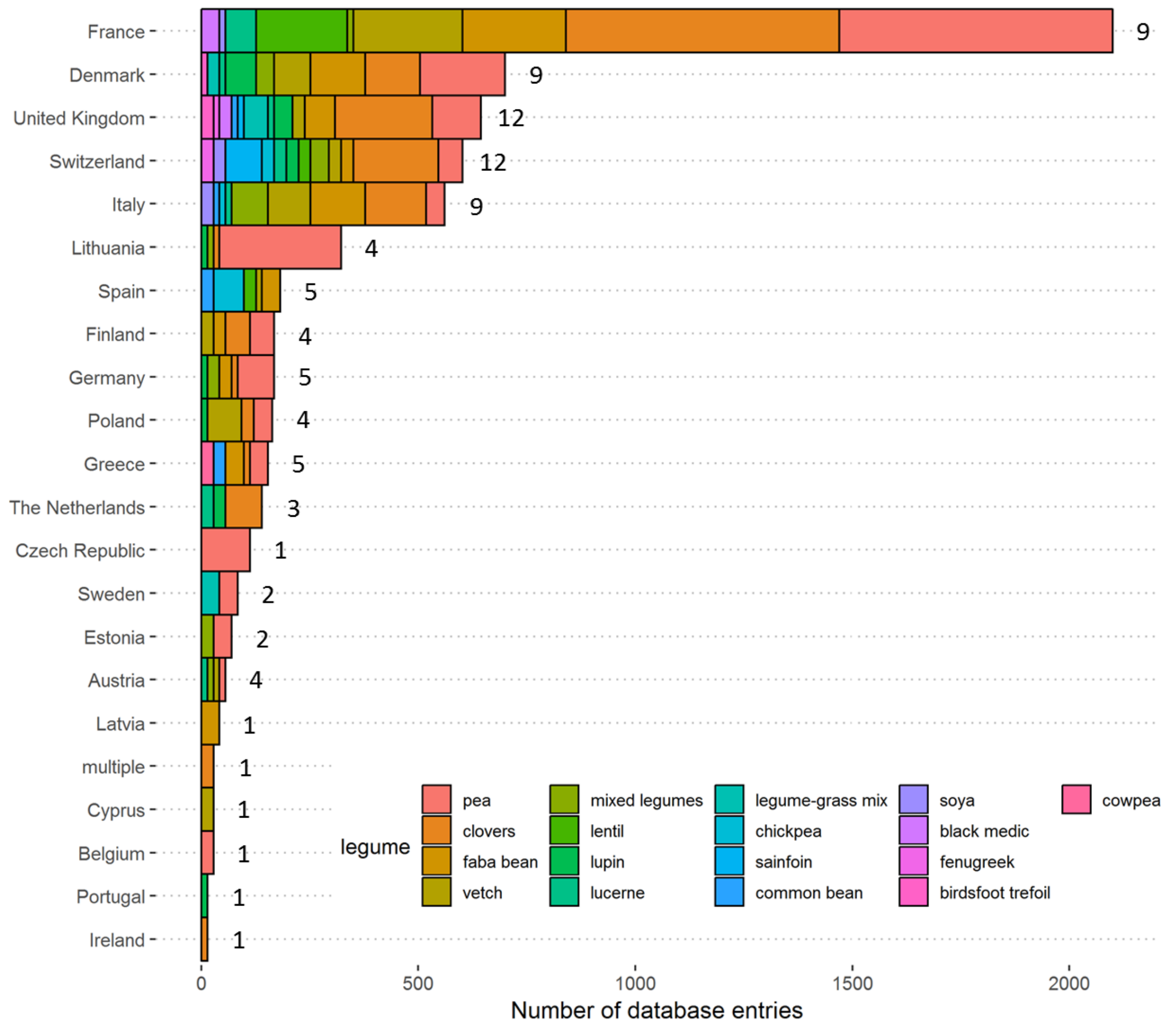

Figure 4. Legume crops studied in each country by number of entries in the database. Numbers to the right of the bars give the total number of species studied per country.

A complete overview of associations between legume species and ES studied is shown in Figure 5. For easy reference, the papers reporting on each combination of legume species and ES is reported in Table 1. Reference numbers cited in the table correspond to the list of articles in the Supplementary Information, section SI.4. In both Figure 5 and Table 1 it is again evident that certain combinations of legumes and ES are much more frequently reported on in the literature than others, highlighting knowledge gaps. In general, there is substantial reporting on production and nutrient related ES, especially for pea and clover.

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Table 1. Records reporting on each ecosystem service and legume species combination for the main legume species in the LegValue on-farm network. See SI.4 for the article affiliated with each reference number.

