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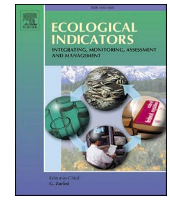

Review

Integrating ecosystem services provided by legumes in agricultural life cycle assessment (LCA): A review of methodologies

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ABSTRACT

Agricultural production is endangering agroecosystems health and functioning, compromising the delivery of many ecosystem services (ES) to prioritize provisioning. Legumes' inclusion in cropping systems appears as a promising solution towards the ecological intensification of agriculture in Europe, providing a multiplicity of ES. Agricultural Life Cycle Assessment (LCA) does not explicitly assess ES; however, the potential benefits offered by an improved representation of agroecosystem processes reveal an urgent need for ES integration into LCA.

Through a systematic review of scientific literature, we collected a list of methods applied to assess legumes ES in European conditions. Methods were grouped following the Common International Classification of Ecosystem Services (CICES) and through general ES definitions. At the end of the process, 148 methods were found, of which: 81.8% were associated with Regulation & Maintenance services; 8.1% to Provisioning services; and 10.1% described methods related to the combination of different CICES sections. No methods for Cultural services were found. Most of the methods were based on direct measurements, except for those ES already part of the current LCA frameworks. The Regulation & Maintenance section is the area with the most fragmented knowledge, with some ES presenting well-established methodologies (e.g. climate change buffering and leaching regulation) and others which are currently not fully integrated into LCA, such as biodiversity maintenance, pest control, and pollination.

Future research should focus on LCA methodologies for the integration of emerging agriculture-related ES. Achieving more comprehensive LCA is necessary to improve the understanding of legumes' role in maintaining agroecosystems functionality.

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1. Introduction

Globally, the economic value of Ecosystem Services (ES) provided by each hectare of agricultural land is estimated to be about 17,360 int$ 2020 (US dollar purchasing power in 2020) ha^{-1} y^{-1} on average (Brander et al., 2024), and human well-being relies directly or indirectly on these services (MA, 2005). Agroecosystems, being highly managed ecosystems, affect and depend on a wide range of ES to provide food, feed, fibres and other materials (Power, 2010). Agricultural intensification during the past decades exacerbated the trade-offs between feed- and food-production and other ES, replacing biological functions typically provided by the ecosystem with fertilizers, pesticides and external inputs, resulting in highly fragile productive systems (Bommarco et al., 2013). Such intensification has been intrinsically linked to the simplification of crop rotations and the adoption of monocultures, which currently prevail in agricultural landscapes (Mortensen and Smith, 2020). The over-specialization of agricultural systems, mainly driven by market pressures, made cereal monocropping relatively more favourable compared to other crops, such as legumes (Zander et al., 2016). However, the value of non-marketed outputs provided by a diversified agroecosystem is often underestimated and can lead to significantly different outcomes for the sustainability of the productive system (Reckling et al., 2016b; Alcon et al., 2024). When exploring the possible pathways to the diversification of the agri-food system, the inclusion of legumes in cropping systems seems to be indispensable, due to their multifunctional role and the multiplicity of benefits they provide (e.g. biological N fixation, climate change buffering, and biodiversity enhancement) (Stagnari et al., 2017; Ferreira et al., 2021).

Legumes represent a large group of crops, able to carry out biological N fixation (BNF) from the atmosphere in symbiosis with *Rhizobium* bacteria (Crews and Peoples, 2004). The decline of these crops in the past decades corresponded to the intensification of agriculture which has been based, among other factors, on the increase of mineral N fertilizer inputs (Crews and Peoples, 2004). Nitrogen supply through BNF by legume crops is often associated with lower GHG emissions when compared to mineral fertilizers (Goglio et al., 2018b; Jensen et al., 2020; Zhang et al., 2024). Strategies for legumes inclusion in crop rotations (e.g. cover cropping, green manuring, intercropping) provide a series of pre-crop benefits, including increasing the yield potential and the nutrient use efficiency on the subsequent crop, and leading to a pest, weed and disease break in the rotation when compared to mono-crops (Preissel et al., 2015; St. Luce et al., 2015; Pelzer et al., 2017). When properly integrated into the cropping system, legumes can provide positive outcomes on soil quality, such as preserving soil organic C (SOC) stocks and enhancing the soil physical and biological properties (Duchene et al., 2017; King and Blesh, 2018; Liu et al., 2023). Besides soil fertility benefits, legume crop reintroduction in the European cropping systems contributes to crop diversification improving the heterogeneity of agricultural landscapes (Nemecek et al., 2015), which has been demonstrated to have a significant impact in the maintenance of multitrophic biodiversity in agricultural contexts (Sirami et al., 2019; Tscharntke et al., 2021). Further, legume crops produce a particularly protein-rich pollen and nectar, which makes them an important nutrient source for wild pollinators, increasing feeding grounds for these species within agricultural systems (Cole et al., 2022).

Legumes also produce good quality dietary protein and are among the products with the lowest GHG emissions for 100 g of protein produced, making them a suitable and more sustainable alternative to meat in human diets (Poore and Nemecek, 2018; Semba et al., 2021). The beneficial effects of legumes crop for the agri-food-system are well aligned with the objectives of the EU Green Deal; this is particularly evident in the EU Strategy Farm to Fork and the EU Biodiversity Strategy 2030 (Bouwma et al., 2018; European Commission, 2020a, 2020b). Environmental benefits of leguminous crops are evident from the large number of Life Cycle Assessment (LCA) studies focusing on legumes and legume-based crop rotations (Costa et al., 2020). LCA is a highly effective tool for evaluating the environmental burdens of many kind of products, but representing crop rotations and interactions into agricultural LCA requires complex and holistic approaches (Goglio et al., 2018a; Costa et al., 2020). Although LCA studies have already demonstrated that crop diversification through legume crops is environmentally favorable (Nemecek et al., 2015), a more comprehensive approach should aim to account for ES within LCA. Despite the extensive body of research on the ES provided by legumes, there remains a disparity in the attention given to different services, with some being extensively studied while others are rather neglected (Ditzler et al., 2021). Explicitly assessing ES into LCA would provide useful insights for the development of future strategies towards a more sustainable agricultural system in Europe and for the monitoring of sustainability objectives (Bouwma et al., 2018; Soldati et al., 2023).

Since the first classification of ES proposed by the Millennium Ecosystem Assessment (MA, 2005) many categorization frameworks have been proposed for ES, such as: The Economics of Ecosystems and Biodiversity (TEEB), the one proposed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Common International Classification of Ecosystem Services (CICES) proposed by the European Environment Agency (De Groot et al., 2010; IPBES et al., 2019; Haines-Young, 2023). Modern Life Cycle Impact Assessment (LCIA) frameworks are already addressing ecosystem quality and the potential biodiversity loss, albeit with different levels of detail (Huijbregts et al., 2017; Bulle et al., 2019; Verones et al., 2020). Current research is now focusing on the integration of ES into LCA, through the improvement of the existing life cycle impact assessment (LCIA) categories or the development of entirely new impact categories (Alejandre et al., 2019; Rugani et al., 2019; De Luca Peña et al., 2022; Hardaker et al., 2022). Few case studies of ES-LCA integration in agricultural contexts have been carried out (Liu et al., 2020; Silva et al., 2024; Taelman et al., 2024; Martínez-García et al., 2025), and all of them highlighted the importance as well as the positive outcomes, of including ES benefits in LCA. Regardless of which solution can better represent ES into LCIA frameworks, gathering knowledge on how ES provided by legumes can be quantified or modelled, classifying them in an international reference framework, is a necessary step to achieve an ES-LCA integration. For this purpose, we selected the CICESv5.2 as a reference system (Haines-Young, 2023), since it provides a structured and comprehensive framework as well as comparison tables with the other main ES classification systems (Haines-Young, 2023). This research aims to: i) identify current ES methods employed in LCA of legume-based cropping systems in Europe; ii) establish which ES requires further methodological development, in order to integrate them into LCA studies; and iii) define a recommendation set for research development of ES metrics to be integrated with LCA of legume-based cropping systems and products, advancing the methodology for assessing the sustainability of European agricultural systems.

