VALERECO

Valorization Legumes Related Ecosystem Services

D1.1: Knowledge synthesis on legumes and their associated biodiversity and ecosystem services

Responsible Authors: Researchers from the University of Coimbra & the University of Pisa

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Responsible Author	Rui S. Oliveira (UC)		
Contributors	Alexandros Tataridas (UC), Helena Freitas (UC), Lorenzo Tramacere (UNIPI), Edoado Monacci (UNIPI), Clarissa Clemente (UNIPI), Daniele Antichi (UNIPI), Silvia Tavarini (UNIPI)		
Reviewer(s)	Jan Kiers (DELPHY), Metaxia Kokkini (AUA)		

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No.	Participant organization name	Short name	Country
1	GEOPONIKO PANEPISTIMIO ATHINON	**AUA**	GR
2	ESC DIJON BOURGOGNE	**BSB**	FR
3	DELPHY BV	**DELPHY**	NL
4	UNIVERSIDADE DE COIMBRA	**UC**	PT
5	REFRAME FOOD ASTIKI MI KERDOSKOPIKI ETAIRIA	**RFF**	GR
6	INSTITUT ZA RATARSTVO I POVRTARSTVO INSTITUT OD NACIONALNOG ZNACAJA ZA REPUBLIKU SRBIJU	**IFVCNS**	RS
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13	AG FUTURA TECHNOLOGII DOOEL SKOPJE	**AGFT**	MK
14	SCUOLA SUPERIORE DI STUDI UNIVERSITARI E DI PERFEZIONAMENTO S ANNA	**SSSA**	IT
15	HELVETAS Swiss Intercooperation	**HELVETAS**	CH

Executive Summary

Legumes offer a broad set of ecosystem services that significantly contribute to sustainable agricultural practices and environmental resilience. Their ability to fix atmospheric nitrogen enhances soil fertility, reduces dependence on synthetic fertilizers, and lowers greenhouse gas emissions. Additionally, legumes improve soil health, prevent erosion, and promote water retention, crucial for climate change adaptation. They also support biodiversity by providing habitats for pollinators and beneficial organisms, thus fostering natural pest control. However, despite their ecological and economic potential, legumes remain underutilized due to various barriers. These include limited awareness of their multifunctionality, technical challenges in integrating legumes into conventional systems, and underdeveloped value chains. Economic constraints, such as high initial costs and low market demand, are compounded by policy frameworks that inadequately support legume-based farming. Social and cultural resistance further hinder their adoption, especially among smallholder farmers.

To unlock the full potential of legumes, a multidisciplinary approach is required. This includes robust research on diverse species and ecosystem services, policy reforms to incentivize adoption, and market strategies to enhance demand. Addressing these barriers will enable the valorization of legume ecosystem services, contributing to sustainable agriculture and global food security. This deliverable: (i) highlights the contribution of legumes to several ecosystem services (soil health improvement, pest control, biodiversity conservation, carbon sequestration, pollination, economic benefits, nitrogen fixation and water management); (ii) identifies research gaps and ecosystem services that need to be valorized; (iii) discusses agronomic, technical, economic, policy, and cultural barriers to the adoption and valorization of legume-based systems; (iv) reviews studies on diverse legume species, ecosystem service quantification, and the integration of legumes into agroecosystems; (v) provides examples of successful legume integration into cropping systems, including intercropping, cover crops, and crop rotations; and (vi) lists existing projects and databases delivering research results on legume ecosystem services.

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List of abbreviations

CAP	Common Agricultural Policy	**MSCA**	Marie Skłodowska-Curie Actions
CCs	Cover Crops	**N**	Nitrogen
EU	European Union	**SOC**	Soil Organic Carbon
GHG	Greenhouse Gases	**SOM**	Soil Organic Matter
HE	Horizon Europe	**WUE**	Water Use Efficiency
LM	Living Mulch		

1. Introduction

Increasing population and food consumption will drive a growing global demand for food in the coming decades. However, farmers face increasing competition for land, water, and energy while striving to mitigate the environmental impacts of food production (Godfray, 2010). To guarantee food security, it is essential to have adequate food production or availability, ensure access to food and the means to afford it, and prioritize its safety, nutritional adequacy (including energy, proteins, and micronutrients), along with maintaining economic stability (Sharma et al., 2024). Since 1961, agricultural intensification has successfully boosted crop yields to meet global food demands (Bommarco et al., 2013). However, this process has simplified agroecosystems and replaced natural biological functions with agrochemicals (Tilman et al., 2001), leading to significant environmental consequences such as reactive nitrogen (N) oversupply, greenhouse gas (GHG) emission, biodiversity loss (Pingali, 2012), soil degradation, chemical runoff, and eutrophication of water bodies (Burney et al., 2010). The widespread use of chemical fertilizers has been central to increasing crop productivity and addressing food security (Vejan et al., 2021). However, continuous application has degraded soil quality by reducing organic matter, altering soil pH, and disrupting microbial activity. Overuse of fertilizers contributes to soil hardening, acidification, and pollution, negatively affecting air, water, and soil while fostering pest outbreaks and further GHG emissions (Rahman et al., 2021). Also, pesticides were widely adopted as highly efficient and cost-effective means. However, their environmental impacts on health, biodiversity, and ecosystem resilience were frequently overlooked (Kanter et al., 2018; Belmain et al., 2022). While the safety of chemicals used to manage arthropods, plant pathogens, and weeds has improved in recent decades (Seiber and Kleinschmidt, 2011), these economic advantages often come at the expense of biodiversity loss (Raven and Wagner, 2021). These issues raise **concerns about the sustainability of agriculture and its reliance on chemical inputs** (Rahman et al., 2021). Moreover, human activities such as deforestation, fossil fuel combustion, and agricultural practices contribute significantly to GHG emissions and climate change (Yuan et al., 2024). Climate change impacts agriculture with rising temperatures, altered precipitation patterns, and increased transpiration rates (Altieri et al., 2015). It exacerbates extreme weather events like droughts and floods, intensifies pressures from weeds, pests, and pathogens (Yuan et al., 2024), and depletes land and soil resources, all of which threaten crop yields and sustainable agricultural development (Eekhout and De Vente, 2022). To address the challenge of ensuring long-term food security, **it is crucial to develop and implement innovative sustainable agricultural practices alongside agroecological farming principles** (Altieri et al., 2015; Wezel et al., 2020) across all levels of agricultural production. These practices focus on producing substantial food quantities by maximizing the benefits of ecological processes and ecosystem services. Unlike conventional methods, agroecological practices avoid or try to minimize the use of standard agricultural techniques such as chemical fertilizers, synthetic pesticides, and technological innovations like genetically modified organisms. Instead, they aim to enhance the sustainability of agroecosystems by leveraging ecological processes and ecosystem services, including nutrient cycling, biological N fixation, pest regulation, soil and water conservation, biodiversity preservation, and carbon sequestration (Wezel et al., 2014). **The development of agroecological practices inevitably raises the issue of diversification**. Over the past decade, a growing body of research has emphasized the need to reintegrate species diversity into cropping systems for several reasons: (i) to enhance the resilience of agroecosystems to disturbances (Vandermeer et al., 1998; Tilman et al., 2006; Malézieux et al., 2009); (ii) to reduce pest outbreaks, including weeds; and (iii) to preserve or boost biodiversity (Médiène et al., 2011). Diversification involves incorporating a greater variety of cultivars, crops, or intercrops into agricultural systems. It can also include leveraging natural biodiversity for farming purposes, as demonstrated in practices such as conservative biological control (Wezel et al., 2020). For example, cropping sequences can be designed to enhance nutrient availability and reduce the need for fertilizers by incorporating leguminous crops into rotations. These crops fix atmospheric nitrogen (N_2), providing a readily available source of N for the subsequent crops. Additionally, they can contribute to soil protection and conservation by increasing ground cover, such as through the use of cover crops (CCs) or winter cash crops. This approach also helps improve soil organic carbon content and fertility, thereby enhancing soil stability (Watson et al., 2002; Dogliotti et al., 2004; Wezel et al., 2014).

Currently, **there is a growing attention to legumes from a sustainable agriculture perspective due to the many ecosystem services they can provide** (Geijzendorffer et al., 2017). By harnessing ecosystem services, agricultural systems can become more resilient to climate change, promote biodiversity, and improve food security for a more sustainable future (Romanelli et al., 2015; Muluneh, 2021). **The importance of ecosystem services highlights the key role that legumes play in agroecology and sustainable intensification**. Indeed, legumes are in line with sustainability principles through their ability to fix N, improve soil health, support biodiversity, and contribute to climate change mitigation (Peoples et al., 2009b; Stagnari et al., 2017; Kebede, 2021). Additionally, legumes play a crucial role in global food security by providing a good amount of proteins useful for food and feed products (Richardson, 2010; Voisin et al., 2014; Jimenez-Lopez et al., 2023). Legumes have also been observed to diversify cropping systems, thereby increasing the sustainability of agricultural practices in Europe (Ditzler et al., 2021; Yu et al., 2024). In light of this, there is an increasing focus on integrating legumes into diverse cropping systems to optimize ecosystem services and address the challenges of modern agriculture in a changing climate. Current agricultural systems must contribute to sustainability not only through high yields, but also by improving the resilience and biodiversity of the environment (Duru et al., 2015; Rehman et al., 2022). Most studies are related to the incorporation of legumes as a service crop (often to facilitate a cash crop) and those that consider them as food or forage crops. Studies that used legumes as a service crop are dominated by those that incorporate them as green manure or CCs in rotation with cereals, while those that use legumes as food or forage crops predominantly refer to systems in which legumes and cereals are combined in rotations or intercropped in rows or as mixtures (Ditzler et al., 2021). Therefore, promoting the importance of ecosystem services in policies and decisions is helping to redefine sustainability by driving countries and industries to adopt more holistic approaches to land use and resource management. Consequentially, optimizing the ecological functions of legumes can promote more sustainable and cost-effective agricultural practices that address the challenges of global food security and climate change (Dutta et al., 2022). Thus, **the aim of this review is to summarize ecosystem services provided by legumes, identify underexplored services, and examine barriers to their utilization**.

2. Glossary of Legumes and related Ecosystem Services

Agroecology: Agroecology is a holistic approach that can redesign agroecosystems by harmonizing agriculture and local communities with natural processes and environmental elements. It involves the application of ecological concepts and principles to the design and management of sustainable agriculture and food systems.

Biodiversity: The variety and variability of life forms on Earth, including the diversity of species, ecosystems, and genetic differences within species. It encompasses the complex interactions between organisms and their environments, and is essential for the stability, resilience, and functioning of ecosystems.

Biodiversity Conservation: The preservation of species and ecosystems. Legumes contribute by providing habitats for soil organisms, pollinators, and natural pest predators. The reintroduction of legumes into cropping systems enhances both above and belowground biodiversity in agroecosystems through their roles in nutrient cycling and symbiotic relationships.

Biological Control (Biocontrol): The use of natural organisms, such as predators, parasites, pathogens, or competitors, to manage and suppress populations of pests, weeds, or other harmful organisms. Diversifying crop rotations with legume crops can break pest and disease cycles, enhancing biological control in agroecosystems.

Biomass: The total mass of living organisms, including plants, animals, microorganisms, and residues derived from them, in a given area or ecosystem. Legumes produce high biomass, contributing to soil health and organic matter.

Carbon Footprint: The total greenhouse gas emissions caused directly or indirectly by an individual, organization, or product. Legumes can reduce emissions by minimizing the need for synthetic N fertilizers in companion or subsequent crops, sometimes improving their yields by releasing symbiotically fixed N into the soil.

Carbon Sequestration: The process of capturing and storing atmospheric carbon dioxide to reduce the greenhouse effect and mitigate climate change. Legumes contribute to carbon sequestration by adding organic matter to the soil and reducing the reliance on synthetic fertilizers, thereby indirectly lowering emissions from fertilizer production.

Cash Crops: Crops grow primarily for their commercial value. Some legumes, like soybeans, chickpea, and lentils, are prominent cash crops globally.

Climate Adaptation and Resilience: The capacity of agricultural systems to cope with climate variability. Legumes play a crucial role in enhancing the resilience and adaptation of agroecosystems to climate stressors by delivering essential ecosystems services that contribute to improve soil health, increase drought tolerance, and more effective pest management under changing climatic condition.

Climate Change Mitigation: Actions taken to reduce or prevent the impacts of climate change. The inclusion of legumes in crop rotations reduces dependence on N fertilizers, lowering the carbon footprint of cropping systems and contributing to climate change mitigation.