		pea	clover	faba	vetch	lentil	lupin	lucerne	mixed pasture	chickpea	soya
production	yield	4, 6, 8, 9, 10, 11, 12, 16, 26, 26, 27, 34, 39, 40, 42, 44, 45, 46, 47, 48, 50, 56, 57, 58, 62, 63, 64, 65, 66, 69, 73, 82, 85, 86, 91, 92, 93, 96, 97, 98, 99, 100, 117, 124, 127	2, 3, 14, 15, 16, 17, 18, 32, 33, 37, 42, 60, 64, 77, 80, 81, 91, 99, 101, 118, 119, 120, 121, 122, 124, 126, 128, 129, 130, 132	7, 8, 14, 16, 35, 36, 39, 42, 43, 50, 51, 60, 61, 65, 70, 71, 72, 79, 82, 83, 123, 124, 125	16, 18, 19, 20, 25, 29, 38, 41, 84, 89, 96, 97, 99, 102, 119, 124, 132	5, 16, 124	16, 33, 44, 50, 65, 67, 82, 100, 119, 125, 132	2, 3, 16, 21, 32, 67, 95, 119	22, 131, 132	5, 14, 16, 83	14, 16, 96, 97
	produce quality	8, 10, 34, 39, 40, 42, 44, 46, 58, 62, 65, 66, 69, 73, 86, 91, 92, 93, 96, 97, 99, 100, 117, 124	2, 3, 14, 17, 18, 32, 42, 77, 80, 91, 99, 118, 120, 121, 122, 124, 126, 128, 129, 132	8, 14, 35, 36, 39, 42, 61, 65, 70, 71, 72, 75, 76, 79, 123, 124, 125	18, 29, 84, 89, 96, 97, 99, 124, 132	124	44, 65, 100, 125, 132	2, 3, 21, 32	131, 132	14, 75, 76	14, 96, 97
soil quality	physical soil quality		33, 81		38, 41	5				5	
	chemical soil quality	10, 27, 34, 44, 45, 46, 47, 48, 50, 57, 59, 64, 82, 90, 92, 93, 96, 97, 100, 124, 127	3, 14, 33, 64, 77, 81, 90, 118, 119, 124, 128, 129, 130, 132	14, 50, 61, 70, 75, 76, 82, 83, 124, 125	19, 20, 24, 25, 29, 41, 84, 89, 96, 97, 102, 119, 124, 132	5, 124	23, 33, 44, 50, 82, 100, 119, 125, 132	3, 28, 95, 119	131, 132	5, 14, 75, 76, 83	14, 96, 97
	biological soil quality	57, 127	14, 111, 112	14, 61, 71, 83, 125		5	23, 125	28, 95		5, 14, 83	14

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Table 1. *cont.*

pest, disease, and weed suppression	pest suppression	74, 85, 114	77, 120	43, 51, 52							
	disease suppression	113									
	weed suppression	4, 26, 40, 44, 46, 50, 117	1, 2, 3, 17, 18, 60, 68, 101, 118, 119, 121, 128, 129, 130	50, 60	18, 19, 20, 25, 119	5	44, 50, 67, 119	1, 2, 3, 21, 67, 119		5	
resource use efficiency	land use efficiency (LER)	6, 8, 9, 10, 11, 45, 46, 47, 48, 50, 56, 57, 58, 64, 65, 66, 73, 86, 91, 92, 93, 98, 124	2, 17, 37, 64, 91, 124, 126	7, 8, 35, 36, 39, 50, 51, 65, 79, 123, 124	19, 124	124	50, 65	2			
	light use efficiency	9, 11, 12, 57	2, 17	7	25			2			
	nutrient use efficiency	4, 8, 9, 10, 11, 12, 16, 34, 42, 44, 45, 47, 48, 50, 57, 58, 65, 73, 86, 92, 93, 96, 97, 124	2, 3, 15, 16, 17, 37, 42, 124, 132	8, 16, 39, 42, 50, 51, 65, 70, 72, 79, 124	16, 19, 20, 25, 84, 96, 97, 102, 124, 132	5, 16, 124	16, 23, 50, 65, 132	2, 3, 16, 21, 95	132	5, 16	16, 96, 97
	water use efficiency	12, 63, 97	2		97			2			97
	labor use efficiency	93									
climate change buffering	GHG emissions	59, 90, 96	3, 14, 90, 94	14, 125	41, 94, 96	5	125	3	22	5, 14	14, 96