2. Review framework

We carried out a systematic review of scientific peer-reviewed literature addressing ES and LCA of legumes and legume-based cropping systems, extracting data on the applied methods to assess ES delivery by legumes. All the papers assessing ES from legumes have been read in full, and the applied methods were collected and classified. The review was carried out in three steps: i) scientific literature search and screening; ii) methods collection and classification; iii) data analysis and visualization.

2.1. Scientific literature search and screening

The literature search was conducted following the PRISMA approach, adapted from Page et al., (2021). Different keywords related to ES, LCA and legumes were combined through the Boolean operators “and” and “or”. More details on the search criteria and the PRISMA flow diagram (Fig. 1) can be found in Supplementary material 1. The publication time horizon has been narrowed to the period of 2004–2024. Since previous research (Tancoigne et al., 2014) showed that exponential growth in the adoption of the term 'ecosystem service' started only after the publication of the Millenium Ecosystem Assessment (MA, 2005), we considered this narrowing reasonable for the scope of our review. Different search engines were employed for the literature search: Web of Science, Scopus and Google Scholar. The search keywords (Supplementary material 1) were defined during six workshops involving experts in various fields, including life cycle assessment, legumes, legume value chain, ecosystem services, and environmental economics. Only peer-reviewed papers were retained, while reports in other languages than English were excluded. In addition to the scientific search engines, other sources of literature search were used, namely: i) papers provided by the experts; and ii) reporting materials, and papers, from previous European projects focusing on related topics (Supplementary material 1). Results from previous EU projects were explored from https://cordis.europa.eu/ (EC, 2024) or in the EU funded projects' websites. At the end of the process, 1834 papers were identified for further analysis.

Duplicates were removed from the article list. Then, the following criteria of exclusion have been applied to the collected papers, consistently with the scope of the review: i) no legumes involved; or ii) discussion paper on ES without operational definitions; or iii) source not focusing on Europe or not including mediterranean conditions on other continents. Within this article, we define "operational definitions" as a series of indications and method descriptions which can allow other scientists and practitioners to use and apply the methods as described in the referenced literature. Cited bibliography from relevant review papers was also included if not already listed. At the end of the screening procedure a total of 202 sources have been read in full, and general bibliographic data were collected in a spreadsheet, namely: title, authors list, year of publication, DOI, keyword combination and source search engine.

2.2. Methods collection and classification

All the selected papers were read in full, and the applied methods were retrieved and classified. Methods were grouped by general ES names (e.g. BNF, Pollination, Weed suppression) and the CICES v5.2 (Haines-Young, 2023). A preliminary screening of relevant CICES classes for legume and legume-based cropping system was done, and other classes were included in the list when new methods were found.

We refer as a "method" to any procedure aimed at giving a quantitative or qualitative evaluation of ES provided by legumes (e.g., direct observations, sampling procedures, models) applied both in field experiments and other assessments (e.g., LCA). For the methods collection, we considered that one paper could contain just one method or many different methods, depending on the topic and the complexity of the study. All the methods were considered potentially related to multiple ES indicators and CICES classes. Complex indicators underlying different metrics for ES were broken down when possible, and the disaggregated methods were included in the list. Once the list was completed, we distinguished methods between those requiring direct observations (observation method) and those based on estimations (estimation method). Observed values usually require a field experiment or lab analysis, while the estimation methods are based on factors (e.g., soil type, geographical area, weather data, management parameters), which are not directly measured. Metrics and indicators which underlie direct measurements were considered observations.

Once data collection was completed, a final refinement was carried out. For all the identified methods, the source paper which best describes the method was identified. Finally, all equivalent methods (based on the same principles and instruments) have been merged, maintaining the original paper source and all the studies applying that specific method.

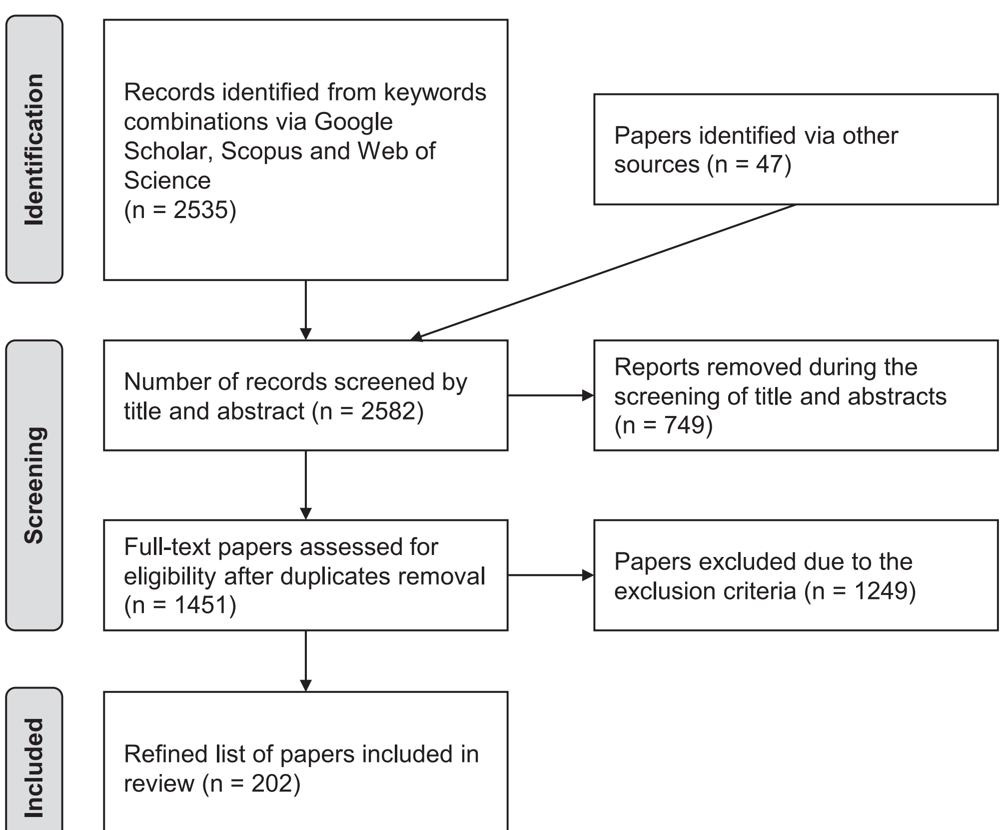

Fig. 1. PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) flow diagram adopted in the search and screening phases.

2.3. Data analysis and visualization

In the Results section, we describe the methods and the source papers in detail. A comprehensive list of all methods, along with the corresponding reviewed papers citing each method, is available in Supplementary Material 2. Descriptive statistics and bar plots were used to present information on the methods available to assess ES delivered by legumes in cropping systems. In the Results, the CICES class and the general ES classification were presented separately, as the two different classifications were not always compatible, while the CICES section of ES – Provisioning, Regulation & Maintenance, or Cultural – was always reported.

The collected list of methods for assessing ES provided by legumes were applied in different kinds of environmental assessments. Most of the sources were agronomic field experiments assessing ES and LCA of cropping systems and agricultural products. Hence, not all the methods are suitable for LCA integration, and the possibility of their application in agricultural LCA will be evaluated in the Discussion.

3. Results

At the end of the method compilation process, a total of 148 methods for ES were collected, and a complete list of the methods can be found in Supplementary Material 2. Most of the methods (81.8 %) were categorized within the Regulation & Maintenance section, which is also the broadest category of CICES in terms of ES fluxes. A lower number of methods (8.1 %) were found for provisioning services, and a similar number of methods (8.8 %) was related to the combination of Provisioning + Regulation & Maintenance services. No methods were found for Cultural services. The only few methods (1.4 %) assessing Cultural services were always combining them with other CICES sections.