Cover Crops (CCs): Crops grown between main crop cycles to prevent soil erosion, improve water infiltration and storage, reduce nutrient losses, increase organic matter content, and compete with weeds. The benefits of legumes as CCs also include the symbiotic fixation of atmospheric N into the soil in a stable form.

Crop Diversification: The practice of growing multiple crop species to enhance biodiversity, improve resilience to pests, diseases, and extreme climate events due to climate change, and increase resource use efficiency, helping to cope with market fluctuations. Legumes are often included in diversified systems for both their ecological and economic benefits.

Crop Rotation: The practice of growing different types of crops in a planned sequence on the same land over several growing seasons to replenish soil nutrients, manage pests and diseases, improve soil fertility, and resource use efficiency, thereby ensuring long-term agricultural sustainability.

Dietary fiber: Indigestible plant-based food that supports digestive health. Legumes are a significant source of dietary fiber.

Drought Tolerance: The ability of crops to withstand dry conditions. Certain legumes, such as chickpeas, are highly drought-tolerant, while others, like clovers, are very sensitive to drought stress.

Ecological Resilience: The ability of ecosystems to recover from disturbances (e.g., harsh climate events caused by climate change) while maintaining their essential functions. Legumes play a crucial role in increasing resilience by enhancing biodiversity, nutrient cycling, and soil fertility.

Economic Benefits: Contributions to the agricultural economy. Legumes can serve as cash crops with high market demand (e.g., soybeans, lentils, chickpeas); lower production costs by reducing dependency on synthetic fertilizers; and support rural livelihoods through diverse uses in food, fodder, and industry.

Ecosystem Services: The benefits humans derive from the functioning of ecosystems. In agricultural systems, these include nutrient cycling, soil fertility, pest control, and carbon sequestration. Legumes significantly contribute to these services by enhancing biodiversity and improving soil fertility through symbiotic N_2 fixation.

Erosion Control: Erosion Control: The prevention of soil erosion through practices and methods such as root stabilization, the use of CCs (both living and dead mulch), agroforestry, and structural interventions. Legume crops, particularly perennial legumes, play a significant role by stabilizing soil and providing dense ground cover, offering protection throughout the year.

Essential Amino Acids: Amino acids required in the diet. Legumes are a rich source of these nutrients, crucial for human and animal health.

Food Security: The availability and affordability of sufficient, safe, and nutritious food, also considering the sustainability of its production. Legumes contribute by being a cost-effective source of plant-based protein and essential nutrients and enhancing agricultural productivity through the delivery of several ecosystem services.

Food Systems: Networks of processes and actors actively involved in food production, distribution, and consumption.

Forage Legumes: Legumes grown as animal feed, such as alfalfa or clover, which also enhance soil health and provide several ecosystem services.

Green Manure: Crops, typically legumes, grown and then incorporated into the soil to improve soil fertility and enhance structure by adding organic matter and nutrients, and supporting biodiversity within the soil ecosystem.

Intercropping: The agricultural practice of growing two or more crops simultaneously in the same field for mutual benefit. This often includes combining legumes with non-legumes to enhance N use efficiency, improve soil fertility, increase crop yields, and manage pests and diseases by disrupting pest cycles and promoting biodiversity.

Legumes: A family of plants (Fabaceae) characterized by their ability to fix N_2 through a symbiotic relationship with N-fixing bacteria in their root nodules.

Multifunctionality: The capacity to provide multiple ecosystem services simultaneously. Legumes exemplify this by enhancing soil health and fertility, supporting pollinator populations, improving carbon sequestration, and reducing greenhouse gas emissions.

Mycorrhizal Fungi: Soil fungi that form symbiotic associations with plant roots, enhancing nutrient uptake and improving plant growth and productivity. Legumes can influence the abundance and diversity of these fungi and, in turn, benefit from the mutualistic relationship.

Nitrogen Fixation: A key ecological process in which N_2 is converted into bioavailable forms by bacteria. Legumes harbor N-fixing bacteria in root nodules. This process reduces the need for synthetic N fertilizers and increases soil N content, benefiting subsequent crops in rotation systems.

Nutrient Cycling: The movement of essential nutrients, such as N and phosphorus within ecosystems. Legumes contribute to nutrient cycling by fixing N, making it available to other plants.

Nutrient Density: The concentration of essential nutrients in a food relative to its calorie content. Legumes are nutrient-dense foods, contributing to balanced diets.

Phosphorus Solubilization: The process by which insoluble forms of phosphorus in the soil are converted into bioavailable forms. This process is often facilitated by legumes, which enhance phosphorus solubilization through their root exudates and symbiotic relationships with soil microorganisms.

Pollination: The transfer of pollen between flowers, crucial for the reproduction of many crops. Legumes, with their nectar-rich flowers, attract a variety of pollinators, such as bees and butterflies, thereby supporting both crop yield and pollinator populations.

Polyculture: Agricultural practice that involves growing multiple different crops simultaneously in the same area. Legumes are a staple of polyculture systems due to their ecological benefits.

Protein Quality: The ability of a protein to provide essential amino acids in the right proportions for human consumption. Legumes are an excellent source of high-quality plant-based proteins.

Pulse Crops: Dried and edible legume seeds, such as lentils, chickpeas, and beans, used as a food source high in protein and fiber.

Rhizobia: A group of N-fixing bacteria that form symbiotic relationships with legumes, enabling N fixation.

Rhizosphere: The soil zone immediately surrounding plant roots where intense microbial activity occurs. Legumes influence this zone significantly by releasing root exudates that promote beneficial microbial activity and enhance nutrient cycling, particularly N fixation.

Root Nodules: Specialized structures on legume roots where N-fixing bacteria reside and convert N_2 into a usable form for plants.

Soil Fertility: The ability of soil to sustain plant growth by supplying essential nutrients in the right balance. Legumes improve soil fertility through symbiotic N fixation and organic matter supply.

Soil Health: The condition of the soil as a living and dynamic system. Legumes play a vital role by increasing soil organic matter through root residues and leaf litter. This process enhances soil structure, reduces compaction, prevents erosion and supports a diverse microbial community in the rhizosphere.

Soil Microbiome: The diverse community of microorganisms in the soil. Legumes enhance microbial diversity and activity through root exudates and symbiotic interactions.

Soil Organic Matter (SOM): The organic components of soil, including decomposed plant and animal residues, as well as microorganisms. Legumes contribute significantly to SOM through their biomass inputs and by supporting the activity of soil microbiota.

Sustainable Agriculture: Farming methods that maintain productivity while minimizing environmental impact, ensuring long-term economic and social health. Legumes are integral to these systems for their role in nutrient management and the provision of several ecosystem services.

Symbiosis: A mutually beneficial relationship, such as that between legumes and N-fixing bacteria (Rhizobia).

Water Management: The efficient use, conservation, and distribution of water across various sectors, including agriculture, industry, and urban areas, to ensure sustainability and meet diverse needs. Legumes support this by improving soil water retention, increasing organic matter and soil structure, reducing water runoff and erosion with their dense root systems especially in case of perennial legumes, and acting in some cases, as drought-resistant crops in arid and semi-arid regions.

Water Retention: The capacity of soil to retain or hold water.

3. Literature review and bibliometric analysis

A bibliometric analysis was conducted on 18.01.2025 in Scopus database using the keywords “legumes” and “ecosystem services”. The primary results returned 565 documents matching these criteria. VOSviewer version 1.6.20 was used to visualize the co-occurrence of keywords showing the links among them based on the bibliographic data downloaded from Scopus. The top 50 keywords with the most occurrences were selected for the visualization and the minimum strength of the link was set at 20 (Figures 1 and 2).

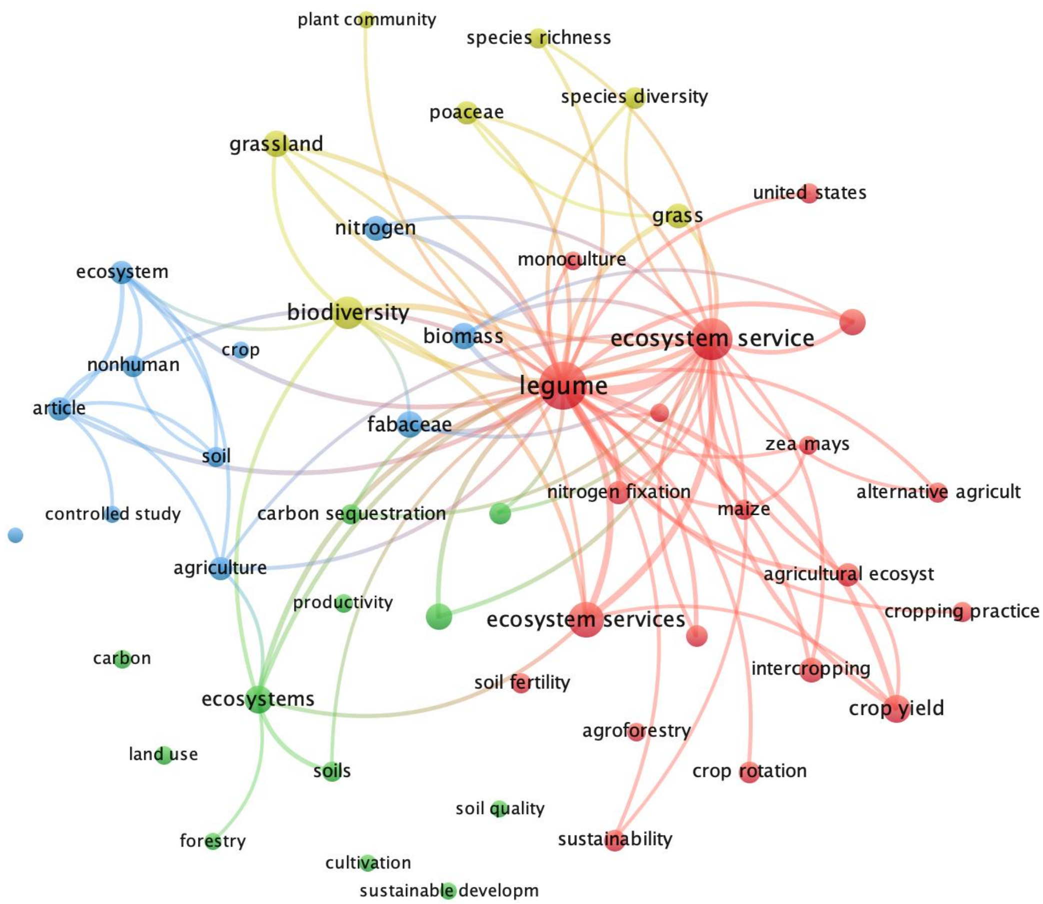

Figure 1: Strength of links between “legumes”, “ecosystem services” and related keywords according to the conducted bibliometric analysis

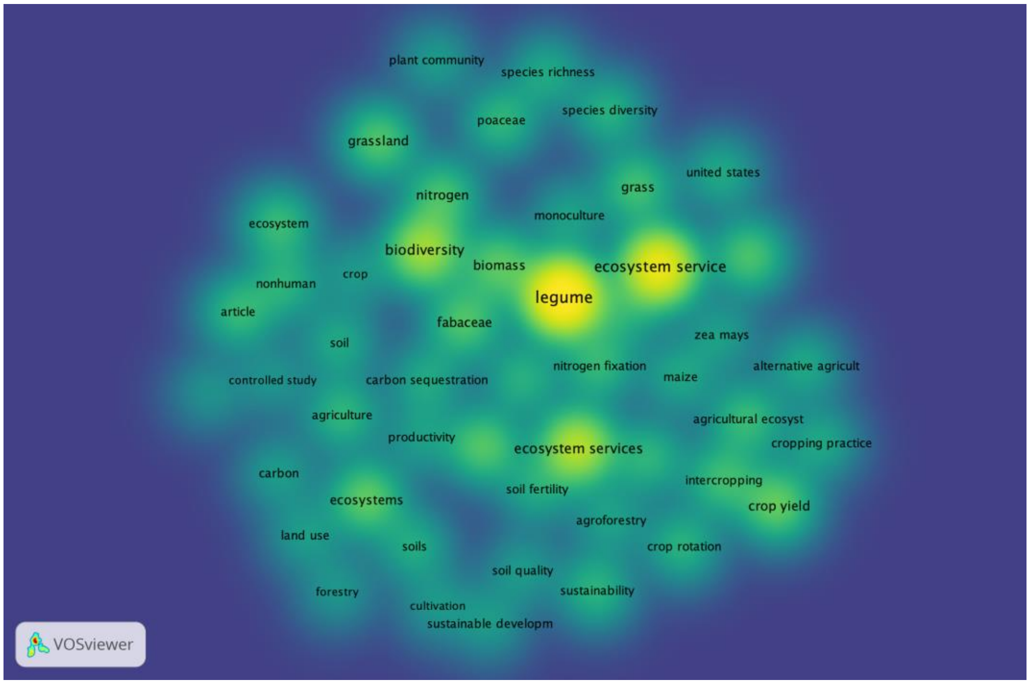

Figure 2: Item density visualization of "legumes", "ecosystem services" and related keywords according to the conducted bibliometric analysis

The bibliometric analysis showed that the two terms started to be included in scientific publications in the early 2000s, with an increasing trend in the number of publications (Figure 3). The majority of publications refer to articles, followed by review papers (Figure 4). The most prevalent subject area to publish was the Agricultural Sciences followed by Environmental Sciences (Figure 5).