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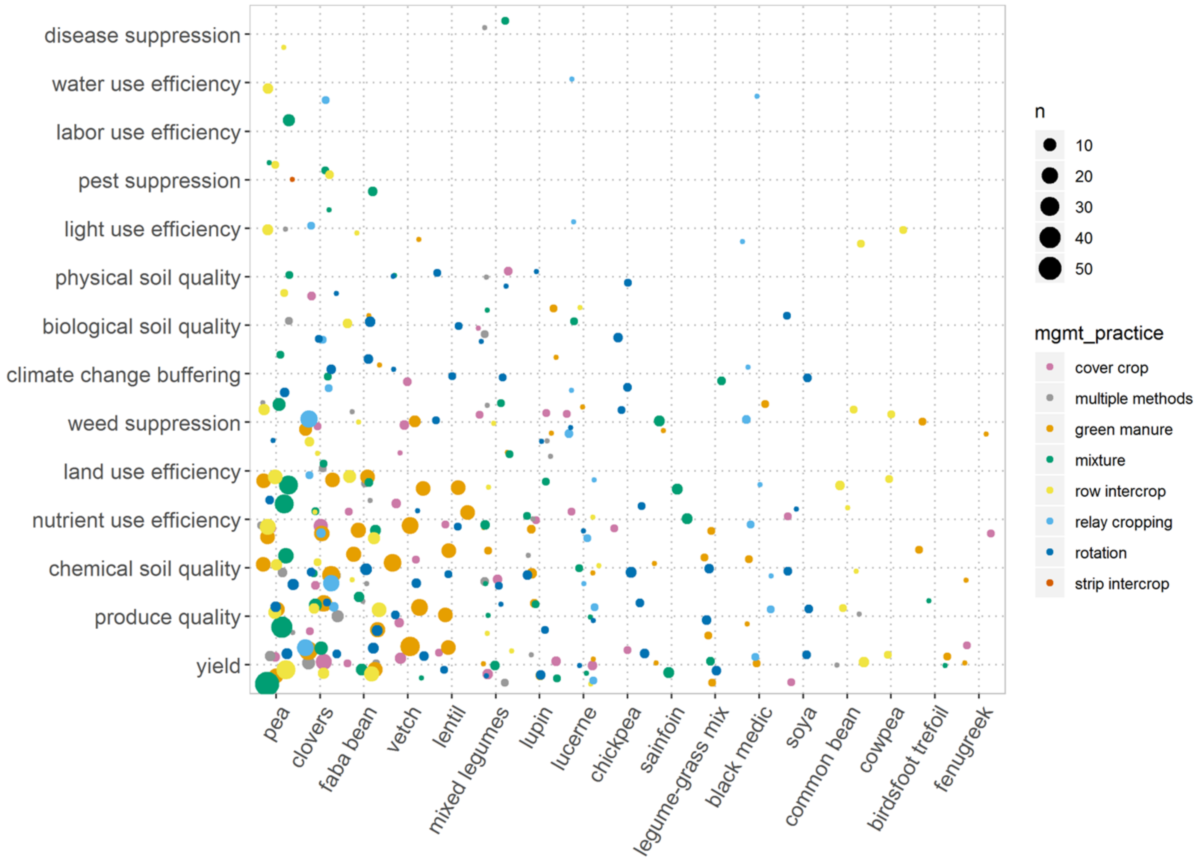

Figure 5. Matrix of associations observed in the literature between legume species (x axis) and ecosystem service measured (y axis). Dot color corresponds to the management practice employed in the study. The larger the dot, the more entries for that combination in the database.

Given the prevalence of studies in the database examining cropping systems with pea–barley and pea–wheat combinations, it is interesting to look more closely at who is primarily interested in these combinations, with which management practices the legumes are incorporated into the cropping system, and which ES are being examined (Figure 6). For pea–wheat, we see that France is most interested in this combination, that the two crops are integrated into the system most often as mixtures, and that yield, resource use efficiency (nutrients, land, and labor), produce quality, and chemical soil quality are the most commonly reported ES. Pea–barley is more often studied in Denmark, where row intercropping is a more prevalent management practice. Differing from pea–wheat, additional ES reported on for pea–barley include water and light use efficiency.

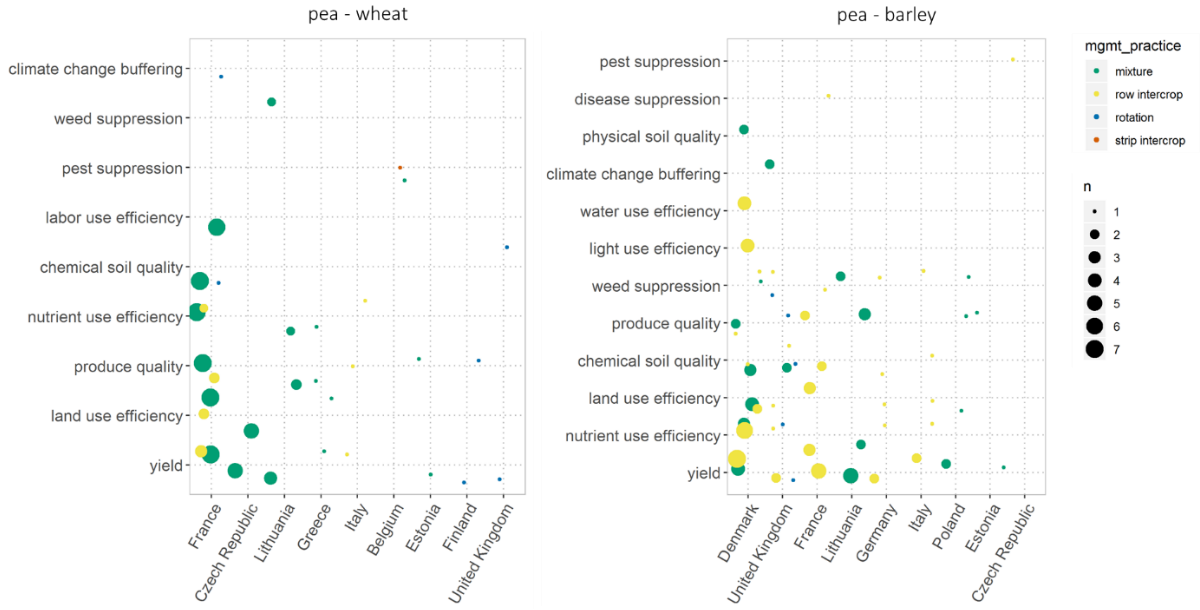

Figure 6. Location and ecosystem service combinations for two of the most common legume—non-legume crop combinations reported in the literature database: pea–wheat (***left***) and pea–barley (***right***). Dot color corresponds to the management practice employed in the study. The larger the dot, the more entries for that combination in the database.