In total, we found methods for 13 CICES classes referred to legumes ES, 4 of them were always combined to other classes in the list, and a total of 9 combinations of CICES classes were found (Fig. 2; Table 1). Overall, most methods (64.2 %) are based on observations, while 35.8 % provide an estimation of ES delivery without direct sampling and measurements. Considering only the Provisioning services, 83.3 % of the methods were observations-based, while the proportion of observation and estimation methods for the section Regulation & Maintenance was 70.2 % and 29.8 %, respectively. The remaining methods, combining different sections of ES, are all estimation methods. Fig. 3 and Fig. 4 show the number of methods collected, grouped by ES and CICES class, respectively, distinguishing between observation and estimation methods.

3.1. Provisioning services (1.1.1.1; 1.1.1.2; 1.1.1.3)

In class 1.1.1.1, which pertains to plants cultivated for nutritional purposes, grain yield was the primary measurement identified. Although no specific reference was provided for this method, it is a widely used metric in most crop-related experiments. The Land Equivalent Ratio (LER) (Willey and Osiru, 1972) is also a widely used metrics for

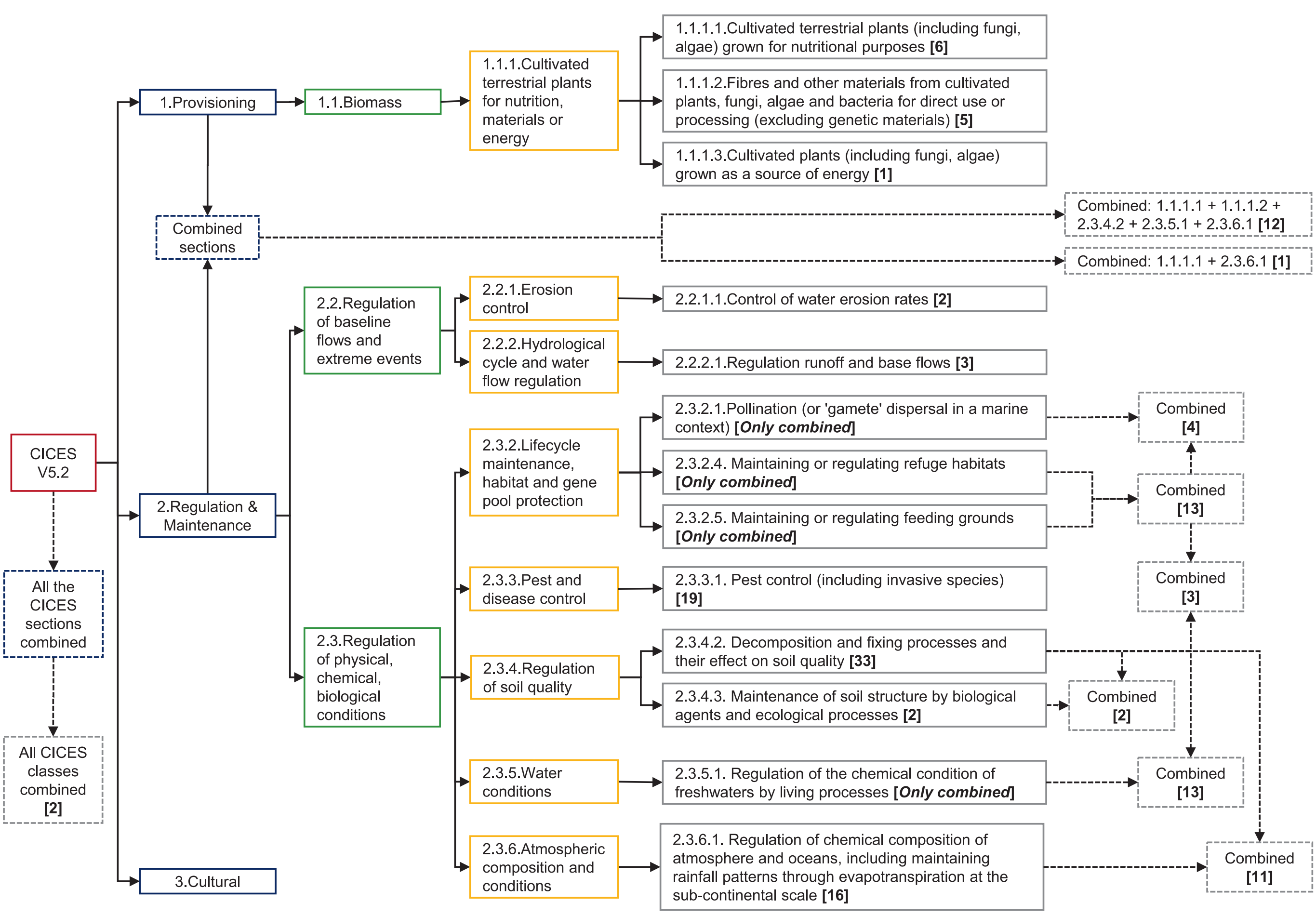

Fig. 2. Number of methods presented by CICES V5.2 taxonomy. Blue outline indicates CICES section, green outline indicates CICES division, yellow outline indicates CICES group, and grey outline indicates CICES class. Combined sections and classes are presented with dashed outline. In 'combined sections' only the class number is shown, and CICES descriptors can be found in the corresponding individual class. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
List of CICES classes assigned to the collected methods. Both single and grouped CICES classes are presented.

ES Section	ES Class
Provisioning services	1.1.1.1. Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes
	1.1.1.2. Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)
	1.1.1.3. Cultivated plants (including fungi, algae) grown as a source of energy
Regulation & Maintenance services	2.2.1.1. Control of water erosion rates
	2.2.2.1. Regulation runoff and base flows
	2.3.2.1. Pollination (or 'gamete' dispersal in a marine context); 2.3.2.4. Maintaining or regulating refuge habitats; 2.3.2.5. Maintaining or regulating feeding grounds
	2.3.2.4. Maintaining or regulating refuge habitats; 2.3.2.5. Maintaining or regulating feeding grounds
	2.3.2.4. Maintaining or regulating refuge habitats; 2.3.2.5. Maintaining or regulating feeding grounds; 2.3.4.2. Decomposition and fixing processes and their effect on soil quality
	2.3.3.1. Pest control (including invasive species)
	2.3.4.2. Decomposition and fixing processes and their effect on soil quality
	2.3.4.2. Decomposition and fixing processes and their effect on soil quality; 2.3.4.3. Maintenance of soil structure by biological agents and ecological processes
	2.3.4.2. Decomposition and fixing processes and their effect on soil quality; 2.3.5.1. Regulation of the chemical condition of freshwaters by living processes
	2.3.4.2. Decomposition and fixing processes and their effect on soil quality; 2.3.6.1. Regulation of chemical composition of atmosphere and oceans, including maintaining rainfall patterns through evapotranspiration at the sub-continental scale
	2.3.4.3. Maintenance of soil structure by biological agents and ecological processes
	2.3.6.1. Regulation of chemical composition of atmosphere and oceans, including maintaining rainfall patterns through evapotranspiration at the sub-continental scale
Provisioning + Regulation & Maintenance	1.1.1.1. Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes; 1.1.1.2. Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials); 2.3.4.2. Decomposition and fixing processes and their effect on soil quality; 2.3.5.1. Regulation of the chemical condition of freshwaters by living processes; 2.3.6.1. Regulation of chemical composition of atmosphere and oceans, including maintaining rainfall patterns through evapotranspiration at the sub-continental scale
	1.1.1.1. Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes; 2.3.6.1. Regulation of chemical composition of atmosphere and oceans, including maintaining rainfall patterns through evapotranspiration at the sub-continental scale
All ES together	All ES classes

assessing the performance of legume-based cropping systems, particularly in those involving intercropping between legumes and winter cereals (Hauggaard-Nielsen et al., 2009) or maize (Latati et al., 2016). For protein provisioning, a regional-scale protein balance (Leinonen et al., 2020) has been applied considering both legumes and livestock and their amino acid composition. The remaining methods assessed food quality, by analyzing the mineral composition and the phenolic content of legumes' grains (Brun et al., 2024).