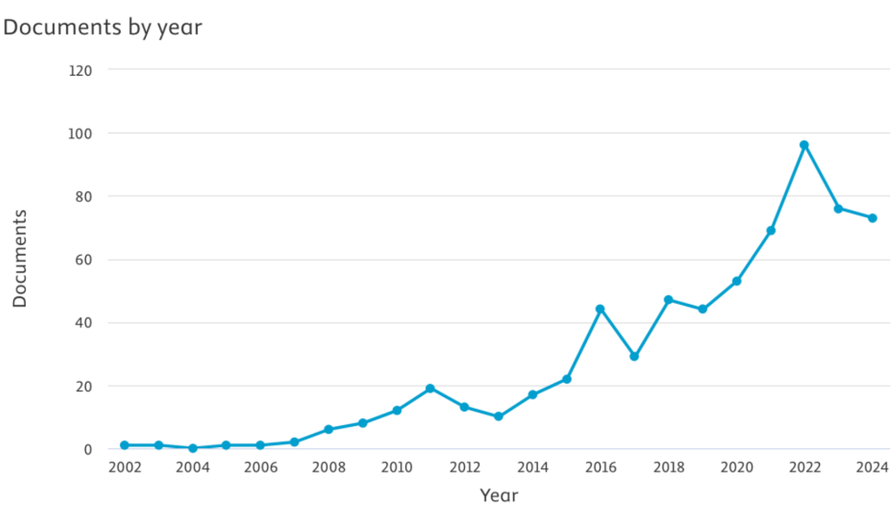

Figure 3: Trend of the number of publications including "legumes" and "ecosystem services"

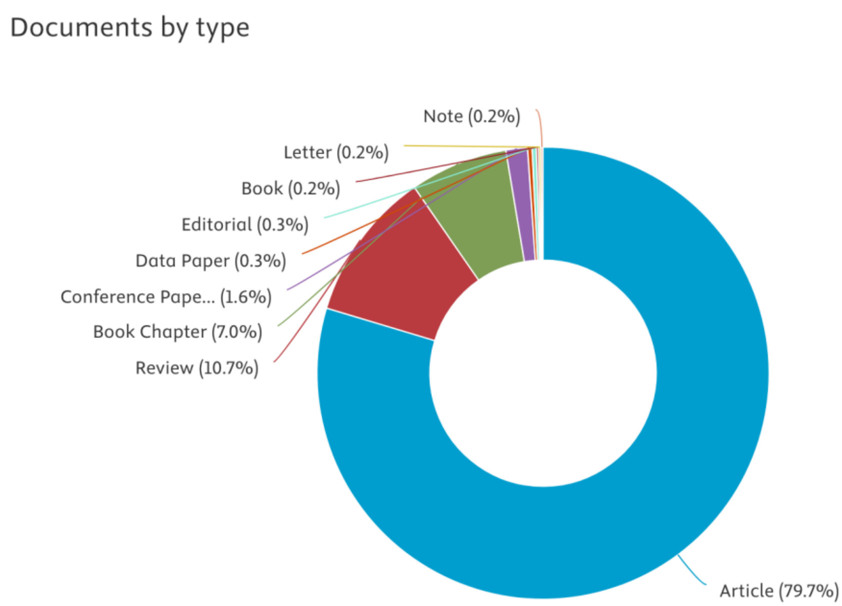

Figure 4: Type of document of publications including "legumes" and "ecosystem services"

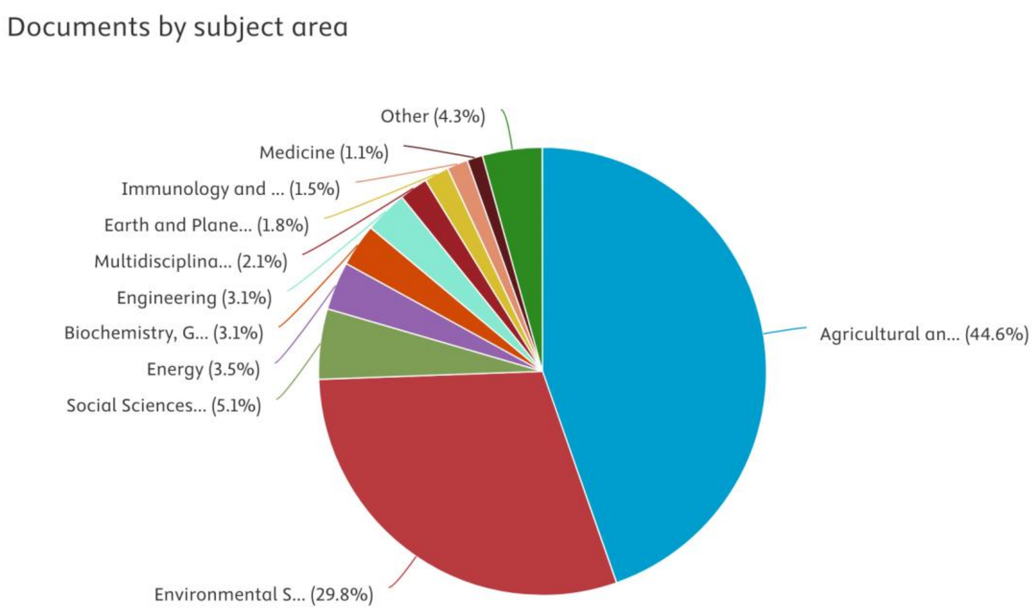

Figure 5: Subject area of publications including "legumes" and "ecosystem services"

4. Ecosystem Services to be valorized

Legumes contribute to a broad set of ecosystem services (provisioning, regulating, cultural) that benefit both the agroecosystems and the overall sustainability of the farming systems. From a sustainable agriculture and agroecological perspective, a prioritization list of legumes-derived ecosystem services has been developed and is detailed below (Figure 6).

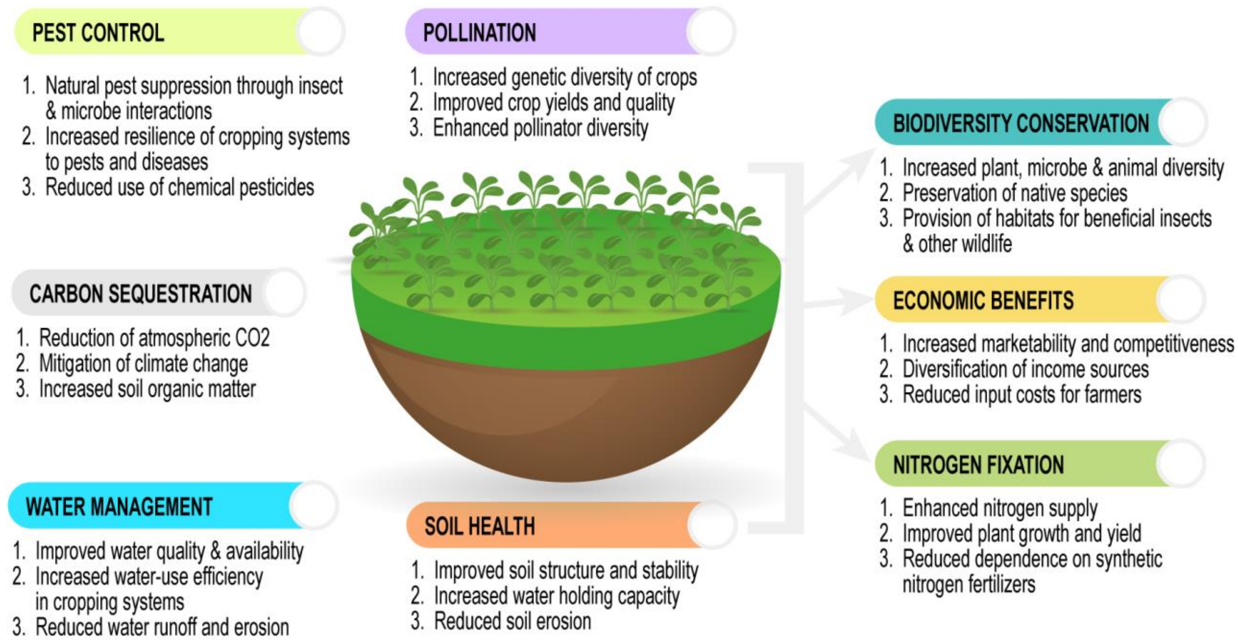

Figure 6: Ecosystem services related to legumes that need to be valorized

4.1 Pest control

Legumes play a pivotal role in advancing natural pest control strategies within sustainable agricultural systems. Their ability to foster ecological interactions significantly enhances natural resistance to pests, reduces reliance on chemical pesticides, and contributes to the overall resilience of agroecosystems. By integrating legumes into agricultural systems, farmers can promote biodiversity and improve the ecological balance of their crops. Legume intercropping practices are particularly effective in enhancing biodiversity and reducing pest populations. For example, Brandmeier et al. (2021) demonstrated that intercropping legumes with cereals increased arthropod diversity and reduced pest populations, without negatively impacting crop yields. Similarly, Hüber et al. (2022) observed that maize-bean intercropping boosted biodiversity, including an increase in bumblebee populations, which helped to naturally control pests and reduce pest damage in European agricultural systems. Moreover, Bedoussac et al. (2015) reviewed cereal-legume intercrops in Europe and found that these systems could reduce pest prevalence, while also increasing yield efficiency, particularly under organic farming conditions. These studies highlight the potential of legume intercropping to support both ecological health and agricultural productivity. The use of legumes as CCs further enhances their role in pest management. For instance, the deployment of faba beans significantly reduced aphid pest density, cutting pesticide use while maintaining crop quality (Köpke and Nemecek, 2010). Additionally, legume-based systems disrupt pest life cycles, as seen in studies on *Desmodium* spp., which repel stem borers in maize-legume intercropping, reducing the need for chemical pesticide applications (Ratto et al., 2022). Such practices underscore the value of legumes in reducing pest pressure while supporting crop health. The integration of legumes into crop rotations or intercropping systems also strengthens agroecosystem resilience by mitigating soil erosion, enhancing microbial activity, and attracting beneficial insects such as pollinators and pest predators (Wyckhuys et al., 2023). Legumes contribute to ecosystem stability by supporting biodiversity, which enhances the resilience of agricultural landscapes against pest outbreaks (Jacquet et al., 2022). This natural form of pest control offers an economically and ecologically sustainable means of maintaining high productivity while reducing costs associated with synthetic pesticide use. The economic benefits of legume integration are also notable. Watson et al. (2017) found that legume integration into crop systems could reduce pesticide costs due to natural pest control and improved crop resilience. These savings, coupled with increases in crop yields, highlight significant financial and environmental gains, demonstrating the value of legumes in fostering sustainable agricultural practices.