3.2. Effects of legumes on ES delivery and drivers of variability

In Table 2 we show a subsample of findings in the reviewed literature on the effect of legumes on ES delivery and the reported associated sources of variability in the delivery of said services, generated as described in Section 2.2. An elaborated table with narrative descriptions of these results is provided in the Supplementary Information, SI.5. Among the findings reported in the selected literature, the specific effects of legumes on ES delivery varied. For certain ES, common trends are clear. For example, the land-use efficiency (expressed as a Land Equivalent Ratio (LER)) of cereal—legume intercrops are shown to almost always be higher than sole crops. Similarly, several papers reported that N fertilization rate was a key driver of variability in provisioning and nutrient use efficiency services, most (but not all) papers pointing to a trend of better yield and nutrient use efficiency gains of intercrops at lower N fertilization rates. For several services, legume species and cultivar were key drivers of variability in ES delivery (e.g. physical soil quality, pest suppression, and water use efficiency); these effects were linked primarily to species/cultivar developmental traits (time of flowering, LAI, plant height, and growing period). Contrasting results were reported for some services, for example yield and nutrient use efficiency of non-legume companion crops in intercrops and rotations were sometimes found to be improved in legume treatments and sometimes not. Year, climate, and other site-related environmental factors were commonly reported sources of variability throughout the literature.

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Table 2. Direction of effect of including legumes in cropping systems on the delivery of ecosystem services, and the associated drivers of variability in the delivery of said services, as reported in a subsample (3-5 papers on each ES) of the reviewed literature. An elaborated table with narrative descriptions of these findings, and the articles affiliated with each table entry, is provided in the Supplementary Information, SI.5.

		Source of variability										
Ecosystem service	Direction of effect *	Climatic zone / environment / site	Year	Soil	Legume species / cultivar	Seeding ratio	Sowing / plant density	Crop spatial arrangement	N fertilization (timing, source, and quantity)	Tillage method	Weeding method	Residue management method
yield	+ / - / o	✓						✓	✓		✓	
produce quality	+	✓			✓		✓		✓	✓		
physical soil quality	+				✓							
chemical soil quality	+ / o	✓										
biological soil quality	+ / o	✓		✓					✓			
pest suppression	+ / o				✓							
disease suppression	+ / -						✓					✓
weed suppression	+ / - / o	✓				✓						✓
land use efficiency	+ / o		✓		✓			✓	✓		✓	
light use efficiency	+				✓				✓			
nutrient use efficiency	+ / o				✓				✓			✓
water use efficiency	+ / -				✓							
labor use efficiency	+											
GHG emissions	- / o									✓		
carbon storage	o		✓									

* Direction of effect refers to a treatment with legume(s) compared to a treatment without legume(s). + = legume treatment performed better, - = legume treatment performed worse, o = no effect.

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4. Discussion and conclusions

This systematic review has revealed that much of the literature reporting on ES from legume crops and legume-based cropping systems is concentrated around a relatively small combination of possible services, crops, management practices, and experiment locations. Papers on production-related services are the most prevalent in the reviewed database, and these primarily report on cereal—grain legume intercrop systems, with experiments located in five main countries (France, Denmark, United Kingdom, Switzerland, and Italy). Among these five countries, there is apparent specialization on a handful of legume species (pea, clover, faba bean, and vetch). Interestingly, these are the same countries and crops already well represented in the LegValue WP1 on-farm experiment network. This finding is relevant from an agricultural extension and policy perspective, revealing that there is little scientific support for understanding the effect of legumes on ES delivery across the variety of locations, crops, and management practices not addressed in the literature. To this end, it points to a strong need in the LegValue project (especially WP1) to design research around these substantial knowledge gaps, as well as to address potential lock-ins that may be influencing research agendas.

By zooming into a subset of the reviewed literature, we illuminated possible trends in the reported effects of legumes on ES delivery at the plot scale; while relevant, it is important to remember that these observations are drawn from only a small subset of the literature database. For the more commonly reported-on production-related ES, there appeared to be primarily positive effects of legumes on ES delivery which were sometimes more pronounced in low N-input systems. These studies reported mostly on yield benefits and cereal grain protein content as an effect of intercropping cereals with grain legumes. This focus is logical as these two services probably have the most direct impact on farmers' ability to market and make a profit from the incorporation of legumes, and therefore gained high priority on research agendas aiming to provide support for farmers in adopting legume crops. For other ES with equal, but perhaps less direct, relevance to marketability and profit (e.g. disease suppression, weed suppression, water use efficiency) we found contrasting reports of legumes' effects on ES delivery with both positive and negative effects described. For these services, it is clear therefore that a closer look at drivers of variability in their delivery is essential in order to better understand how to leverage the benefits of legumes. Services for which the underlying processes operate at the farm or landscape scale were not represented in the reviewed literature, pointing to a big opportunity for new research aimed at understanding the effects of legume-based cropping systems on, for example, pollination services.

Connecting research needs with the topics farmers are interested in, and using this information to direct the activities of WP1 and other WPs, could be a particularly important and productive outcome of LegValue. The overview of which services (and combinations with which crops and locations) are not well reported in the reviewed literature gives a clear indication of where knowledge gaps exist and where future research efforts should be focused. These gaps provide valuable insight into how WP1 can more successfully contribute to achieving the overall aims of the LegValue project, in particular by providing a basis for comparing the state of the art with the information farmers have indicated they need to more successfully incorporate legumes into their cropping systems.