Class 1.1.1.2 was composed of a variety of direct measurements of biomass production, which were the most applied methods. The measurements considered either the aboveground, belowground, or total crop biomass. The grazing value (Daget and Poissonet, 1971) is a metric for considering the quality of the biomass produced, providing an index of the agronomic value of a pasture considering the percentage contribution of each species. Finally, a ground cover image assessment with a machine learning model was used to assess the biomass composition in relation to the competition of different species in crop mixtures (Bousselin et al., 2024).

Only one paper describing a method for class 1.1.1.3 – plants cultivated for energy production – was found, which consists of a lab methane production assay of mallow (*Malva verticillata* L.) and white clover (*Melilotus albus* Medik.) mixtures (Kintl et al., 2022).

3.2. Regulation & Maintenance services

Most of the methods (63.6 %) in the Regulation & Maintenance section belonged to the CICES classes related to nutrient and carbon cycles, and their effects on soil (classes 2.3.4.2 and 2.3.4.3), air (class 2.3.6.1) and water composition (class 2.3.5.1). These classes were assigned individually or in combination with each other. The second biggest CICES class (16.0 % of the methods) was weed and pest control (class 2.3.3.1), while 10.1 % of the methods focused on the maintenance of habitats and feeding grounds (classes 2.3.2.4 + 2.3.2.5). Pollination (class 2.3.2.1.), which is always related to refuge habitats and feeding grounds, only accounts for 3.4 % of the methods. The remaining methods regarded soil erosion (class 2.2.1.1) and the regulation of runoff and base flows (class 2.2.2.1), with 1.7 % and 2.5 % of the methods, respectively.

3.2.1. Nutrient cycling, BNF and soil properties (2.3.4.2 and 2.3.4.3)

Most of the methods in these CICES classes referred to nutrient cycling and soil chemical quality. Despite the large number of methods, this grouping includes laboratory analyses of soil and crop samples aimed at determining the concentration of specific nutrients. Hence, many methods describe lab procedures for determining soil/plant N concentration in various forms, available P in the soil, and the presence of other macro- and micro-nutrients (Mat Hassan et al., 2013; Diacono et al., 2018; Prendergast-Miller et al., 2021). These analyses are often carried out in field experiments to assess the effects of legumes on soil fertility, and are frequently accompanied by observations of the yield, biomass, and N uptake or a specific compound concentration in the following crop. Measurements and analyses allow the calculation of agronomic indexes, such as the N agronomic efficiency, the N partial factor productivity, the N use efficiency or the N nutrition index (Wittwer and Van Der Heijden, 2020; Geng et al., 2023), which are commonly calculated. At the same time, different kinds of N balances can also be performed, and the number of terms included in the balance can vary substantially (Camarotto et al., 2018; Wittwer and Van Der Heijden, 2020). Some field experiments addressing legumes effects on nutrient cycling also use sensors to measure the crop reflectance/transmittance on certain wavelengths, for further estimation of N and P content in the biomass (Kleinebecker et al., 2014), chlorophylls content (Guiducci et al., 2018), or to calculate vegetation indexes (Wittwer and Van Der Heijden, 2020). Only one indicator was found to assess soil fertility through an aggregated Nutrient index (Vanino et al., 2022).

Since this review focused on legume cropping systems, aspects related to nutrient cycling – particularly biological nitrogen fixation (BNF) – were well represented. The N-difference method is among the simplest methods to assess BNF and is based on the difference between the N content in the legume crop against a reference crop grown in the same conditions (Pampana et al., 2018). BNF is frequently calculated in the field using the N-15 isotopic composition of plant tissues to estimate the N derived from atmosphere through the difference in concentration of legumes crops against non-fixing crops, either enriching the soil with

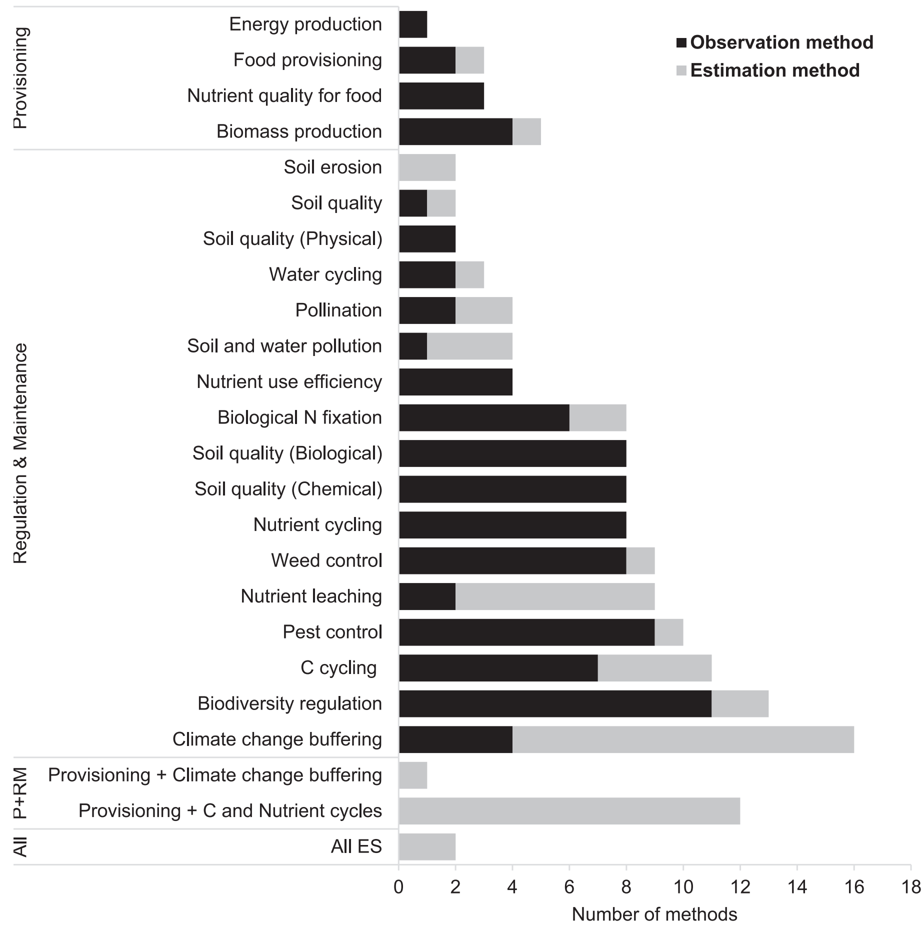

Fig. 3. Number of collected methods classified by general ES definition. Also the CICES section is reported on the left, and combined sections are presented. Section 'P + RM' stands for the combination of Provisioning + Regulation & Maintenance services.

N-15 enriched fertilizer or not (Büchi et al., 2015; De Notaris et al., 2023). Other methods to evaluate the fixing activity involve measuring the number and the dry weight of root nodules in crop roots (Banik et al., 2006) or their enzymatic activity (Niewiadomska et al., 2015). N supplied by a legume cover crop can also be obtained by multiplying the produced dry matter and the N concentration in the buried biomass (Ciaccia et al., 2015). This method also applies to temporary intercropping (Guiducci et al., 2018). Methods for estimating BNF without observed values are based on literature factors and correlations (Iannetta et al., 2016) or linear models between BNF and legumes dry matter shoot or yield (Anglade et al., 2015).

Soil biological quality methods were also assigned to class 2.3.4.2. These methods were mostly related to the microbial community activities in the soil, such as measurements of soil respiration through titration or specific instruments (Bousselin et al., 2021; Mirzad et al., 2023), measurements of soil nitrification potential under optimum conditions (Bousselin et al., 2021), or the determination of soil enzymatic activity combined with soil DNA extraction for PCR sequencing (Cuartero et al., 2022). Biological soil quality was also evaluated through other *taxa* than bacteria, with papers focusing on the symbiosis with arbuscular mycorrhizae (Köhl et al., 2014; Pellegrino et al., 2020) or assessing the effects of legumes on earthworm populations (Prendergast-Miller et al., 2021).

Methods assessing soil physical properties and soil structure were classified as 2.3.4.3, for which we only found two observation methods: the bulk density (BD) (Grossman and Reinsch, 2002) and the degree of compaction, an indicator based on the BD of a soil against a reference BD (Piccoli et al., 2022).