4.2 Pollination

Pollination is a cornerstone of ecosystem services, playing a critical role in agricultural productivity, biodiversity conservation, and ecosystem stability. Legumes, as flowering plants, significantly contribute to these processes by fostering pollinator diversity, promoting cross-pollination, and supporting agricultural systems. Legumes provide abundant floral resources, including nectar and pollen, which attract a wide variety of pollinators such as bees, butterflies, and moths. Studies have highlighted the importance of legumes in maintaining pollinator populations. For example, Raderschall et al. (2021) observed that legume-rich landscapes increased pollinator density compared to monoculture fields, translating into higher biodiversity and agricultural resilience. Additionally, Köpke and Nemecek (2010) emphasized that legumes provide continuous floral resources, ensuring the sustenance of pollinator populations throughout the growing season. Cross-pollination in legumes enhances genetic diversity, ensuring crop adaptability and resilience to environmental stress. For instance, in faba beans (*Vicia faba*), open pollination by bees resulted in an increase in pod formation and improvement in seed weight compared to self-pollinated plants (Bartomeus et al., 2014). Such benefits are crucial for both natural ecosystems and agriculture, as they ensure higher quality yields and improved food security. The reliance of leguminous crops such as peas, beans, and alfalfa on pollination underscores their role in agricultural productivity. Pollinator activity has been shown to enhance yields by up to 40% in clover fields, reducing the need for synthetic inputs (Ferrante et al., 2025). Furthermore, intercropping legumes with cereals enhances the overall productivity of neighboring crops by attracting shared pollinators (Galloni et al., 2007). In natural ecosystems, legumes act as keystone species, stabilizing pollinator networks by providing consistent resources. Research by Tamburini et al. (2019) highlighted that pollinator-dependent legumes improve biodiversity and enhance the stability of agroecosystems. Additionally, legumes enrich soils through symbiotic N fixation, indirectly supporting flowering plant diversity and, consequently, pollinator populations.

4.3 Biodiversity conservation

As keystone species in many ecosystems, legumes contribute significantly to biodiversity conservation by promoting ecological balance, supporting native species, and providing critical habitats. Their integration into sustainable agriculture and natural ecosystems underscores their crucial role in maintaining biodiversity. These plants enhance biological communities at multiple levels by fostering diversity among plants, microbes, and animals. For example, Martinelli et al. (2022) indicated that legume-dominated systems in Mediterranean Europe increase soil microbial diversity, which in turn supports nutrient cycling and ecosystem stability. The microbial diversity associated with legumes underpins their broader ecological benefits, improving soil health and resilience. Furthermore, the floral resources they provide attract a range of pollinators and beneficial insects, such as bees and predatory beetles, which play essential roles in pest management and pollination. Semi-natural habitats enriched with legumes have been shown to enhance insect diversity, supporting species such as bees, butterflies, and beetles. Sainfoin (*Onobrychis viciifolia*) and vetches (*Vicia* spp.) are particularly valuable in fragmented European landscapes, providing stable floral resources that sustain pollinator populations throughout the growing season (Harris and Ratnieks, 2022). In addition to their impact on microbes and insects, these plants, through their association with N-fixing bacteria, play a vital role in preserving native flora. By enriching soils, they create favorable conditions for native plant species to thrive. Duru et al. (2015) observed that the integration of legumes into European grasslands increased the diversity of native herbaceous plants. These improvements in plant diversity also stabilize ecosystems, indirectly benefiting fauna. For instance, clover fields support populations of native pollinators such as bumblebees, which are essential for ecological balance and agricultural productivity (Ferrante et al., 2025). Beyond pollinators, legumes provide critical habitats for diverse wildlife. Their dense foliage offers protection for small mammals, reducing predation risks, while also serving as cover for birds in agricultural landscapes. Del Portillo et al. (2022) highlighted the value of alfalfa fields, noting that their structural complexity benefits small mammal communities and provides essential refuge for avian species. Finally, through habitat creation and by hosting N-fixing bacteria, legumes help maintain ecosystem balance. Acting as buffers against biodiversity loss, legume-dominated systems ensure ecosystem functionality, even under agricultural intensification (Wrage et al., 2011). By reducing reliance on synthetic fertilizers and pesticides, they also protect aquatic ecosystems from nutrient runoff, preserving aquatic biodiversity.

4.4 Carbon sequestration

Legumes play a pivotal role in mitigating climate change by contributing to carbon sequestration through various mechanisms. Their integration into agricultural systems has demonstrated significant potential to reduce atmospheric carbon dioxide (CO_2), enhance soil organic matter, and improve long-term soil health. Legume-inclusive systems capture atmospheric carbon and incorporate it into the soil. This is achieved through their high biomass production and the stimulation of microbial activity, which promotes the stabilization of organic carbon in the soil. Work by Willaume et al. (2025) revealed that legume CCs in Mediterranean farming systems enhanced soil carbon storage compared to bare fallow systems. Additionally, Yao et al. (2025) showed that legume-rice rotations globally improved carbon sequestration with an increase in soil organic carbon content. In long-term experiments conducted in Europe, legume-grass pastures were shown to decrease CO_2 emissions by maintaining soil carbon stocks and enhancing soil structure (Kabir et al., 2024). The integration of legumes in crop rotations or intercropping systems reduces greenhouse gas emissions by minimizing the need for synthetic fertilizers. The N-fixing bacteria associated with legumes reduce the reliance on N-based fertilizers, which are major sources of nitrous oxide (N_2O), a potent greenhouse gas. By promoting sustainable practices and enhancing soil health, legumes not only sequester carbon but also provide multiple co-benefits for ecosystems. Their adoption in agricultural landscapes offers a scalable solution to climate change mitigation while supporting global food security and soil sustainability.

4.5 Economic benefits

Legumes, encompassing both grain varieties (e.g., pea, faba bean, lupin, and soybean) and forage types (such as alfalfa, white clover, and red clover), are important crops for enhancing diversity in crop rotations (Jouan et al., 2019). These crops have the capacity to perform well across various agricultural systems in the region, but their broader adoption depends heavily on increased consumer and retailer demand, that effectively is growing (Westhoek et al., 2011; Zander et al., 2016; Squire et al. 2019). However, the cultivation of grain legumes remains limited, covering just 2% of the EU's agricultural area in 2017 (rising to 4% when including forage legumes) (Eurostat, 2018). This limited adoption can be attributed to several factors, such as a focus on a narrow range of crops, stagnant yields, policy decisions, and the undervaluation of legumes' economic benefits at the farm level. Additionally, there is a lack of awareness and difficulty in quantifying the advantages of integrating legumes into cropping systems (Von Richthofen et al., 2006; Cernay et al., 2015; Preissel et al., 2015; Reckling et al., 2016; Zander et al., 2016; Antichi et al., 2023). At the farm level, legumes are often seen as less profitable in the short term compared to crops like wheat or rapeseed. However, this perception can change when pedoclimatic conditions favor legumes (Döring 2015) or in organic farming, where higher margins are possible (Carof et al., 2019; Jouan et al., 2019). At the rotation scale, legumes improve profitability by reducing N fertilizer use and enhancing the yields of subsequent crops (Cernay et al., 2015; Jouan et al., 2019). These benefits, known as "pre-crop effects," include N provision through biological fixation and breaking the continuous cultivation of similar crops (typically cereals), which disrupts disease, weed, and pest cycles (Robson et al., 2002; Kirkegaard et al., 2008; Peoples et al., 2009a; Preissel et al., 2017). This reduction in production costs, partly driven by decreased pesticide use, can enhance farmers' profits and improve income stability (Malézieux et al., 2009; Papendiek et al., 2016). Overall, more diversified agricultural systems that incorporate legumes as a source of N tend to be more sustainable when compared to less diverse systems, particularly in terms of food security and reliance on fossil energy, in addition to their ecological benefits (Papendiek et al., 2016). Moreover, because of the growing demand for plant products, i.e. protein and oils, and to the increased economic and environmental pressures on agro-ecosystems, it emerges that grain legumes would play a major role in future cropping systems. Regarding the feed sector, improved legume pasture and forage species offer significant potential to enhance profitability and reduce risks for producers. These species contribute to higher-quality feed, leading to improved animal growth and reproduction rates, increased farm stocking densities, earlier access to prime livestock markets, and lower costs for supplementary feeding. Additionally, their integration supports better crop rotations and land conservation practices (Thomas et al., 2018; Monjardino et al., 2022). In mixed farming systems, the inclusion of improved legume pastures in rotations can enhance crop yields through benefits such as improved soil fertility and structure, alongside breaks in weed and disease cycles (Angus and Peoples, 2012; Bell and Moore, 2014; McBeath et al., 2015; Monjardino et al., 2022). This approach also adds resilience and value to farm businesses by optimizing cost structures and creating diversified income opportunities (Zull et al., 2017; Ghahramani et al., 2020; Bell et al., 2021; Monjardino et al., 2022). Expanding the market for legumes beyond the food and feed industries offers additional opportunities to enhance their economic value at the crop level. Legumes can be targeted toward premium, high-quality niches, including applications in non-food sectors. For instance, they can serve as renewable resources for biorefineries, as highlighted by Papendiek et al. (2016). Integrating fodder legume production with Green Biorefineries could provide various added advantages. The resulting press cake has multiple applications, such as producing solid fuels fibrous composite materials, or animal feed. Meanwhile, the press juice serves as a valuable fermentation medium for the biochemical industry (Papendiek et al., 2016). Studies on fermentation have demonstrated that press juice from fodder legumes is an excellent alternative to synthetic compounds in established processes like the production of polyhydroxyalkanoates (Davis et al., 2013; Koller et al., 2005). More broadly, Green Biorefinery technologies align with the anticipated growth in non-food industries, which will increasingly depend on renewable raw materials as feedstock (Papendiek et al., 2016). Legumes are often economically undervalued due to insufficient recognition of their broader contributions to cropping systems and their market potential. However, these crops can achieve elevated economic performance, particularly under specific conditions: (i) when N fertilizer use is limited, such as in organic farming systems or water protection zones, (ii) when legume grains have a high market value, as seen with soybean, grains for food production, or those used for local or on-farm animal feeding, (iii) when alternative broadleaf crops are less profitable, and (iv) when grain legumes facilitate effective reduced-tillage practices (Preissel et al., 2017).

4.6 Water management

Water is essential for agricultural production, and effective water management is one of the most pressing challenges in the face of climate change and global population growth (Fang et al., 2023). As water scarcity intensifies and food demand rises, it is crucial to explore solutions that enhance water use efficiency (WUE) while preserving both water quality and crop yields. Crop management strategies that incorporate diversification practices to promote biodiversity, both above and below ground, have been shown to reduce environmental impacts while maintaining productivity (Tamburini et al., 2020). Among these strategies, the inclusion of legumes in monocultures or simplified crop rotations has been extensively studied in agricultural systems (Ditzler et al., 2021). Legumes provide significant ecological and social benefits, improving resource efficiency and sustainability in agroecosystems. Their ability to fix N_2 reduces the need for synthetic N fertilizers, mitigating environmental impacts such as eutrophication and acidification (Xu et al., 2019; Weiner et al., 2024) and preventing surface and groundwater pollution caused by nitrate contamination (Quemada et al., 2013). Integrating legumes into crop rotations, combined with appropriate management practices, can help reduce the environmental impacts of agri-food systems (Ferreira et al., 2021). Cover crops, including legumes, protect soil by improving cohesion and enhancing resistance to erosion through mechanisms such as root entanglement, mucus secretion, and the release of exudates (Pang et al., 2023). These crops are more effective than bare soil at mitigating raindrop impact and preventing sediment loss (Blanco-Canqui et al., 2015). Using legumes as CCs or forage crops is an effective strategy for reducing soil erosion and water runoff (Slim et al., 2011). Their deep root systems allow legumes to access moisture from deeper soil layers, particularly when the topsoil dries out, thus enhancing drought tolerance (Wang et al., 2021; Rajmohan et al., 2025). Legume roots also enhance soil macroporosity, improving infiltration and water retention (Huang et al., 2017; Parvin et al., 2023). However, root system architecture varies by legume genotype, and their drought tolerance and ability to improve WUE depend on their capacity to adapt root morphology under drought stress (Fenta et al., 2014; Bhaskarla et al., 2020; Wang et al., 2021), as well as their ability to activate tolerance mechanisms (Nadeem et al., 2019). Singh et al. (2023) reported that managing summer legume CCs as green manures improves soil physical properties, increases infiltration, facilitates faster water movement into the soil, and enhances water storage capacity. Furthermore, they found that these CCs also reduce evaporation by providing ground cover and contribute to higher soil moisture levels during the growing season of the subsequent crop. Nevertheless, CCs extract water from the soil for their growth, which can reduce the water available for succeeding crops (Garba et al., 2022; Vujić et al., 2021). Additionally, if the biomass of the CCs is low, it may result in increased water loss through evaporation (Chen et al., 2024). The increasing frequency of droughts worldwide presents a significant challenge to agriculture, often leading to reduced crop yields. In this context, perennial legumes hold considerable promise due to their drought tolerance (Fang et al., 2023). Their deep taproots allow them to access water resources that other species cannot reach. Alfalfa (*Medicago sativa* L.), for instance, is commonly cultivated in water-scarce regions due to its ability to access deep soil water through its extensive taproot system (Zhu et al., 2016). Nevertheless, Wang et al. (2021) reported that long-term continuous production of alfalfa leads to significant depletion of soil water. Therefore, crop diversification is essential for effective water management. Li et al. (2023) demonstrated that intercropping legumes, such as alfalfa, with grass cover, such as fescue (*Festuca arundinacea* Schreb.), significantly improves WUE. This approach effectively reduces total water loss by minimizing surface runoff and leaching. However, it is important to carefully choose companion crops to enhance system productivity and achieve balanced water management across the crops (Ren et al., 2019). Overall, legumes offer a highly effective strategy for enhancing the sustainability of agroecosystems. Their capacity to conserve natural resources, promote land biodiversity, and optimize water management practices makes them a crucial component in improving agricultural sustainability.