Through the work of LegValue's Martina Modotti et al. with the farm network component of WP1 ("Services supplied by current and future farming systems"), a preliminary understanding has been gained as to what farmers are looking for. In a survey of 134 European farmers, it

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was found that among farmers' top interests was to have better support around crop management topics, and in particular they wanted information on pest, disease, and weed control in legume-based systems. Though less frequently noted, farmers also cited economic and cultural services in their expectations of what legumes could provide, neither of which were documented in this literature review. Links between ES delivery and legume profitability (and other socio-economic indicators) could very well be connected to the low share of legumes in the EU, and understanding these links could be key to developing effective pathways towards bolstering the adoption of legume-based systems (particularly relevant for WP5[1]).

The preliminary indication provided by this review of key drivers of variability in the delivery of ES from legumes in EU cropping systems further reinforces the need to cater WP1 research activities towards acquiring knowledge relevant to farmers. In the subsample of carefully read papers the top three most reported drivers were environmental factors related to climatic zone and experiment site, legume species or cultivar, and N fertilization (timing, source, and quantity). N fertilization was not included explicitly in the organization of the review database, although space was allotted to note it, but it appeared as a driver for 7 out of 15 ES (in just a small subsample of the literature) and should clearly be accounted for in further development and analysis of the review. Other drivers that appeared in the literature but were not explicit in the database were those related to additional cultivation practices such as tillage, weeding methods, and residue management. Along with fertilization, these are practices related directly to farmers' requests for information on crop management (as cited in the WP1 farmer survey), providing further impetus for investigating these drivers in the WP1 experiment network.

Better understanding of sources of variability in ES delivery from legumes can be obtained through further analysis of the literature database. One approach would be to assess the whole database with the same method of counting as done with the sub-sample, resulting in a tally of which drivers are reported for each ES that could illuminate useful trends. As a next (quantitative) step, a meta-analysis of the strength, direction, and drivers of legume treatment effect may be possible for some ES. As part of the review process, all papers included in the database were assessed for eligibility for a potential meta-analysis and initial screening returned 74 eligible papers (54% of the total). While worthy of consideration, it should be carefully deliberated whether this effort will indeed be useful, given the sparse matrix of location, species, and crop management practice combinations reported on in the reviewed literature.

Overall, the results of this review point to a continued need for intra-WP1 collaborations that build on the project's work to date in driving the success of WP1. Additionally, it highlights the value of cross-linkages with other WPs (WP5 in particular) in revealing synergies that augment the success of LegValue as a whole. Knowing dually that a) explicit knowledge gaps exist in the literature and b) farmers want this missing information provides strong impetus for the LegValue project, and for WP1 in particular, to work collaboratively towards filling these gaps.

5. Partners involved

This report was researched and written by Lenora Ditzler (WU), in collaboration with Dirk van Apeldoorn (WU), Fernando Pellegrini (SSSA), Daniele Antichi (UNIPI), Paolo Barberi (SSSA), and Walter Rossing (WU).

[1] WP5 is focused on "Transition path analysis for the development of EU based-legume value chains"

Supplementary Information

SI.1 Search terms

Search terms and Boolean operators used in 21 August 2018 Scopus search:

TITLE-ABS-KEY((agricult* OR agronom* OR farm*) AND (agrobiodivers* OR polyculture OR “diversi* farm” OR "crop* diversi*" OR “multiple crop*” OR "mixed crop*" OR "variet* mix*" OR intercrop* OR "strip crop*" OR "row crop*" OR "relay crop*" OR "crop* rotation*" OR "green manur*" OR "cover crop*" OR "under sow*" OR agroforest* OR legum*) AND (“ecosystem service*" OR sustainab* OR "soil structure" OR "soil organic matter" OR "soil quality" OR "soil carbon" OR "carbon sequestration" OR "soil erosion" OR "soil biological diversity" OR "soil biological activity" OR "biogeochemical cycling" OR run-off OR "surface soil moisture" OR "water holding capacity" OR "water infiltration" OR porosity OR permeability OR percolation OR "water use efficiency" OR "aggregate formation" OR "aggregate stability" OR "soil aggregat*" OR "cation exchange capacity" OR "microorganism abundance" OR mycorrhiza* OR "*nutrient* management" OR "nutrient retention" OR "nutrient cycling" OR micronutrient* OR macronutrient* OR "nutrient* uptake" OR (“nitrogen W/2 leaching”) OR (“nitrate W/2 leaching”) OR (“phosph* W/2 runoff”) OR (“phosph* W/2 solubilisation”) OR ("weed W/4 control") OR "weed density" OR ("weed W/4 suppression") OR ("weed W/4 management") OR "weed pressure" OR ("weed W/4 abundance") OR "weed seed density" OR "weed biomass" OR allelopath* OR ("disease W/4 management") OR ("disease W/4 control") OR ("disease W/4 suppression") OR ("disease W/4 incidence") OR ("disease W/4 resistance") OR ("disease W/4 prevention") OR ("pest W/4 suppression") OR ("pest W/4 management") OR ("pest W/4 control") OR ("pest W/4 regulation") OR ("pest W/4 abundance") OR ("pest W/4 incidence") OR biocontrol OR "biological control" OR predation OR natural enem* OR herbivor* OR ("pest W/4 damage") OR "crop loss" OR "beneficial insect*" OR "beneficial arthropod*" OR pollinat* OR “break crop” OR "greenhouse gas*" OR "energy use" OR "energy consumption" OR "energy use efficiency" OR emission OR adapt* OR "carbon capture" OR “nitrous oxide” OR *yield* OR producti* OR "land equivalen* ratio" OR "produce quality" OR "grain protein content" OR "farm* income" OR "farm labor" OR "farm* revenue" OR ("cultivation W/4 cost") OR "farm profit*" OR “economic risk reduction” OR recover* OR resilien* OR stabil* OR resistance OR robust*))