Only two methods were found to assess combined aspects of soil quality (2.3.4.2 + 2.3.4.3). The SALCAsoilquality (Oberholzer et al., 2012) is an impact assessment method designed for LCA which aggregates 9 indicators related to soil physical, chemical and biological quality in a single metric to assess the effect of agricultural management practices. The stock adequacy method (Hewitt et al., 2015) evaluates the adequacy of a soil to support the provision of ES under a specific land use, deriving stock adequacy indexes from ES provision response curves to key soil properties.

3.2.2. Carbon cycling and emissions to air and water (2.3.4.2 + 2.3.5.1. Or 2.3.6.1)

This paragraph describes the methods for the decomposition and fixing processes, which also affect the chemical composition of freshwater and atmosphere. All the methods related to carbon cycling, climate change buffering, nutrient leaching and other pollutants emissions were included, except for agroecosystem models assessing multiple sources of field emissions and considering soil C and N dynamics together with crop yield, biomass and other ES sections, which are described in paragraph 4.3.

Similarly to nutrient cycling, C cycling is often studied in field experiments through laboratory analyses of soil aimed at determining SOC with different methods and instruments, which do not differ substantially in the principles (Guardia et al., 2016; Krauss et al., 2017; Vanino et al., 2022). The plant C concentration, the C-13 isotope analysis and the lignin composition of the root system can be used to study the effects of different crop residues on the soil C dynamics over time (Creme et al., 2017; Chen et al., 2018; Bousselin et al., 2024). The effect on C cycling of heterotrophic respiration in soils was also assessed, using closed chambers for CO_2 fluxes measurements of soil insulated from crop roots

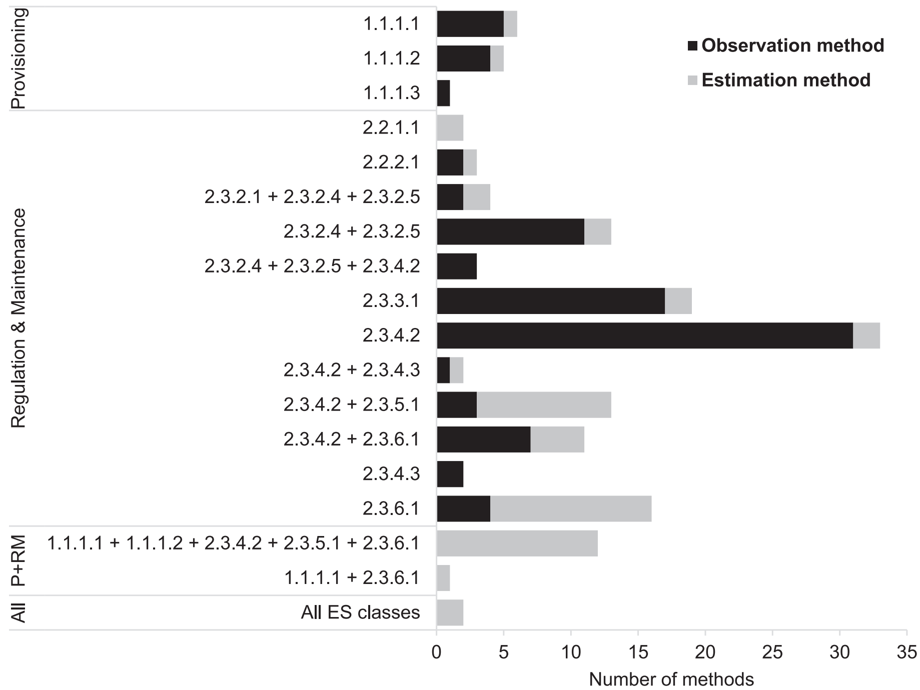

Fig. 4. Number of collected methods classified by CICES V5.2. Combined section and classes are also presented. Section 'P + RM' stands for the combination of Provisioning + Regulation & Maintenance services. CICES classes descriptors are the following: 1.1.1.1. Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes; 1.1.1.2. Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials); 1.1.1.3. Cultivated plants (including fungi, algae) grown as a source of energy; 2.2.1.1. Control of water erosion rates; 2.2.2.1. Regulation runoff and base flows; 2.3.2.1. Pollination (or 'gamete' dispersal in a marine context); 2.3.2.4. Maintaining or regulating refuge habitats; 2.3.2.5. Maintaining or regulating feeding grounds; 2.3.3.1. Pest control (including invasive species); 2.3.4.2. Decomposition and fixing processes and their effect on soil quality; 2.3.4.3. Maintenance of soil structure by biological agents and ecological processes; 2.3.5.1. Regulation of the chemical condition of freshwaters by living processes; 2.3.6.1. Regulation of chemical composition of atmosphere and oceans, including maintaining rainfall patterns through evapotranspiration at the sub-continental scale.

(Francioni et al., 2019), under different land uses. Models specifically estimating C turnover without including other ES in the results are the ICBM (Karlsson et al., 2015), the MOMOS (Ibrahim et al., 2013), the RothC (Yao et al., 2017) and SALCAfieldC (Nemecek et al., 2024); each based on different C pools and principles.

The assessment of crop effects on climate change buffering is often carried out with broad Life Cycle Inventories (LCI) databases, which underlie international guidelines and emission factors (IPCC, 1996, 2006, 2019; EEA, 2019). These guidelines provide methods with different levels of complexity, and both Tier 1 and Tier 2 methodologies are often applied in the reviewed papers. In addition to these methods, some studies can supplement the results with other emission factors from literature (Nemecek et al., 2015; Bais-Moleman et al., 2019) or direct measurements. Direct measurements of green-house gases (GHG) emissions from the field can be obtained with micrometeorological techniques, such as the eddy covariance (Feigenwinter et al., 2023) and the flux-gradient method (Goglio et al., 2018b). Another possibility is to measure GHG fluxes from soil through specially designed chambers (Rochette and Eriksen-Hamel, 2008; Krauss et al., 2017) which allow measurements of gas concentration within the chamber at different time steps. Once measured, gas exchanges can be also studied as a function of system diversification through the biodiversity-ecosystem function modelling framework (Ribas et al., 2015), regressing the response variables against species proportion and evenness (Ribas et al., 2015).

Methods for nutrient leaching regulation (2.3.4.2 + 2.3.5.1) can be distinguished between N and P leaching. N leaching can be calculated as a function of the N surplus and the soil leaching probability (Reckling et al., 2016a) or through regression models (Anglade et al., 2015; Lago-Olveira et al., 2024). Models specifically developed for N leaching are the SALCAnitrate (Nemecek et al., 2024) and the LIXIM model, which simulates both water and N fluxes in the soil (Amossé et al., 2014). Observations related to N leaching involve the measurement of NO_3^- concentration in water extracted from suction cups (Farneselli et al., 2018), which can be coupled with a daily water balance (Brozyna et al., 2013). For P leaching, Costa et al. (2021) adopted an emission factor found in literature, while the only available model was the SALCAfieldP (Nemecek et al., 2024). Also in this case, nutrient leaching can be estimated together with other ES, through the models described in section 5.3.

Other soil and water pollutants causing human and ecosystem toxicity are heavy metals and pesticides. Heavy metals can be assessed by the SALCAheavymetals model (Nemecek et al., 2024) while the pestLCI consensus model (Nemecek et al., 2022) has been specifically designed for estimating pesticides emission fractions to different environmental compartments. Pesticides risks can be also assessed with the treatment frequency index, a simple proxy value based on the applied rates of each active substance divided by its standard approved rate (Longis et al., 2024). Only one paper focusing on the effects of legumes on polycyclic aromatic hydrocarbons deposition on soil was found (Sawicka et al., 2023).