4.7 Soil health

Soil health is a critical factor in maintaining sustainable agricultural systems and ensuring long-term productivity (Kibblewhite et al., 2008). It encompasses a range of physical, chemical, and biological properties that collectively support plant growth, water retention, and resistance to environmental stressors. Enhancing soil health not only increases the soil's ability to sustain healthy crops but also strengthens its resilience to challenges such as drought, erosion, and degradation (Kopittke et al., 2019). Key aspects of soil health include the protection and stabilization of soil organic carbon (SOC), which improves soil structure, promotes aeration, and increases stability. These improvements enhance water-holding capacity, contributing to drought resistance (Somasundaram et al., 2017), while increased ground cover and root stability help prevent erosion (De Baets et al., 2011). Collectively, these benefits ensure the long-term vitality of the soil, preserving its capacity to sustain agricultural productivity and provide essential ecosystem services. Crop diversification is an effective strategy for combatting soil degradation and boosting resilience in the face of climate change (Yan et al., 2024). Agricultural practices such as land use and crop management influence the dynamics of SOC and soil aggregates (Kumar et al., 2019). Incorporating legumes into crop rotations offers a sustainable alternative to N fertilizer-based systems, enhancing N availability for subsequent crops and improving overall soil fertility. Microbial activity plays a crucial role in soil health, as microorganisms are central to nutrient cycling (Ferreira et al., 2013). Legumes, in particular, foster the formation and stabilization of soil aggregates, which helps protect SOC (Oliveira et al., 2019). Legumes release N-rich exudates that enhance N availability for the soil microbiota, supporting protein synthesis and various stress-mitigation mechanisms (Wobeng et al., 2020). Furthermore, legumes develop cluster roots that mobilize phosphorus more efficiently (Chen et al., 2023; Shane and Lambers, 2005), addressing phosphorus deficiencies in both plants and microorganisms (Yu et al., 2021). Their extensive root growth improves soil structure by creating porosity, facilitating the establishment of root systems for subsequent crops, and ensuring aerobic conditions, even during heavy rainfall (Wobeng et al., 2020). Legume CCs, with their low carbon-to-nitrogen (C:N) ratio residues and high biomass production, stimulate microbial biomass and activity, thereby enhancing soil health and productivity (Khan et al., 2020; Duarte et al., 2024). This is achieved by increasing organic matter content, promoting the formation of stable soil aggregates, and boosting N availability (Kocira et al., 2020). Additionally, legumes improve soil structure by enhancing infiltration rates, reducing soil water evaporation, and increasing soil moisture retention (Blanco-Canqui et al., 2012; Nielsen et al., 2015). Legume CCs used as mulch also increase light reflection due to the lighter color of the soil surface (Kocira et al., 2020), lowering soil temperature and enhancing resource efficiency (Harasim et al., 2020). Indeed, the introduction of forage legumes into crop rotations, which is associated with greater aggregate stability compared to forage grasses (Whittaker et al., 2023), leaves the soil undisturbed, thus providing unparalleled protection from abiotic stresses. This not only strengthens the soil's resilience against environmental challenges but also significantly enhances its ability to recover and thrive, ensuring its long-term vitality and sustaining agricultural productivity for generations to come. Through these mechanisms, legumes play a vital role in enhancing soil health, resilience, and productivity within sustainable agricultural systems.

4.8 Nitrogen fixation

Biological N fixation is a very important process that significantly improves N supply in agricultural systems, especially in legume-based cropping systems. This process occurs due to a symbiotic relationship established between the legume crop and N-fixing bacteria, such as *Rhizobium* species, which convert N_2 into a bioavailable form (ammonium, NH_4^+) that can be utilized by plants (Sinharoy et al., 2024). This mechanism is able, on the one hand, to increase the availability of N in the soil, which is essential for plant growth and development, and, on the other hand, to reduce the dependence on external N inputs. The widespread use of chemical fertilizers has led to several environmental problems, including N leaching, soil acidification, and greenhouse gas emissions, especially N_2O (Parr, 2024). Excessive fertilizer application can also cause nutrient runoff into water bodies, leading to eutrophication, hypoxia, and biodiversity loss in aquatic ecosystems (Sinharoy et al., 2024). From an economic view, fertilizer costs are also one of the main expenses in conventional agriculture. Therefore, minimizing dependence on external N inputs can make agriculture more profitable, directly translating into cost savings for farmers. Accordingly, an increase of the level of fixed N could be achieved by adopting management practices that influence biological N fixation in crop production systems, such as selection of specific legume genotypes, inoculation with effective rhizobia, and use of good agronomic practices and cropping systems (Kebede, 2021). Furthermore, additional N input to the soil can be provided by the decomposition of legume residues, which mainly depends on how their residues are exploited (whether incorporated, totally removed from the field or burned) (Thilakarathna et al., 2016). In general, the use of legume crops in a cropping system, including rotation, intercropping, green manure and legume-enriched pastures, shows significant advantages over sole cropping systems in terms of reduced chemical fertilizer use, GHG emissions and significant and progressive yield increases on subsequent crops (Zemmouri et al., 2022; Del Papa et al., 2024). For example, intercropping of legumes and cereals can offer the opportunity to increase the fixed N supply in a cropping system both in the short term through direct N transfer and in the long term through residue mineralization (Watson et al., 2017). Improved fallows also involve sowing a beneficial legume crop during the fallow period to restore soil fertility and improve subsequent crop productivity (Kebede, 2021). Thus, legumes are considered competitive crops in terms of both environmental and socioeconomic benefits with the potential to be included in modern farming systems, characterized by reduced crop diversity and excessive use of chemical fertilizers inputs (Stagnari et al., 2017). In conclusion, through legume crops, a more sustainable and environmentally friendly approach to N management is adopted through the natural supply of N to the soil. Furthermore, the integration of legumes in cropping systems could help to improve soil organic matter, reduce soil erosion and increase soil microbial diversity, all of which contribute to overall soil health and sustainability (Kebede, 2021). Farmers adopting legume-based systems could reduce input costs while benefiting from improved soil fertility and higher yields associated with biological N fixation (Kebede, 2021). For this reason, promoting biological N fixation in legume-based cropping systems is essential to achieve sustainable, environmentally friendly and cost-effective agricultural practices.

5. Barriers to valorizing legume ecosystem services

Legumes provide a wide range of underutilized ecosystem services that **have significant potential to improve the sustainability and resilience of agricultural systems**. While the ability of legumes to improve soil fertility through N fixation is well known, there is **limited knowledge exploring indirect benefits such as water use efficiency, climate change mitigation, and biodiversity promotion**. The lack of research on these aspects makes it difficult to fully assess the ecological potential of legume crops (Stagnari et al., 2017). Legumes have the potential to improve soil structure through their deep and extensive root systems, which improve water infiltration and retention, especially in arid and semi-arid regions where water scarcity is a major challenge (Kebede, 2021). However, there is **limited research on how pulses specifically contribute to water conservation at large scales and how their inclusion in agroecosystems can limit water stress** during droughts and extreme temperatures. In fact, most current research focuses mainly on yield-related benefits, leaving a gap in understanding the broader ecosystem services provided by legumes, particularly in enhancing climate resilience through crop diversification (Ditzler et al., 2021). Furthermore, the effectiveness of ecosystem services can vary significantly depending on environmental and agronomic management factors, such as cultivation practices and residue management (Meena et al., 2018; Schulz et al., 2020). Indeed, few studies have explored how these variables influence service provision, limiting the understanding of the optimal conditions to maximize ecosystem benefits (Stagnari et al., 2017; Ditzler et al., 2021). Even in the context of biodiversity, there are a limited number of studies directly measuring its impact, limiting the full understanding of the role of legumes in enhancing biodiversity within farming systems (Everwand et al., 2017). Although some studies have explored the effect of legumes on reducing pests and diseases, the results are often contradictory and the mechanisms through which legumes might provide beneficial effects are not well defined (Kaur et al., 2023). It is also worth highlighting the **limited relationship between research and farmers' needs**: farmers adopting innovative practices such as integrating legumes into their cropping systems need practical support in agronomic management and optimizing ecosystem benefits (Mawois et al., 2019). However, research often does not sufficiently address these needs, with most studies focusing on production aspects rather than management issues that farmers face on a daily basis (Magrini et al., 2018). Overall, these gaps suggest that **research on legumes and their ecosystem services is still in its infancy and that further investigation is needed to better understand how legume crops can be optimally used to improve the sustainability and resilience of agricultural systems**. Filling these research gaps will be essential to fully exploit the legume's potential in sustainable agricultural systems, especially in the context of increasing climate variability and water scarcity (Magrini et al., 2018).

As mentioned before in Section 4, legumes provide critical ecosystem services. However, the aforementioned **research gaps remain to be further investigated and linked with several interlinked agronomic-technical, economic, cultural and policy barriers**. Valorizing the underutilized ecosystem services provided by pulses requires a multidisciplinary approach, more farmer incentives, and supportive marketing and policy frameworks. Multidisciplinary research is essential to understand the wide range of ecosystem services provided by legumes, such as improved soil fertility, water retention and pest control, and to develop best practices for their integration into different agroecological systems. Incentive subsidies and financial rewards can encourage farmers to adopt legume-based agroecosystems by offsetting initial costs and providing economic benefits for sustainable practices (Ditzler et al., 2021). Therefore, strong marketing strategies and policy frameworks are needed to promote the benefits of legumes, ensuring that farmers, consumers and policy makers are aware of their ecological and economic advantages. Lastly, by addressing these aspects, we can promote the adoption of legume-based cropping systems and realize their potential for sustainable agriculture.

The transition to legume-based farming systems often faces **technical and agronomic challenges**, hindering the adoption by farmers. A major barrier is the complexity of managing legume-based cropping systems, particularly intercropping systems involving legumes and cereals. For instance, Mamine and Farès (2020) highlighted issues such as the synchronization of growth cycles, competition for resources, and the difficulty of optimizing intercropping for both yield and ecosystem services. Another agronomic issue is the lack of breeding programs tailored to legumes. Many legumes remain under-researched compared to staple crops like wheat and maize. As a result, challenges such as pest and disease resistance, adaptability to varying climatic conditions, and seed quality remain prevalent. Overall, a major impediment to valorizing legume ecosystem services is the limited knowledge about their long-term agroecological impacts. Current research is heavily concentrated on a few legume species—notably peas, clovers, and faba beans—and their immediate production benefits, such as N fixation and yield improvement in subsequent crops. Yet, other vital ecosystem services, such as pest and disease suppression, water regulation, and contributions to biodiversity, are underexplored. This narrow focus limits the understanding of legumes' multifunctionality and their integration into diverse agroecosystems. Moreover, most studies are conducted at plot-level or within-season scales, failing to capture the broader landscape-level effects and long-term benefits of legumes. Such a reductionist approach often overlooks interactions between ecosystem services, resulting in fragmented knowledge that is insufficient for practical application at the farm level. Farmers frequently report a lack of tailored technical guidance for incorporating legumes into their cropping systems, reflecting a gap in research translation and extension services. In addition, the absence of cost-effective technologies for processing legumes reduces their economic potential and limits their appeal in industrial applications. **Economic constraints** also significantly hinder the adoption of legume-inclusive systems. Legumes often have higher establishment costs due to the need for specific seeds (which may not be available at reasonable prices and quantities) and additional machinery. Furthermore, their yields are generally more variable and less predictable compared to conventional cereal or other arable crops, making them less attractive to risk-averse farmers (especially smallholder farmers who are not able to bear high risks). These challenges are exacerbated by the limited market demand for legume products (reported before) and the absence of well-structured value chains to support their commercialization. Another economic barrier is the inadequate monetization of the ecosystem services provided by legumes, despite some progress made in the last CAP. For instance, while N fixation reduces the need for synthetic fertilizers, these cost savings are rarely accounted for monetization schemes. Similarly, the contributions of legumes to biodiversity, carbon sequestration, and soil health are often invisible in current market structures, which predominantly reward yield over sustainability. Farmers, therefore, lack financial incentives to adopt legume-inclusive practices and prioritize crops with higher market demand and stable prices, leaving legumes at a competitive disadvantage. The development of robust legume value chains requires supportive policies and market stability to encourage farmers' participation (Balázs et al., 2021). **Policy frameworks have not adequately supported the adoption of legume-based systems**. The CAP provides subsidies for monocultures but offers no comparable and limited support for intercropped or mixed systems that include legumes. This lack of recognition creates disincentives for farmers, who may risk financial losses or reduced subsidies for adopting diverse cropping systems. Additionally, agri-environmental schemes often fail to account for the multiple ecosystem services provided by legumes, further limiting their appeal. Institutional barriers also arise from poorly integrated value chains. Legume products often face logistical challenges, including inefficient harvest, storage, and processing. For instance, mixed grain-legume harvests require specialized machinery and facilities to separate and store the different components. Without economies of scale, such investments are prohibitively expensive for individual farmers (who are the majority of EU farmers) or small cooperatives. In addition, the absence of robust training and education frameworks for smallholders, such as extension services, creates further gaps that limit farmers' ability to adopt legume-based systems and access resources, training, and markets. Finally, a prevalent barrier across the EU related to the valorization of ecosystem services provided by legumes is linked to **cultural aspects**. Many farmers are reluctant to adopt legume-based systems due to unfamiliarity or perceived risks, often claiming cultural resistance to shifting to agroecological and regenerative farming practices. Consumers, on the other hand, are often reluctant to consume more legumes due to dietary choices favoring other protein-food sources.