Terms used to search within screened records (on basis of title, abstract, and keywords) for studies including legumes grown in the LegValue research network:

legum* OR alfalfa OR lucerne OR chickpea* OR *clover* OR fava* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "medicago sativa" OR "cicer arientum" OR trifolium OR "vicia faba" OR "lens culinaris" OR "lupinus genus” OR "pisum sativum" OR "glycine max" OR "vicia sp."

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°727672

LEGVALUE

SI.2 Literature database structure

Table SI.2. Literature database categories as defined for the purposes of this review.

Database column	Entry format / subcategories	Description & notes
Legume crop	Species	
Non-legume companion / reference crop	Species	
Country	EU country abbreviation	
Experiment site	Region/town name	
Latitude	Coordinate	
Longitude	Coordinate	
Climatic zone	Köppen climate classification	
Soil type	Textural class	
Management practice	Cover crop	A crop grown between seasons to provide soil cover and/or catch nutrients
	Green manure	A crop grown between or during saleable 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 alternating 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 sown part-way through the growing season so that the first crop is harvested before the second reaches maturity
Sowing density legume	kg ha^{-1}	
Sowing density non-legume	kg ha^{-1}	
Seeding ratio	% legume : % non-legume	Relevant for crop mixtures only
Between-row spacing	cm	
In-row spacing	cm	
Additional management practices examined	Tillage, fertilization, residue management, etc.	Other management practices included in experimental design
Management system	Conventional or organic	
Produce type	Fresh or dried	Type of harvested crop product
Produce use	Grazed, animal feed, human food, or biofuel	Destination of crop product
Scale measured	Plot, field, farm, or landscape	Scale at which ES is measured
Effect dimension	Immediate or residual	When legume effect is measured: during or after the legume growing season

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Table SI.2 *cont.*

Physical soil quality	y / n	Paper reported on physical soil quality indicators
Chemical soil quality	y / n	Paper reported on chemical soil quality indicators
Biological soil quality	y / n	Paper reported on biological soil quality indicators
Weed suppression	y / n	Paper reported on weed suppression indicators
Pest suppression	y / n	Paper reported on pest suppression indicators
Disease suppression	y / n	Paper reported on disease suppression indicators
Yield	y / n	Paper reported yield(s)
Produce quality	y / n	Paper reported on crop produce quality indicators
Land use efficiency	y / n	Paper reported land use efficiency indicator(s)
Light use efficiency	y / n	Paper reported light use efficiency indicator(s)
Nutrient use efficiency	y / n	Paper reported nutrient use efficiency indicator(s)
Water use efficiency	y / n	Paper reported water use efficiency indicator(s)
Labor use efficiency	y / n	Paper reported labor use efficiency indicator(s)
Climate change buffering	y / n	Paper reported on climate buffering indicators