3.2.3. *Pest and weed control (2.3.3.1)*

Pest control by legumes is mainly assessed through direct observations. The experiments can involve sampling herbivorous insects and predators (Schulz-Kesting et al., 2021), measuring the predation attack rates on artificial, or alive, insect baits (Puliga et al., 2023), sampling aphids with specific trap cards (Boetzl et al., 2023) or counting the number of parasitized aphids (Schulz-Kesting et al., 2021). Samplings can also focus on other species than arthropods, such as nematodes, distinguish between root-feeding and predator species (Boetzl et al., 2023). Indicators include the disease severity index (DSI), based on the number of plants presenting a certain range of disease damages (Boetzl et al., 2023). The only simulation model we found for pest control is the IPSIM approach, a non-specific modelling framework which predicts the injury profile (IP) of a cropping system through a hierarchical aggregative approach, using a series of qualitative attributes to describe the cropping practices, soil, climate, and pest interactions (Meunier et al., 2022).

Legumes effect on weeds is often assessed with measurement of weed biomass and species composition, both in intercropping and after legumes cover crops (Campiglia et al., 2010; Corre-Hellou et al., 2011). Weed composition can be also evaluated by biodiversity indicators, such as the Shannon diversity index, the Shannon evenness and the Margalef index (Campiglia et al., 2012; Mirzad et al., 2023). Indicators for weed response to legume cover crops are the weed control index (Vrignon-Brenas et al., 2018) and the relative response index (Campiglia et al., 2014). The competitiveness of legumes against weeds can be assessed with the weed interference index (Guiguitant et al., 2020), which is a function of maximum crop leaf area index (LAI) divided by the time needed to reach the maximum LAI. Other observations involve the observation of weed seeds predation (Puliga et al., 2023).

3.2.4. Biodiversity regulation (2.3.2.4 + 2.3.2.5)

Most of the papers dealing with the maintenance of refuge habitats and feeding grounds (2.3.2.4 + 2.3.2.5) were focusing on arthropods. Different sampling methods can be applied, such as flight interception traps (Caballero-López et al., 2016), pitfall traps (Verdinelli et al., 2022) and suction samplers (Caballero-López et al., 2010). These observations are then used to calculate various diversity and evenness indexes or the activity density of certain species (Bommarco et al., 2012; Puliga et al., 2023). Diversity indexes can also be applied to other species, such as birds (Concepción and Díaz, 2019). An habitat scoring system was proposed based on the overlapping of crop sowing and harvest periods, but specifically for intercropping experiments (Juventia et al., 2022). The SALCAbiodiversity method assesses the effects of management practices of farmland landscapes on 11 indicator-species groups, which can be aggregated in a single biodiversity score (Jeanneret et al., 2014).

3.2.5. Soil erosion (2.2.1.1), water cycling (2.2.2.1) and pollination (2.3.2.1)

No field experiments assessing soil erosion were found through literature screening. The only method collected for this ES was the SALCAerosion (Nemecek et al., 2024), which follows the theoretical background of the Revised Universal Soil Loss Equation (RUSLE) (Renard, 1997).

The effects on water cycles can be assessed in field experiments using soil moisture sensors (Camarotto et al., 2018). A method for water scarcity which does not require direct measurement is the AWARE method (Boulay et al., 2018), often used in LCA, based on the quantification of the relative available water remaining per area once the demand of humans and aquatic ecosystems has been met (Lago-Olveira et al., 2024).

For pollination support, Eckerter et al. (2022) proposed an experiment in which floral resources in agricultural landscapes were mapped to understand the effects of different crop species on pollinators density and seed setting of broad bean species. Another proxy value for pollinators is the nectariferous value, based on the quality and quantity of nectar produced by a certain species (Bagella et al., 2020).

3.3. Combined ES sections

Three combined CICES sections were found among the reviewed methods. Two were related to the combination of Provisioning + Regulation & Maintenance and one to the combination of all the CICES sections.

Concerning the Provisioning + Regulation & Maintenance sections, the first combination involved food provisioning and climate change buffering (1.1.1.1 + 2.3.6.1; combination A), while the second one combined food and biomass production, C cycling and nutrient cycling; often including sub-models for nutrients emissions to atmosphere and water (1.1.1.1 + 1.1.1.2 + 2.3.4.2 + 2.3.5.1 + 2.3.6.1; combination B). For combination A, the only method identified was the ecosystem energy balance. This approach evaluates system performance by comparing the energy content of the food produced with the energy consumed by agricultural practices (Diacono et al., 2018). Combination B includes various kinds of crop-soil models, with different levels of accuracy in describing the agroecological processes involved. The modelling strategy varies depending on the aspects in which the models focuses most, which could be yield forecasting, such as in APSIM (Holzworth et al., 2014) and STICS (Brisson et al., 2003) models, or the C and N dynamics in the soil, such as in CENTURY (Parton et al., 1987), DayCent (Parton et al., 1998) and DNDC (Li et al., 1992). A complete list of the collected models can be found in Supplementary material 2.

The third combination of CICES sections was assessing all the types of ES contemporarily (Provisioning + Regulation & Maintenance + Cultural). The most representative method in this ES grouping is the Ecosystem Services Valuation Database (ESVD) which gathers the economic value of ES around different regions of the world in monetary units (Brander et al., 2024).

4. Discussion

4.1. Trends in ES-LCA integration

The variety of methods identified reflected well the multidisciplinary nature of the topic, with papers emerging from a wide range of subject areas, though they all related to agricultural production. Nonetheless, there remained a disparity regarding ES assessed and the availability of methods to evaluate that ES. This mismatch cannot be attributed solely to the low ES integration into LCA, which is in any case established, because many of the sources were solely focusing on quantifying ES delivery, and methods to assess certain ES are still underdeveloped. With this work, we covered important aspects of currently applied methods in ES assessment, establishing the basis for future ES-LCA integration.

The results of this review, regarding the ES studied in current scientific literature, are consistent with – and expand upon – those reported by Ditzler et al. (2021). By incorporating LCA and other assessment methods into our review framework, we also included studies addressing GHG emissions and climate change mitigation, which were not represented in previous studies (Ditzler et al., 2021). Our results reinforce the idea that the focus of research agendas should shift towards the valorization of ES delivery (Ditzler et al., 2021), with more urgency if we consider the functional potential of ES-LCA integration (Alejandre et al., 2019; Hardaker et al., 2022; Taelman et al., 2024). Method availability is not the only barrier to ES inclusion into LCA, since a high number of methods can reflect knowledge fragmentation i.e., many methods reported, albeit in different styles, for the same ES. This characterizes the whole Regulation & Maintenance section compared to the Provisioning section; as the latter presents only a small number of well-established methods. On the other hand, the large number of methods available for certain ES, with some of them directly coming from LCA studies, indicates that some ES appear already integrated, even when not explicitly declared (e.g. carbon and nutrient cycling). A previous study by Alejandre et al. (2019) reported the CICES v5.1 (Haines-Young and Potschin, 2018) to be partially covered by the ReCiPe2016 (Huijbregts et al., 2017) mid-point categories. Being the CICES v5.2 essentially an update of the previous version, the overlapped categories are possibly the same, including the ones covering the aspects of SOC and atmosphere composition. Tools for estimating SOC and GHG dynamics in agricultural LCA were indeed largely discussed in previous studies (Goglio et al., 2015, 2024; Pelaracci et al., 2025), and even if previous research was not specifically focusing on legume ES, similar conclusions can be drawn from this review. The previous studies showed an inverse relationship between accuracy and applicability of the methods, making the methodological choice particularly critical (Goglio et al., 2024; Pelaracci et al., 2025).

The CICES class with more methods found was 2.3.4.2, which refers to the decomposition and fixing processes that affect soil quality. Indeed, BNF and the effects on soil fertility are widely recognized as a key-trait of legumes ES in scientific literature (Crews and Peoples, 2004; Zander et al., 2016; Jensen et al., 2020; Ditzler et al., 2021). The great majority of the methods in this class (93.9 %) were based on direct observations, which are highly demanding in terms of time and human resources. Some classes, integrating methods originating from environmental impact assessment and LCA (such as climate change buffering and nutrient leaching), highlight the potential role of simulation tools for ES integration in LCA. For this reason, agroecosystem models could be a suitable option for estimating the effects of legume crops on nutrient cycles and BNF together with other ES. Such models would require proper quantitative calibrations and expertise in modelling, thus, limiting their application to scientific purposes (Goglio et al., 2024; Pelaracci et al., 2025). Integrating these ES into LCA studies demands modelling the temporal-scale interactions among successive crops in rotations. In this case, a system approach is suggested, avoiding allocation approaches whenever possible (Goglio et al., 2018a; Costa et al., 2020).