In a nutshell, some of the barriers to valorizing legume ecosystem services are described in Table 1.

Table 1: Barriers to valorizing ecosystem services provided by legumes

Barriers to valorizing legume ecosystem services	
Knowledge	Limited awareness of the full range of ecosystem services provided by legumes; lack or insufficient research
Agronomic-Technical	Agronomic and environmental challenges in integrating legumes into existing systems; complex decision-making by farmers; lack of expertise to shift to diversified mixed cropping systems; lack or insufficient machinery and equipment; unstable yields
Economic (market)	Lack or reduced profitability; financial disincentives; higher initial costs for legume establishment; low demand from markets; poorly developed market and value chains; lack of awareness from consumers; noncompetitive market and limited market access
Policy	High-yield target for subsidies compared to diversified systems; lack of monetary incentives
Cultural (social)	Reluctance to adopt new practices/crops; marginalized smallholder farmers; dietary choices

6. Future research directions

To explore the potential of legume derived ecosystem services, a multi-faceted approach that includes research, behavioral, market and policy reforms is required. Researchers should broaden their investigations to **include underrepresented legume species, climate-ready legumes and a wider range of ecosystem services**, considering all available provisioning, regulating and cultural services. Long-term and landscape-level studies are necessary to capture the cumulative and synergistic effects of legumes on agroecosystems. Another field that requires further research is the **quantification of ecosystem services**, highlighting the need for standardized metrics and methodologies to assist the widespread integration of them into diversified farming systems. In addition, the quantification of non-visible benefits like the impact on soil microbiome health is crucial. Among many emerging technologies, **genomics, breeding and biotechnology should be further developed** for enhancing legume traits to optimize ecosystem services. Although technological and research advancements that are lab-based will significantly contribute to the valorization and upscaling of legumes-derived ecosystem services, there is a need to **make research more interdisciplinary and multidisciplinary, as well as open and fair.** For that reason, future research directions also lie in **strengthening extension services and educational-training programs** by providing farmers with accessible technical support and education on legume management is critical. Field demonstrations, farmer-to-farmer knowledge exchange, and tailored advisory services can help bridge the gap between research and practice (Mawois et al., 2019). **Co-creation** is also essential to allow the participation of various stakeholders in the decision-making process through participatory action research or citizen science methodologies. Furthermore, more tailor research is needed at the market structure to develop robust value chains for legume products, including investments in cultivating, processing and storage infrastructure, as well as marketing strategies such as eco-labelling to highlight the environmental benefits of legume-based products. It is noteworthy to mention that fair pricing for sustainably and agroecologically produced legumes could incentivize adoption and consumption, thus necessitating **marketing research** to evaluate various monetization schemes for ecosystem services. To this end, **consumer awareness campaigns** highlighting the ecological and nutritional benefits of legumes could further boost demand. Finally, policy reforms are needed to **design policies that reward ecosystem services provided by legumes**, such as payments for N fixation or carbon sequestration. Their integration could be realized in the context of the next Common Agricultural Policy (CAP) plans of the Member States post 2027, involving payment schemes and incentives to include legume-based intercropping and mixed systems (e.g., agroforestry) to compensate, primarily organic and regenerative, farmers for any production costs and risks.

7. Case studies and best practices

Legumes are included in cropping systems in several ways, often to exploit their ecosystem services. Among the management practices valorizing the ecosystem services should be included: (i) cover crops (e.g., green manure, living mulch, dead mulch), (ii) mixed cropping, rotation, (iii) intercropping (e.g., row intercrop, strip intercrop, relay cropping) (Dietzler et al., 2021). Cover crops enhance soil quality, creating more favorable conditions for the growth, development, and productivity of main crops. Additionally, they play a crucial role in mitigating weed infestations (Amossé et al., 2013; Blanco-Canqui et al., 2015; Kocira et al., 2020). CCs can be utilized in various ways: they may precede the main crop, being crushed, treated with herbicides, ploughed under, or left as dead mulch on the soil surface, where the subsequent crop is sown directly through the mulch. Alternatively, they can be cultivated alongside the main crop as living mulch (Kocira et al., 2020). The use of the legume CCs as green manure is well known (Bàrberi and Mazzoncini, 2001; Bilalis et al., 2009; Abou Chehade et al., 2019; Carlesi et al., 2020; Adeux et al., 2021), especially in the Mediterranean area, where soil erosion and fertility reduction phenomena are exacerbated by climate change. However, innovative practices such as permanent living and dead mulch, needs more attention, mostly in the context of organic and conservative agriculture. Living mulch (LM) systems integrate CCs into cash crop rotations, allowing them to grow together in an intercropping arrangement for at least part of the cash crop's lifecycle. By maintaining continuous soil coverage both temporally and spatially, LM systems have demonstrated the ability to prevent soil erosion, reduce nitrate leaching, improve soil and water quality, and enhance biodiversity across microbial, plant, and animal communities (Sportelli et al., 2022). Leguminous LM systems, in particular, can aid in weed suppression while supporting crop yields, especially in organic arable and vegetable systems, such as relay intercropping. However, their success largely depends on selecting appropriate legume species (Vincent-Caboud et al., 2017; Leoni et al., 2020; Leoni et al., 2022). An effective LM system should minimize competition with the main crop for resources while suppressing weeds (Leoni et al., 2020). For this purpose, legumes suited for LM must exhibit specific morphological, physiological, and phenological traits and be adapted to local conditions. Research has thus focused on identifying and selecting legume varieties with desirable attributes, such as full ground coverage, prostrate growth habits, and low canopy height (Mohammadi, 2012). Studies in countries like the USA, France, and Italy have focused on screening local ecotypes to develop cultivars adapted to specific environments. This selection work primarily involves species from the genera *Trifolium* (e.g., *Trifolium repens*, *Trifolium subterraneum*) and *Medicago* (e.g., annual species like *Medicago lupulina*) (Ocumpaugh et al., 2004; Prosperi et al., 2000; Leoni et al., 2020; Leoni et al., 2022; Leoni et al., 2024). Relay intercropping involves delaying the sowing of a legume into an already established winter cereal (Amossé et al., 2013). While the cereal restricts the legume's growth, this is generally sufficient to suppress weeds. After the cereal harvest, legumes are expected to persist in the field, maintaining soil cover until the subsequent cash crop is sown (Vrignon-Brenas et al., 2016). This practice helps prevent bare soil between cash crops or during the period between cereal harvest and CC establishment (Amossé et al., 2013). Perennial legumes like *Medicago sativa* and *Trifolium repens* can serve both as CCs and forage crops, depending on farmers' needs. When used as forage, they allow earlier establishment, up to nine months before the usual rotation timing, improving land use efficiency and reducing tillage (Leoni et al., 2022). Annual and self-seeding legumes can also fit relay intercropping systems, providing weed suppression as living mulch during the cereal growth phase. These legumes complete their lifecycle alongside the cereal, leaving behind a dense biomass layer that acts as dead mulch until the next crop cycle. Self-seeding legumes, in particular, persist through summer as mulch and re-establish themselves in autumn, offering consistent cover until the next spring crop (Leoni et al., 2022). The suitability of specific legumes, such as *Medicago sativa*, *Medicago lupulina*, *Trifolium repens*, *Trifolium subterraneum*, and *Hedysarum coronarium*, depends on local environmental conditions. When well-matched to local contexts, relay intercropping effectively maintains continuous soil cover, reduces tillage, and enhances weed control without negatively impacting wheat yields (Leoni et al., 2022). Successful application of conservation agriculture systems normally implies the use of winter CCs grown before a spring sown cash crop such as sunflower (*Helianthus annus* L.), maize (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.] or sorghum [*Sorghum bicolor* (L.) Moench], especially in Mediterranean area. When the cash crop is a nonlegume species, one key ecosystem service provided by CC use is N supply. As such, a legume CC (e.g. hairy vetch, *Vicia villosa* Roth) being able to supply an adequate amount of N through symbiotic N_2-fixation, is the optimal choice (Costantini et al. 2020). In organic no-till systems, the major issue is the CC termination, and the alternatives to glyphosate are mechanical or physical means, such as flail choppers, mowers, flame weeders and roller crimpers (Vincent-Caboud et al. 2019). Antichi et al. (2022) in central Italy established an on-farm trial where they tested a roller crimper to terminate a vetch CC at three different vegetative stages (early, intermediate and late respectively) before sunflower cash crop. Although they obtained good results in weed suppression, the timing of termination was crucial; indeed, they observed the better termination rate in late spring; these results were confirmed by Price et al. (2019) in the USA, indeed winter legumes often tend to conclude their cycle late in spring, creating issues with the sowing of the spring crop. However, hairy vetch produces a high amount of biomass, (more than 8 t d m ha^{-1}, Tosti et al., 2012) and thanks to its N-fixing capacity (275 kg N ha^{-1}, Tosti et al., 2014) seems to be a good species to serve as a dead mulch, although studies including generally legume CCs are very scarce. Legumes often produce less biomass than hairy vetch. In contrast, cereals are efficient in resource use, establish rapidly, and generate high-residue biomass that decays slowly (Thapa et al., 2018). Cereal rye (*Secale cereale* L.), in particular, excels in no-till systems for its weed control efficiency (Thapa et al., 2018; Abou Chehade et al., 2019). However, improper management may lead to soil N immobilization or crop injury due to allelochemicals released during decomposition (Wells et al., 2013; Cheade et al., 2023). Combining CCs into mixtures offers a strategy to balance ecosystem services under reduced tillage. Multispecies CCs leverage functional complementarity, enhancing niche differentiation and resource use efficiency (Abou Chehade et al., 2023). Studies highlight the benefits of such mixtures, including overyielding, improved weed suppression (Ranaldo et al., 2019; Tramacere et al., 2024), and better N retention and supply compared to monocultures (Lawson et al., 2015; Finney et al., 2016; Thapa et al., 2018). Simple cereal–legume bicultures are particularly effective and easier to manage than more complex mixtures (Hayden et al., 2012; Hayden et al., 2014; Thapa et al., 2018). These bicultures utilize complementary traits, such as tall, climbing legumes like vetch (*Vicia sp.*) paired with grasses like rye, which have upright canopies and fibrous root systems. Such combinations can outperform monocultures, producing over 60% more biomass and equaling vetch's N contribution (Thapa et al., 2018). Other legumes, such as clovers (*Trifolium* spp.), with their rapid growth and deep, branched taproots, also contribute to weed suppression and soil coverage (Ranaldo et al., 2019). Properly balanced cereal–legume ratios ensure a low residue C:N ratio, facilitating N availability for the cash crop, particularly in low-mineralization conditions typical of no-till systems (Lawson et al., 2015; Radicetti et al., 2016; Cheade et al., 2023).

The following subsections aim to catalogue scientific findings from previously funded Marie Skłodowska-Curie Actions (MSCA) projects, Horizon 2020, and Horizon Europe (HE) projects.