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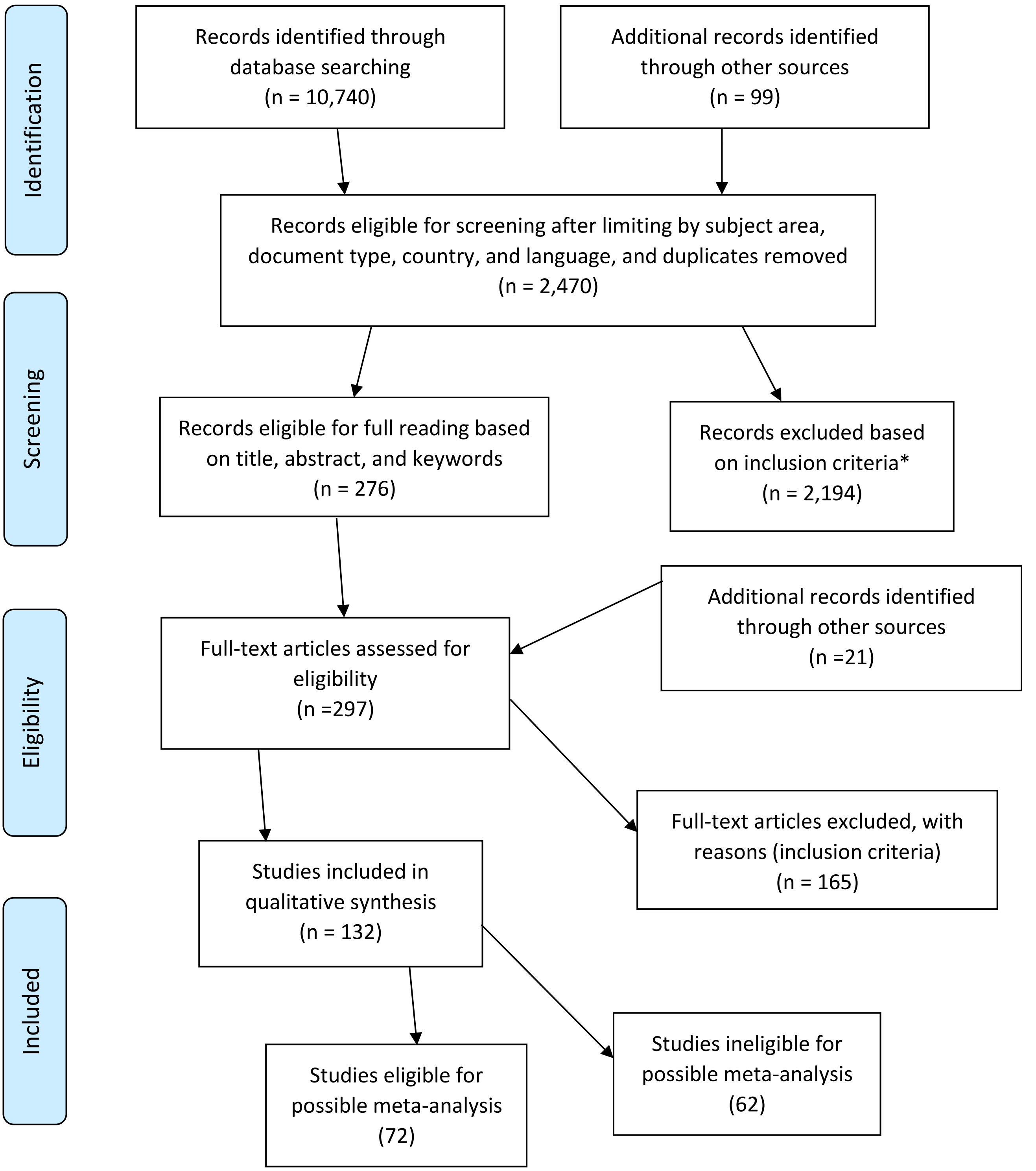
SI.3 Prisma flow-chart



*Inclusion criteria:

- The research was conducted in the EU
- The research involved one (or more) of the legume species grown in the LegValue network (see SI.1 for the species list)
- The research involved a field experiment (on-station or on-farm, no pot trials)
- An ecosystem service, other than or in addition to yield, was measured
- A non-legume reference system was used as a control
- No reviews or meta-analyses

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SI.4 Literature included in the review

Reference nr.	Reference
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SI.5 Ecosystem services and sources of variability: sample subset

Table SI.5. Example findings reported in the literature on specific ecosystem services provided by legumes in the cropping system, and sources of variability in the delivery of these services. See SI.4 for the article affiliated with each reference number. This table elaborates the information provided in Table 2, Section 3.2.

		Example findings	Sources of variability
production	yield	Yield of total pea—wheat intercrop was higher than sole wheat for treatments with little or no N fertilization, but lower or similar with higher N dose (11); similar organic sunflower yields were achieved in a treatment with a 4-year lucerne ley and no N fertilizer as in an annual sequence with 130 kg N ha^{-1} N fertilizer (21); in pea–wheat intercrops, pea yields ha^{-1} were higher than sole pea, and wheat was close to conventionally managed wheat yields (93); winter pea in a rotation as a preceding crop for durum wheat increased wheat grain production compared to sunflower (97); intercropping wheat with clover resulted in grain yield losses compared to pure wheat in some agro-environmental zones and not in others where subclover growth was limited by low temperatures or dry conditions (101).	Sunflower yield was influenced by all experimental factors (rotation, N fertilization, weeding method), but rotation was strongest (21); agro-environmental zone, mineral N fertilization, and spatial arrangement affected yield of intercropped wheat and clover (yield in intercrop was better at little or no N fertilization and in cold or dry climates) (101).
	produce quality	Maize silage crude protein content was enhanced by intercropping with bean planted at the same time (31); forage yield and nutritive value of grass sward was better when mixed with legumes (32); crop rotations that included a legume had marked effects on wheat quality (increased grain protein content) (75).	Variability in enhancement of crude protein in maize silage by intercropping with common bean came from sowing densities of the two species (31); composition of mixtures (combination of grass + legume species) was source of variability, grass component of mixtures had less effect than the legume component on herbage yield and quality (32); rainfall, tillage practice, and N fertilization all had influence on wheat quality indices across treatments (75).
soil quality	physical soil quality	Crop rotations enriched with legumes resulted in higher soil mesoporosity and lower microporosity, ensured better supply of plant-available water and revealed higher soil resistance to dry conditions compared to a non-legume rotation (33).	Choice of legume species affected level of improvement in physical soil indices (33).
	chemical soil quality	Legume crops enriched soil N through fixation and presence of relay intercropped legumes had no significant effect on N leaching during winter compared to control (neither reduced nor increased) (3); differences in SOM between treatments (mono-cropping vs. rotation with legume) were not significant after two years of study (14); NO_{3-} leaching tended to be smaller in intercrop treatments, although not significantly different from the sole cropped pea and barley (47).	Differences were attributed to climate and not treatment (14).