4.2. Emerging fields in agricultural ES research

The second largest CICES class in terms of number of methods (2.3.3.1, n = 19), encompassed the aspects related to pest (n = 10) and weed (n = 9) control, and 89.5 % of the methods were observation based. For pest control, the only estimation method found is the ISPIM model (Aubertot and Robin, 2013), which overcomes the complexity of agroecosystem representation through a hierarchical aggregative approach of crop stressors, but whose result is not a quantitative metric. Instead, the only metric we found for estimating the effects on weed control was the weed interference index, which measures how long a crop takes to reach its maximum leaf-area index (LAI) as a proxy for competitiveness against weeds. This metric is coarse and only partially applicable in LCA, as it lacks cropping system specificity and overlooks interactions within the rotation. Current evidence does indicate that crop-weed interactions matter, but the data remains sparse. As Ditzler et al., (2021) note, more research is needed on the temporal dynamics of these interactions. Developing new methods to incorporate this ecosystem service into LCA would make the assessment framework more comprehensive and should be a priority for future work.

In a similar manner, for 2.3.2.4 and 2.3.2.5 classes, related to the maintenance of refuge habitats and feeding grounds (biodiversity maintenance effects), many different indices can be calculated based on species richness and evenness. However, all of them imply direct observations, which also require a certain expertise for species identification. The habitat score proposed by Juventia et al. (2022) is only based on the sowing and harvesting period of intercropped species. However, it was too specific and had a low descriptive potential for the agro-ecosystem interactions to be further developed. The SALCAbiodiversity (Jeanneret et al., 2014) is the only LCA method already developed found in this review. Previous studies looked deeper in the topic of biodiversity representation into LCA, addressing the available methods and indicators, even if not specifically focusing on legumes (Damiani et al., 2023; Zhen et al., 2025). Following both Damiani et al. (2023) and Zhen et al. (2025), biodiversity pressures are not yet well covered in LCA. Indicator-based methods seem to outperform the expert-based scoring systems (Zhen et al., 2025) and their development could allow a better representation of the drivers of biodiversity loss, to improve the taxonomic coverage of biodiversity methods (Damiani et al., 2023). The scarcity of LCA biodiversity models and estimation methods in this review may be attributed to the specific focus on legumes and to the geographical restriction to European contexts.

Regarding the three minor classes found (i.e. soil erosion, water cycling and pollination), different considerations can be made depending on the targeted ES. Whitin class 2.2.1.1, the only soil erosion model found is RUSLE (Renard, 1997), while the other work is basically a parametrization of this equation (Nemecek et al., 2024). Regarding RUSLE (Renard, 1997), the quantity of eroded soil per hectare per year is calculated considering canopy, management practices, rainfall, erosivity, and field characteristics. In the SALCA framework, which is an LCA framework specifically designed for agriculture, the results from the erosion sub-model are considered as emission pathways for phosphorus (P) and heavy metals (Nemecek et al., 2024). The absence of experiments on soil erosion indicates that a deeper understanding of the effects of legumes inclusion in cropping systems (e.g., as cover crops) is necessary, focusing particularly on variations in soil quality and SOC due to regulation of soil erosion (Poesen, 2018; Jian et al., 2020), which could provide valuable insights for future ES-LCA integration. The aspects covered by class 2.2.2.1 – water cycling – are indirectly related to soil erosion, since soil moisture sensors were used to investigate the effects of crop and land management on water infiltration, which relates two of the five variables of the RUSLE model (Renard, 1997). While the AWARE method is a characterization model for water scarcity in LCA (Boulay et al., 2018), it can be applied to different cropping systems, including legume-based (Lago-Olveira et al., 2024). Finally, class 2.3.2.1, related to pollination, had only 4 methods included. Even if none of them is suitable for LCA adoption as it stands, the methods well capture the relevance and the complexity of the topic, assessing the importance of resources availability for pollinators and the effect of their presence on crop yields (Eckerter et al., 2022). The need for impact assessment methods for pollinators was already discussed (Crenna et al., 2017; Alejandre et al., 2019) and methodologies based on expert knowledge and land use are currently being developed (Alejandre et al., 2022).

4.3. Cultural services and ES monetization: Limitations and uncertainty management

Our study gives an overview of ES-LCA integration in agricultural systems, including its difficulties. Among the limitations, there is the absence of Cultural ES assessments, which are rare in agricultural systems and largely overlooked in legume-based systems. In our review, adopting estimate values from the ESVD (Brander et al., 2024) resulted as the most suitable strategy for assessing Cultural services. Nonetheless, whitin this broad database, which encompasses several ES, only 18 studies (comprising 73 value estimates) assess Cultural ES values from agricultural systems – namely related to aesthetics (23 value estimates), recreation and tourism (23 value estimates), and existence and bequest values (27 value estimates). Out of these 18 studies, only 1 study (comprising 4 value estimates) focused on Cultural ES values from legume-based systems. Therefore, we can confirm the general lack of focus on and/or interest in Cultural ES values from agricultural systems, in general, and those from legumes-based systems in particular, in agreement with the present review. In addition, although several methods for the monetary assessment of Cultural ES values exist in literature (see, e.g., (Pascual et al., 2010; De Groot et al., 2012), several Cultural ES values (such as spiritual and cognitive values) are difficult to quantify and are not widely studied (Cheng et al., 2019; Brander et al., 2024), increasing the barriers to their integration. Finally, the absence of monetary ES value estimation approaches in our review is possibly contingent to the scope of the review. However, the ESVD data fully align with the current findings (Brander et al., 2024).

Ecosystem goods and services mapping and assessment toolkits, such as inVEST (https://naturalcapitalproject.stanford.edu/software/invest) and ARIES (Villa et al., 2014), are potentially capable of representing Cultural ES and could possibly be integrated into LCA. A recent study from Lago-Olveira et al. (2025) adopted models from InVEST to develop LCA characterization factors for different ES, although their case study is limited to Regulation & Maintenance ES. Theoretical frameworks developed for integrating ES into LCA are, however, also trying to account for Cultural ES, highlighting the importance and the difficulties of this integration (Alejandre et al., 2019; Rugani et al., 2019; De Luca Peña et al., 2022; Hardaker et al., 2022). Martínez-García et al., (2025) performed an ES-LCA integration based on monetary ES values from various sources, which involved a recreation index (Albaladejo-García et al., 2023) for the integration of cultural services. A similar approach was adopted by Taelman et al., (2024), which integrated monetary ES values from the ESVD (Brander et al., 2024) into LCA.

When facing ES-LCA integration, monetization is often regarded as a possible strategy (Alejandre et al., 2019; Rugani et al., 2019; De Luca Peña et al., 2022; Hardaker et al., 2022), and this is particularly evident when considering non-physical ES, such as cultural services (Taelman et al., 2024; Martínez-García et al., 2025). Providing monetary ES values allows for easily accessible and readable comparisons between many different ES (Brander et al., 2024), nonetheless, it may bring some limitations in accuracy. This is mainly due to data quality issues, as the number of sources, spatial heterogeneity and the applied methods can vary significantly depending on the considered ES (Brander et al., 2024; Taelman et al., 2024). In addition, there may be difficulties when transferring monetary ES values to different bio-physical, socio-economic and policy-governance contexts (Brander et al., 2024; Silva et al., 2024). Considering these, monetization can be regarded as a feasible approach for integrating Cultural ES whenever it is consistent with the objectives of the study, even though subject to uncertainties associated with the attribution of monetary values (Taelman et al., 2024).