7.1 Legumes related ecosystem services mapped in projects

Tables 2-10, display a list of examples of legumes related ecosystem services mapped from previous or ongoing European projects.

Disclaimers:

- Several legumes (either as pulses and grain legumes, forage or cover crops) are studied from the same project in various studies, thus, all reported ecosystem services are listed;
- Only the most relevant references were selected for further analysis of the legume ecosystem services;
- The purpose is to show the diversity of ecosystem services based on the use of the legume, the experiment, and the conditions.

Table 2: Examples of ecosystem services provided by legumes

Legume ecosystem services			
Pest control	**Pollination**	**Biodiversity conservation**	**Carbon sequestration**
1. Natural pest suppression through insect & microbe interactions	1. Increased genetic diversity of crops	1. Increased plant, microbe and animal diversity	1. Reduction of atmospheric CO_2
2. Increased resilience of cropping systems to pests and diseases	2. Improved crop yields and quality	2. Preservation of native species	2. Mitigation of climate change
3. Reduced use of chemical pesticides	3. Enhanced pollinator diversity	3. Provision of habitats for beneficial insects & other wildlife	3. Increased soil organic matter
Economic benefits	**Water management**	**Soil health**	**Nitrogen fixation**
1. Increased marketability and	1. Improved water quality &	1. Improved soil structure and	1. Enhanced nitrogen supply

competitiveness	availability	stability	
2. Diversification of income sources	2. Increased water-use efficiency in cropping systems	2. Increased water holding capacity	2. Improved plant growth and yield
3. Reduced input costs for farmers	3. Reduced water runoff and erosion	3. Reduced soil erosion	3. Reduced dependence on synthetic nitrogen fertilizers

Table 3: Examples of legume ecosystem services from TRUE Project

Legume	Type									Other ES	Barriers
Trifolium repens	Forage				2				3		Adoption by farmers - low effective, integrated, and successful policy strategies
Vicia faba	Pulse				1				1		Lack of knowledge of best management practices and ambiguity about the usefulness of white and red clover along the knowledge transfer chain in Ireland.
Pisum sativum	Pulse				1				1		
Trifolium pratense	Forage				2				1		
Medicago sativa	Forage				2				1		
Vicia faba	Forage				2				1		
Phaseolus spp.	Forage		2			2			2		
Pisum spp.	Forage		2			2			2		
Vicia spp.	Forage		2			2			2		
Trifolium spp. (living mulch)	Cover crop		1	3	3			1	1	Reduced surface water pollution	The lack of crop varieties optimized for performance and use in combination with clover living- mulches and other green understories is a key inhibitor to uptake; limited options for in-crop management of clover competition against the main cash crop, which can be deployed within a growing season (i.e., not prior to drilling or after harvest); limited options for in-crop management of weeds, especially where poor establishment or post-winter recovery of clover allows weeds ingress to the crop and allows them to gain a foothold.
Vicia faba	Heritage var.		2,3								
*MIX	Green manure				3				3	Improved soil microbial activity & water retention;	

										suppressed weeds	
Phaseolus spp./*Zea mays*	Intercropping								2		Major barriers to uptake of these approaches include: small production unit areas, lack of high yielding varieties, the prevalence of diseases and pests, inadequate markets and value chain capacities (especially after a good season and surplus yield production), shortage of extension services, and the general unaffordability and inaccessibility of agriproducts. Success will require the development of national policies to enhance infrastructural support systems for supply and accessibility of agriproducts, and value chain capacities systems, from rural area input suppliers to consumers.

*MIX = crimson clover (*Trifolium incarnatum* L.), Persian clover (*Trifolium resupinatum* L.), berseem clover (*Trifolium alexandrium* L.), fenugreek (*Trigonella foenum- graecum*), trefoil (*Medicago lupulina* L.), winter vetch (*Vicia sativa*), forage peas (*Pisum sativum* L.) and blue lupins (*Lupinus angustifolius* L.), mixture of vetch and rye (*Secale cereale* L.)

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Suso et al., 2016 - https://doi.org/10.3389/fpls.2016.00333
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Table 4: Examples of legume ecosystem services from PROTEIN2FOOD Project

Legume	Type									Other ES	Barriers
Vicia faba	Pulse	2	3	3		1,2			1		A considerable gap between the measured and modelled soil mineral nitrogen. This gap is likely to be related to differences between the modelled versus measured soil moisture levels. Calibration of the model still resulted in an overestimation of soil mineral nitrogen, but also decreased the estimated amount of nitrogen fixation by the crops. This is due to the parameter in the model, which estimates the threshold level of soil mineral N below which all nitrogen is fixated.
Lupinus albus	Pulse		3	3		1,2			1		
Lupinus angustifolius	Pulse		3	3		1,2			1		
Pisum sativum	Pulse	2				1,2			1,3		The most difficult factors to control in field trials are the environmental conditions (weather, pests and diseases, soil conditions). High variations of environmental factors reduce the consistency of results.
Vicia lens	Pulse	2				1,2			1,3	Weed suppression	

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Vogelsang-O'Dwyer et al., 2020 - https://doi.org/10.3390/foods9020230

Table 5: Examples of legume ecosystem services from ReMIX Project

Legume	Type									Other ES	Barriers
Arachis hypogaea	Pulse					1,2			1,2		
Vicia lens	Pulse					1,2			1,3		Factors that can influence intercrop performances, such as the type of combine harvester and traits of lentil cultivars that can affect mechanical harvest efficiency. Furthermore, questions remain about how to reduce the cost of grain cleaning and sorting tools, which would increase economic performance of intercrops. Effective biocontrol methods and lentil cultivars tolerant to bruchids are still needed, as bruchids greatly decrease lentil yield in organic farming
Pisum sativum	Pulse	2				1,2	2	1	1,2	Limit weed development	
Vicia faba	Pulse	2				1,2			1,2,3		Diverse farming requires diverse knowledge and skills: farmers lack support due to limited research, education and advisory services on diverse farming; Farmers' experience is that legislation is insufficient to meet their needs as diverse farms; the improvements in breeds and varieties are not developed for multifunctionality
Medicago sativa	Forage	2			3	1,2		1	1,2	Limit weed development	
Glycine max	Pulse					1	2		2,3		

References

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(lentil) Loic et al., 2018 - https://doi.org/10.1007/s13593-018-0515-5 ; Verret et al., 2020 - https://doi.org/10.1016/j.eja.2020.126018 ; Justes et al., 2021 - https://doi.org/10.15302/j-fase-2021414

(pea) Pankou et al., 2021 - https://doi.org/10.15835/nbha49412488 ; Verret et al., 2020 - https://doi.org/10.1016/j.eja.2020.126018 ; Aare et al., 2021 https://doi.org/10.1016/j.agsy.2021.103053 ; Annicchiarico et al., 2021 - https://doi.org/10.3389/fpls.2021.731949 ; Jensen et al., 2020 - https://doi.org/10.7764/ijanr.v47i3.2241 . Conference proceedings: Dhamala et al., 2021 - Intercropping of oat and pea to address field-scale soil heterogeneity ; Mikò et al., 2021 - Selection of Winter Cereals for Cereal-pea Mixtures to Improve Biodiversity and LER.
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DIVERSify

Table 6: Examples of legume ecosystem services from DIVERSify Project

Legume	Type									Other ES	Barriers
Lupinus sp.	Pulse								3		
Vicia faba	Pulse					2			1	Increasing crop diversification and biodiversity	The intercropping wheat-faba bean showed issues in processing of two different production chains that does not allow a positive feeling regarding these crops by farmers.
Pisum sativum	Pulse					2			1		
Trifolium repens	Cover crop								1		
Phaseolus coccineus	Pulse					2			2		*Phaseolus coccineus* beans have shown reduced yields in large-scale Phaseolus-maize intercropping systems. This has been attributed to competition for air circulation (leading to increased pathogen pressure due to higher humidity and stagnant air in the inner parts of the field) and a lack of pollinators in those areas. Since *P. coccineus* beans rely on insect pollination, it was suggested that pollinators tend to avoid flying into the densely vegetated, narrow, and structurally complex inner zones, focusing instead on the outer rows of the mixed-culture field.
Lotus	Cover crop	2							1	Increasing crop diversification and biodiversity	

corniculatus											
Trifolium repens	Cover crop	2							1	Increasing crop diversification and biodiversity	
Trifolium pratense	Cover crop	2							1	Increasing crop diversification and biodiversity	
Desmodium uncinatum	Cover crop									Allelochemicals released into the soil stimulate germination of parasitic plant when the host plant is not present (suicidal germination)	
Vicia villosa	Cover crop	2							1	Increasing crop diversification and biodiversity	
Vicia sativa	Cover crop	2							1	Increasing crop diversification and biodiversity	
Trigonella foenum-graecum	Cover crop	2							1	Increasing crop diversification and biodiversity	
Lens culinaris	Cover crop	2							1	Increasing crop diversification and biodiversity	
Vicia faba	Pulse	2									
Trifolium squarrosum	Forage									Reduced water demand	

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Table 7: Examples of legume ecosystem services from Legumes Translated Project

Legume	Type									Other ES	Barriers
Trifolium spp.	Forage		3								

Trifolium incarnatum	Forage		3								
Trifolium pratense	Forage		3								
Vicia faba	Forage		3								
Medicago sativa	Forage					3		1	1	Enhanced nutrient uptake from deeper layer of the soil	
Lupinus sp.	Forage								1	Reduced water demand	
Medicago sativa	Forage								3		
Vicia faba	Pulse								2	Reduce the environmental impact of crop rotation	
Pisum sativum	Pulse								2,3		
Phaseolus vulgaris	Pulse								2		
Glycine max	Pulse							1	1		
Vicia faba	Pulse			1					3		
Pisum sativum	Pulse			1					3		
Vicia faba	Pulse								2,3		The effects of grain legumes as pre-crop depend on the rotations in which they are introduced and are highest in cereal-dominated rotations
Pisum sativum	Pulse								2,3		

References

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IWMPRAISE

Table 8: Examples of legume ecosystem services from Legumes IWMPRAISE Project

Legume	Type									Other ES	Barriers
Medicago sativa	Cover crop								1,3	Higher gross margin, weed suppression	
Trifolium repens	Cover crop								1,3	Higher gross margin, weed suppression	
Hedysarum coronarium	Cover crop								1,3	Higher gross margin, weed suppression	
Trifolium incarnatum	Cover crop										Residues promoted grass weeds growth
Trifolium resupinatum	Cover crop									Higher gross margin, weed suppression	Reduced weed biomass during the intercropping period however, residues in the following spring supported weed growth (especially grass species)
Trifolium subterraneum	Cover crop								1,3		
Trifolium repens	Cover crop									Soil cover and weed suppression	
Lotus cornicolatus	Cover crop									Soil cover and weed suppression	
Trifolium repens	Cover crop									Soil cover and weed suppression	
Trifolium subterraneum	Cover crop									Soil cover and weed suppression	
Medicago polymopha	Cover crop									Soil cover and weed suppression	
Medicago spp.	Cover crop								1		
Vicia faba	Cover crop								1		
Trifolium repens	Cover crop								1		
Medicago sativa	Cover crop								3	Soil cover and weed suppression	

Trifolium repens	Cover crop								3	Soil cover and weed suppression	
Medicago lupulina	Cover crop								3	Soil cover and weed suppression	
Hedysarum coronarium	Cover crop								3	Soil cover and weed suppression	
Trifolium subterraneum	Cover crop								3	Soil cover and weed suppression	
Trifolium resupinatum	Cover crop								3	Soil cover and weed suppression	Boosted weed growth in the following spring
Vicia villosa	Cover crop								3	Soil cover and weed suppression	Boosted weed growth in the following spring
Medicago truncatula	Cover crop								3	Soil cover and weed suppression	Boosted weed growth in the following spring
Medicago scutellata	Cover crop								3	Soil cover and weed suppression	Boosted weed growth in the following spring
Vicia villosa	Cover crop								3	Soil cover and weed suppression	

References

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Table 9: Examples of legume ecosystem services from Legumes AGROMIX Project

Legume	Type									Other ES	Barriers
Hedysarum coronarium	Forage								1,3		
Hedysarum coronarium	Forage			1					2,3		

References

https://doi.org/10.3390/agronomy13071761 ; https://doi.org/10.1007/s10457-024-01012-8

Table 10: Examples of legume ecosystem services from Legumes DiverIMPACTS Project

Legume	Type									Other ES	Barriers
Vicia faba	Pulse					3			3		
Pisum sativum	Pulse					3			3	Increase in protein intake in the cows' diet	
Glycine max	Pulse								1		
Trifolium alexandrinum	Cover crop	3							1	Enhanced soil cover and weed suppression	
Vicia faba	Cover crop	3							1	Enhanced soil cover and weed suppression	
Pisum sativum	Cover crop								1,2	Weed suppression	
Pisum sativum	Pulse	1									
Pisum sativum	Pulse								2		
Pisum sativum	Pulse									Enhanced protein content in mixture crop	

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7.2 EU-funded projects from CORDIS

An initial search of EU-funded and national projects conducting research on legumes and their related ecosystem services was carried out in CORDIS in autumn 2024. The results showed that there are more than 50 implemented or ongoing projects that include experimentation or analysis on legumes and ecosystem services. The exhaustive list of projects is provided in Table 11.