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Table SI.5 *cont.*			
soil quality	biological soil quality	Biological fertility indices increased in both treatments (rotations with and without legumes), although it was higher in the legume than the monoculture treatment (14); cropping system had no effects on microbial indices (contents of microbial biomass C, N, P, and fungal ergosterol in soil and CO_2 production) (57); continuous cereal cultivation negatively affected the biological fertility status of the soil, however the decline was not significantly mitigated when including a preceding legume intercropped combination (110).	All biological parameters of the soil showed great variability linked to site and not to treatment (14); increase in microbial indices resulted from organic fertilizers, rather than cropping system (sole crops vs. intercropped cereal with legume) (57); soil type and environmental conditions rather than crop treatments were major determinants of bacterial community structure (110).
pest, disease, and weed suppression	pest suppression	Density of aphid colonies was significantly higher in pure stands of wheat and pea during the main occurrence periods, compared with mix and strip cropping, although flying beneficials were more abundant in pure stands (74); intercropping white cabbage with clover had a clear pest reducing effect on fresh market cabbage (77); pest control was improved by intercropping cabbage with clover compared to sole cabbage (120).	Clover species was a source of variability in pest suppressiveness of clover intercropped with cabbage (77).
pest, disease, and weed suppression	disease suppression	Reduction in disease (in both cereal and legume) was observed in all intercropped systems compared to sole crops, with a general disease reduction in the range of 20–40% (49); incidence of disease was highest for barley grown after lucerne compared to other legumes and timothy (115).	Variability in disease incidence in barley grown in rotation with legumes was also attributed to residue management and plant population density (115).
	weed suppression	Relay-intercropped forage legumes helped control weeds in organic cereal production (1); weed number and mass were mostly not significantly different between sole cereal and intercrops (4); weed density and dry matter reduced in intercrops compared to sole crops due to decrease in available light (13); a preceding cover crop of oat exerted stronger weed reduction on the following pepper crop than vetch, although vetch showed higher above-ground biomass and total N content (19); wheat—subterranean clover intercropping reduced weed infestation compared to sole wheat (101).	Percentage of legume in sowing mixture affected weed suppression ability of cereal due to productive stem number and height (4); crop residues used as mulch were more effective at weed suppression than incorporated residues (19); there was variability in degree of weed suppression by clover across pedo-climatic experimental sites (101).
resource use efficiency	land use efficiency	Yield of wheat was not significantly affected by treatment (sole vs. living mulch of subterranean clover) (17); land equivalent ratio (LER) of intercropped peas and oats exceeded 1, indicating a yield advantage over sole cropping (57); intercropped pea—wheat was more efficient than sole cropped wheat, particularly under low-input conditions (93); intercropped wheat and grain legumes were more efficient for some legume species but only in some years (109).	Year, arrangement of two species (wide or narrow row intercropping vs. within-row mixing), and weed management had significant effect on yield of intercrops (17); N fertilizer rate was source of variability in LER (lower input systems tended to be more efficient) (93); productivity of intercrops (wheat + grain legume) depended on the species of grain legume, but results varied over the experimental years (109).

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Table SI.5 *cont.*

resource use efficiency	light use efficiency	Better light use observed in intercrop due to species dynamic complementarity for leaf area index (LAI) and height (9); intercropping led to higher soil canopy cover (LAI) than sole crops across all sampling dates (13); pea—oat intercropping significantly decreased photosynthetic rate of peas but significantly increased the photosynthetic rate of oats (57).	Timing and quantity of N availability affected crop growth and interspecies competition and therefore light use (9); species of legume intercropped with maize affected canopy cover (13); manure and compost application (vs. no application) affected photosynthetic rate of pea—oat intercrops (57).
	nutrient use efficiency	Relay intercropped legumes did not affect N uptake of companion winter wheat crop but significantly increased N uptake of succeeding spring crop (maize or wheat) (3); N uptake of durum wheat was greater under intercrop with faba beans than as sole wheat and LER values for nitrogen yield were all considerably higher than 1 indicating a better utilization of soil N sources by the intercrop than by sole crops (79); NUE of succeeding crop (eggplant) was higher in vetch cover crop treatment, although residue management was more effective for improving NUE (102).	LER-nitrogen was higher in treatments with little or no N fertilizer (11); efficiency of soil N utilization was positively affected by N fertilization rate (79); cover crop species and residue management were both sources of variability in NUE of succeeding crop (102).
	water use efficiency	All treatments used similar amounts of water, but intercrops produced more dry matter than sole crops and therefore had consistently greater water use efficiency (63); cropping systems without grain legumes had the highest water use efficiency for producing C in aerial biomass and yield in cereals (97).	Cultivar had an effect on water use efficiency (63).
	labor use efficiency	The estimated amount of energy consumed per ton of harvested grains was two to three times higher with conventionally managed wheat than with pea–wheat mixtures (fertilized or not) (93).	Fertilizer rate was not a source of variability (93).
climate change buffering	GHG emissions	Vetch resulted in higher N_2O losses than barley in conventional and minimum tillage, whereas similar fluxes were observed under no-till, and neither tillage nor crop influenced CH_4 or CO_2 emissions (41); N_20 losses were significantly different between the treatments (generally higher in intercrop with legume than sole cereal) (90).	Tillage (conventional, minimum, or no-till) had a strong influence on cumulative N_20 emissions (41); legume cultivar had a strong effect on variability of N_20 emissions (90).
	carbon storage	In a rotation with and without legumes organic C content declined steadily each year in all treatments (14).	Variation in decline of C stocks across years was attributed to year not treatment (14).

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