4.4. Towards a more comprehensive LCA methodology

Legumes can provide a wide range of ES, with strong interconnections between each other, as shown by the diversity of CICES classes related to legumes. The interrelation between different ES makes their integration into LCA a priority for future research, since a better and harmonized representation of ecosystem interactions allows to improve the current LCA practices, bringing to more comprehensive assessments (Alejandre et al., 2019; Rugani et al., 2019; Hardaker et al., 2022; Taelman et al., 2024). Here, we provide a series of recommendations for legumes ES integration into LCA on the basis of our systematic review of ES service assessment methods.

4.4.1. ES- LCA integration in practice

Our results confirm the large variety of ES provided by legumes (Ditzler et al., 2021) and paves the way for their integration into agricultural LCA.

Among provisioning services related to legumes, protein provisioning is probably one of the most relevant (Poore and Nemecek, 2018; Semba et al., 2021). The existing literature suggests that the integration of this service into LCA involves the selection multiple functional units, of which at least one nutrition related, and the adoption of a cropping system approach (Goglio et al., 2018a; Costa et al., 2020; McAuliffe et al., 2020). In this way, legumes provisioning services are already integrated, and explicitly stated, into common LCA practices.

In Section 5.2.1. we presented a wide list of methods for all the aspects related to soil quality, among which BNF stands out for the relevance to legumes. Nitrogen off-set from BNF has multiple positive outcomes on different emission pathways (Goglio et al., 2018b; Poore and Nemecek, 2018; Jensen et al., 2020; Zhang et al., 2024). Currently, specialized Life Cycle Inventory (LCI) databases, such as ecoinvent (Wernet et al., 2016), do not estimate this ES. Thus, when nitrogen off-set is not available as primary data, other estimation methods must be applied, such as the one proposed by Iannetta et al., (2016) or more complex modelling approaches (Goglio et al., 2018b).

Similar conclusions can be drawn from section 5.2.2.: the methods for climate change buffering, SOC dynamics, and nutrient leaching seem to be easily integrable, if not already integrated, with methods covering different levels of applicability and accuracy (Goglio et al., 2024; Pelaracci et al., 2025). In this case, finding a compromise between accuracy and applicability is the key, thus, we recommend selecting the method consistently with LCA objectives and data availability, together with informing the intended audience on the limitations of the study (ISO, 2006a, 2006b).

Biodiversity Regulation & Maintenance is a relevant topic in agricultural LCA, and legumes resulted to be capable of providing habitats and feeding grounds for multiple species and *taxa*, since many methods were collected both for micro- and macro- fauna. Despite our review did not gather many LCA biodiversity methods. Further, there is not a general consensus on the LCA method to assess biodiversity (Zhen et al., 2025). Despite its limitations, SALCA biodiversity could be used potentially if necessary.

For the minor classes found, we still found some methods which are strictly related lo LCA, such as the AWARE method for water scarcity (Boulay et al., 2018) and the SALCAerosion (Nemecek et al., 2024). Both of them have already been applied on legume crops and are a suitable option for accounting legumes ES into agricultural LCA.

Regarding cultural services integration, monetization has already been applied in the literature (Taelman et al., 2024; Martínez-García et al., 2025) though they have never been adopted for legume cropping systems. The opportunities and challenges of this approach have been largely discussed in Section 6.3, and there remain some uncertainties in the integration of these services.

4.4.2. Recommendations for future research

The lack of methodologies for certain ES cannot be overlooked in future research, and different ES will require different strategies to be integrated into LCA. More ES need to be integrated into LCA, and there are many ES in which methodological knowledge is still fragmented. For these classes we recommend future research to develop more consensus on legumes and agricultural ES.

This is the first attempt to systematically address methodological issues related to legumes ES. The proposed review framework allowed to critically analyze methods availability for each CICES class, comparing different methodologies and highlighting current knowledge gaps. A further step towards the selection of ES methods for real case studies would be a further harmonization of these methods, following, e.g., the approaches proposed in other studies for different topics related to agricultural LCA (Goglio et al., 2023, 2024; Pelaracci et al., 2025).

Other suggestions for future research concern the methodological development of new LCA methods explicitly related to ES, which could be integrated into specialized ES-LCI databases. The results showed a great interest in the effects of legumes on the overall soil quality, including not only chemical, but also physical and biological aspects, in addition to harmonizing soil quality methods, identifying metrics to assess the effects of legumes on the overall soil health is paramount, since a wide range of ecosystem functions depend on (FAO et al., 2020).

Further knowledge gaps are also related to pest and weed control. Most of the methods addressing these ES are observation based, and previous research showed that most of the papers are based on short-term experiments (Ditzler et al., 2021), hence, we want to encourage future research in developing weed and pest control methods, focusing on crop interactions on a temporal scale, in order to integrate them into LCA. Biodiversity maintenance assessment methods should be also improved, with a deeper focus on legumes ES. Finally, we would also highlight the need of developing methodologies for pollination ES, since it is a relevant topic for legume crops, with potential feedback on overall biodiversity and crop yields.

4.4.3. Limitations of the study

This work represents the first step towards the integration of legumes ES into agricultural LCA. Despite this work successfully represented the overall methodology framework for legumes ES, it is important to highlight that our study only focuses on European and Mediterranean contexts. This limits the generalizability of our results, especially considering the relevance of ES in other regions, e.g., in tropical areas (Carrasco et al., 2017; Shimamoto et al., 2018), where different crops and climatic conditions could influence the method applicability.

Finally, the adopted review framework does not allow to provide indications on which ES method would perform better in a LCA study, except through the description of the method itself. A further classification of these methods to understand how to properly integrate ES into LCA would be useful. We have already discussed the importance of harmonizing these methods (Goglio et al., 2023, 2024; Pelaracci et al., 2025), and despite this being beyond the scope of the review, we consider them as successful strategies for a quantitative representation of methods characteristics, capable of giving more practical information on methods selection for LCA practitioners.

5. Conclusions

In this research, we systematically gathered methods to assess a wide range of ES provided by legumes. Through the CICES classification, the collected methods have been assigned to an international and recognized framework for ES assessment, making the LCA-ES integration independent of a specifically designed LCIA framework. Our findings are valuable both for LCA partitioners and scientists working on agronomy or environmental- and agricultural-economics, since the collected methods came from those different fields of research. The inclusion of other studies than LCA allowed not to overlook many promising procedures, in recognition of the importance of multidisciplinary and holistic approaches for the development of new LCA methodologies. Our results suggest that the strategy for ES integration in agricultural LCA should involve simultaneously pursuing two distinct paths: i) for the ES which are already integrated into most LCA studies (e.g., climate change buffering, eutrophication regulation), we suggest to select the methods among those reported, consistently with the LCA scope and data requirements; ii) for the several ES which are not currently integrable into LCA, but for which there is scientific evidence on the effects of legumes (e.g., pest control and pollination), we recommend future research to develop novel LCA methodologies that can achieve a deeper understanding on legumes interactions with the agroecosystem. Filling the knowledge gaps on ES provided by legumes is essential to overcome the barriers to wider legumes adoption across the EU, harnessing legumes ES to improve crop diversification within European feed- and food-systems.

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CRediT authorship contribution statement

Stefano Cimarelli: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Pietro Goglio:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Dalila Serpa:** Investigation. **Carlotta Quagliolo:** Investigation. **Teodora Dorca-Preda:** Investigation. **Abbigel Sadhu:** Investigation. **Kamala Rai:** Investigation. **Peter Roebeling:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition. **Thomas Nemecek:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition. **Anna Maria Cipolla:** Investigation. **Anne Schneider:** Project administration, Funding acquisition, Conceptualization. **Sergiy Smetana:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Marta Vasconcelos:** Project administration, Funding acquisition, Conceptualization. **Umut Kartal:** Investigation. **Katri Joensuu:** Investigation. **Janos-Istvan Petrusan:** Project administration, Funding acquisition. **Sylvie Dauguet:** Investigation. **Axel Falchetti-Cartier:** Investigation. **Thomas Wilkinson:** Project administration, Funding acquisition. **Pietro Iannetta:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.114462.

Data availability

Data will be made available on request.

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