Table 11: List of implemented or ongoing projects that include experimentation or analysis on legumes and ecosystem services

Acronym	Project title	Duration	CORDIS link	Project website
Marie Skłodowska-Curie Actions (MSCA) projects				
FITTER	Friends with benefits – the role of endophytic bacteria in legume nodules containing nitrogen-fixing rhizobia	2023-2025	https://cordis.europa.eu/project/id/101063271	
MYCOBEANS	EXPLORING (EMERGING) MYCOTOXINS RISK IN BEANS: A GLOBAL ALLIANCE FOR CLIMATE CHANGE RESILIENCE – MYCOBEANS	2024-2027	https://cordis.europa.eu/project/id/101131125	
FeSYM	Cytosolic Iron Delivery for Symbiotic Nitrogen Fixation	2024-2025	https://cordis.europa.eu/project/id/101103149	
LegumeLegacy	LegumeLegacy – Optimising multiple benefits of grass, legume and herb mixtures in crop rotations: modelling mechanisms and legacy effects	2023-2027	https://cordis.europa.eu/project/id/101072579	https://legumelegacy.scss.tcd.ie/
SYM-EFFECT	Enhancing Nitrogen-Fixing Symbiosis in Crops using Rhizobia Bacterial Effectors	2025-2026	https://cordis.europa.eu/project/id/101149917	
GLDAFRICA	GLOBAL BIODIVERSITY LEGUME ASSESSMENTS IN AFRICA: WEST CENTRAL AFRICA AS A CASE STUDY	2015-2017	https://cordis.europa.eu/project/id/659152	
TRITRONITRO	UNDERSTANDING TRITROPHIC INTERACTIONS: PLANT-MICROBE-INSECT. ITS IMPLICATION ON INTEGRATED PLANT PROTECTION AND BIOLOGICAL NITROGEN FIXATION OF LEGUMES	2019-2021	https://cordis.europa.eu/project/id/793707	

Acronym	Project title	Duration	CORDIS link	Project website
FAB	Functional Agricultural Biodiversity: Optimising ecosystem service provision via functional agricultural biodiversity	2019-2022	https://cordis.europa.eu/project/id/841952	
Horizon 2020 projects				
LIFT	Low-Input Farming and Territories - Integrating knowledge for improving ecosystem-based farming	2018-2022	https://cordis.europa.eu/project/id/770747	https://www.lift-h2020.eu/
LIVESEED	Improve performance of organic agriculture by boosting organic seed and plant breeding efforts across Europe	2017-2021	https://cordis.europa.eu/project/id/727230	https://www.liveseed.eu/
Diverfarming	Crop diversification and low-input farming across Europe: from practitioners' engagement and ecosystems services to increased revenues and chain organisation	2017-2022	https://cordis.europa.eu/project/id/728003	http://www.diverfarming.eu/index.php/en/
DIVINFOOD	Co-constructing interactive short and mid-tier food chains to value agrobiodiversity in healthy plant-based food	2022-2027	https://cordis.europa.eu/project/id/101000383	
DIVERSIFOOD	Embedding crop diversity and networking for local high quality food systems	2015-2019	https://cordis.europa.eu/project/id/633571	https://diversifood.eu/
LEGVALUE	Fostering sustainable legume-based farming systems and agri-feed and food chains in the EU	2017-2021	https://cordis.europa.eu/project/id/727672	https://www.legumehub.eu/legvalue/
DIVERSify	Designing InnoVative plant teams for Ecosystem Resilience and agricultural Sustainability	2017-2021	https://cordis.europa.eu/project/id/727284	https://plant-teams.org/
TRUE	Transition paths to sustainable legume-based systems in Europe	2017-2021	https://cordis.europa.eu/project/id/727973	https://true-project.webarchive.hutton.ac.uk/index.htm

Acronym	Project title	Duration	CORDIS link	Project website
INCREASE	Intelligent Collections of Food Legumes Genetic Resources for European Agrofood Systems	2020-2026	https://cordis.europa.eu/project/id/862862	https://www.pulsesincrease.eu/
Legumes Translated	Translating knowledge for legume-based farming for feed and food systems.	2018-2022	https://cordis.europa.eu/project/id/817634	https://www.legumestranslated.eu/
EUCLEG	Breeding forage and grain legumes to increase EU's and China's protein self-sufficiency	2017-2021	https://cordis.europa.eu/project/id/727312	http://www.eucleg.eu/
PROTEIN2FOOD	Development of high quality food protein through sustainable production and processing	2015-2020	https://cordis.europa.eu/project/id/635727	
ReMIX	Redesigning European cropping systems based on species MIXtures	2017-2021	https://cordis.europa.eu/project/id/727217	https://www.remix-intercrops.eu/
DiverIMPACTS	Diversification through Rotation, Intercropping, Multiple cropping, Promoted with Actors and value-Chains Towards Sustainability	2017-2022	https://cordis.europa.eu/project/id/727482	https://www.diverimpacts.net/index.html
IWMPRAISE	Integrated Weed Management: PRActical Implementation and Solutions for Europe	2017-2022	https://cordis.europa.eu/project/id/727321	https://iwmpraise.eu/
AGROMIX	AGROforestry and MIXed farming systems - Participatory research to drive the transition to a resilient and efficient land use in Europe	2020-2024	https://cordis.europa.eu/project/id/862993	https://agromixproject.eu/
SUPER-G	Developing SUstainable PERmanent Grassland systems and policies	2018-2024	https://cordis.europa.eu/project/id/774124	https://www.super-g.eu/
CORE Organic Cofund	Coordination of European Transnational Research in Organic Food and Farming Systems Cofund	2016-2022	https://cordis.europa.eu/project/id/727495	https://projects.au.dk/coreorganiccofund
RADIANT	ReAlising DynamIc vAlue chaiNs for underuTilised crops	2021-2025	https://cordis.europa.eu	https://www.radiantproject.eu/

Acronym	Project title	Duration	CORDIS link	Project website
			/project/id/101000622	
UNISECO	Understanding and improving the sustainability of agro-ecological farming systems in the EU	2018-2021	https://cordis.europa.eu/project/id/773901	https://uniseco-project.eu/
SMART PROTEIN	Smart Protein for a Changing World. Future-proof alternative terrestrial protein sources for human nutrition encouraging environment regeneration, processing feasibility and consumer trust and acceptance	2020-2024	https://cordis.europa.eu/project/id/862957	https://smartproteinproject.eu/
SolACE	Solutions for improving Agroecosystem and Crop Efficiency for water and nutrient use	2017-2022	https://cordis.europa.eu/project/id/727247	https://www.solace-eu.net/index.html
AE4EU	Agroecology for Europe	2021-2023	https://cordis.europa.eu/project/id/101000478	https://www.ae4eu.eu/
EcoStack	Stacking of ecosystem services: mechanisms and interactions for optimal crop protection, pollination enhancement, and productivity	2018-2024	https://cordis.europa.eu/project/id/773554	https://ecostack-h2020.eu/
ESMERALDA	Enhancing ecoSysteM sERvices mApping for poLicy and Decision mAking	2015-2018	https://cordis.europa.eu/project/id/642007	http://www.esmeralda-project.eu/
Horizon Europe projects				
LEGUMES	Valorising and balancing the ecosystem service benefits offered by legumes, and legume-based cropped systems	2024-2027	https://legumesproject.eu/	https://legumesproject.eu/
Legume generation	Boosting innovation in breeding for the next generation of legume crops for Europe	2023-2028	https://www.legumegeneration.eu/	https://www.legumegeneration.eu/
LEGENDARY	KnowLEdGE creation and iNcreasing acreage of legumes in	2024-2028	https://www.legendaryp	https://www.legendaryproject.

Acronym	Project title	Duration	CORDIS link	Project website
	Diversified cropping systems by quAntification of theiR ecosYstem services.		roject.eu/	eu/
LEGUMINOSE	Legume-cereal intercropping for sustainable agriculture across Europe	2022-2026	https://www.leguminose.eu/	https://www.leguminose.eu/
BELIS	Breeding European Legumes for Increased Sustainability	2023-2028	http://www.belisproject.eu/	http://www.belisproject.eu/
VALPRO Path	new VALue landscapes for plant PROtein Pathways	2022-2026	https://valpropath.eu/	https://valpropath.eu/
Root2RES	Root2Resilience: Root phenotyping and genetic improvement for rotational crops resilient to environmental change	2022-2027	https://root2res.eu/	https://root2res.eu/
OrganicYieldsUP	Improving yields in organic cropping systems	2024-2028	https://www.organicyieldsup.eu/	https://www.organicyieldsup.eu/
Climate Farm Demo	A EUROPEAN-WIDE NETWORK OF PILOT FARMERS IMPLEMENTING AND DEMONSTRATING CLIMATE SMART SOLUTIONS FOR A CARBON NEUTRAL EUROPE	2022-2029	https://climatefarmdemo.eu/	https://climatefarmdemo.eu/
Agroecology-TRANSECT	Trans-disciplinary approaches for systemic economic, ecological and climate change transitions	2022-2026	https://www.agroecology-transect.net/	https://www.agroecology-transect.net/
IntercropValuES	Developing Intercropping for agrifood Value chains and Ecosystem Services delivery in Europe and Southern countries	2022-2026	https://intercropvalues.eu/	https://intercropvalues.eu/
ECONUTRI	Innovative concepts and technologies for ECOlogically sustainable NUTRIent management in agriculture aiming to prevent, mitigate and eliminate pollution in soils, water and air	2022-2026	https://econutri-project.eu/	https://econutri-project.eu/

Acronym	Project title	Duration	CORDIS link	Project website
Grazing4AgroEcology	European Network to promote grazing and to support grazing-based farms on their economic and ecologic performances as well as on animal welfare	2022-2026	https://grazing4agroecology.eu/	https://grazing4agroecology.eu/
BIOservicES	LINKING SOIL BIODIVERSITY AND ECOSYSTEM FUNCTIONS AND SERVICES IN DIFFERENT LAND USES: FROM THE IDENTIFICATION OF DRIVERS, PRESSURES AND CLIMATE CHANGE RESILIENCE TO THEIR ECONOMIC VALUATION	2023-2028	https://bioservices.co/	https://bioservices.co/
AgroServ	Integrated SERvices supporting a sustainable AGROecological transition	2022-2027	https://agroserv.eu/	https://agroserv.eu/
CANALLS	Driving agroecological transitions in the humid tropics of Central and Eastern Africa through traNsdisciplinary Agroecology Living LabS (CANALLS)	2023-2026	https://www.canalls-project.eu/	https://www.canalls-project.eu/
GUARDEN	safeGUARDing biodivErsity aNd critical ecosystem services across sectors and scales	2022-2025		
URBANE	One Health approaches to support agroecological transformation of peri-urban farming	2022-2026	https://urbane-project.eu/wp-urbane/	https://urbane-project.eu/wp-urbane/
CIRAWA	Agro-ecological strategies for resilient farming in West Africa	2023-2027	https://cirawa.eu/	https://cirawa.eu/

8. Conclusion

Legumes offer multifaceted benefits, ranging from improving soil health and biodiversity conservation to mitigating climate change and supporting food security. Their unique ability to fix N reduces reliance on synthetic fertilizers, simultaneously enhancing soil fertility. Furthermore, legumes bolster agroecosystem resilience through natural pest control, pollination support, and water management among many ecosystem services. Despite these advantages, the underutilization of legumes persists due to economic, technical, and policy-related barriers. Limited awareness, inadequate research on their ecosystem services, and weak market infrastructure hinder widespread adoption. Overcoming these challenges demands a holistic approach, combining research innovations, farmer education, supportive policy frameworks, and robust market strategies.

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