VALERECO

Valorization Legumes Related Ecosystem Services

D1.2: Meta-analysis on beneficial effect of legume integration into cropping systems

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Executive Summary

In a context of economic and environmental concerns in agriculture, legumes appear to be suitable alternative crops to diversify current cropping systems and reduce their dependence on synthetic nitrogen fertilisers and protein from imported soybean. Integrating legumes into cropping systems also offers additional benefits, such as improved soil health through nitrogen fixation and enhanced structure, increased crop yields and water use efficiency, and reduced pest and weed pressure. However, legume cultivation has declined globally in recent decades due to low and unstable yields, leading to reduced high-quality protein production and loss of ecosystem services.

Legume crops have long-term and complex impacts on cropping systems, and the evaluation of these effects is challenging, resulting in a lack of awareness of their positive rotational effects. Furthermore, most of the research on legumes in European cropping systems focuses on a few legume species and ecosystem services and biodiversity that are not directly related to production. The aim of this deliverable was to use meta-analysis identify (i) beneficial effects and barriers to introduction of legume crops into cropping systems, (ii) give recommendations for effective use of legume crops for crop diversification and (iii) identify research gaps and give recommendations for the future research needed.

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List of abbreviations

CC	Cover crop
GHG	Greenhouse gasses
SOC	Soil organic carbon
HEU	Horizon Europe

1. Introduction

Crop production in Europe is highly specialized and currently relies on a very small number of crop species, raising questions about the sustainability of farming (Tilman et al., 2002). However, **enhancing diversity** spatially (e.g., intercropping) or temporally (e.g., crop rotation) **in cropping systems** may promote ecosystem services, carbon sequestration, and soil fertility and potentially reduces the dependence on external inputs while maintaining high crop yields and production stability (Zhao et al., 2022). Also **cropping system's sustainability and profitability can be enhanced through robust cropping systems**, meaning designing agroecosystems resilient to external stressors via diversification (Li et al., 2019). Furthermore, Duru et al. (2015), highlight the multifunctional advantage of multiple diversification components (field, farm, landscape) on ecosystem service provision of agroecosystems. However, these effects are site- and context specific.

Diversification through the **inclusion of legumes in European cropping systems** is one of the key strategies to enhance local and global crop production while minimizing negative environmental impacts (Zhao et al., 2022). However, legume cultivation has declined globally in recent decades due to low and unstable yields, leading to reduced high-quality protein production and loss of ecosystem services (Cusworth et al., 2021). **Integrating legumes into cropping systems offers multiple benefits**, including improved soil health through nitrogen fixation and enhanced structure, increased crop yields and water use efficiency, and reduced pest and weed pressure. These effects result in higher land productivity and sustainability while reducing the need for synthetic fertilizers and other inputs (Everwand et al., 2017; Stagnari et al. 2017; González del Portillo et al., 2022; Vollheyde et al., 2024).

Soil health and fertility

- **Nitrogen fixation:** Legumes, through symbiotic relationships with soil bacteria, convert atmospheric nitrogen into a form available to plants, reducing the need for synthetic nitrogen fertilizers.
- **Improved soil structure:** Their root systems break up compacted soil layers, improve aeration, and contribute to the formation of better soil aggregates, which enhances water infiltration and retention.
- **Increased organic matter:** Legumes add organic matter to the soil through decomposition of residues, which boosts soil fertility and helps bind soil particles.
- **Nutrient availability:** They can help make other soil nutrients more available. For example, they can improve the uptake of phosphorus by making it more soluble.
- **Enhanced biological quality:** Legume-based systems can support a more diverse microbial community in the soil.

Biodiversity

- **Rich genetic diversity:** Legumes have a vast genetic diversity, with over 16,000 known species, although only a small fraction is widely cultivated. This diversity provides a broad range of traits, such as resistance to drought, heat, salinity, and pests, which are vital for developing resilient agricultural systems in the face of climate change. Conserving and utilizing this genetic potential is crucial for long-term food security and crop improvement efforts.

- **Enhanced planned diversity at the field, farm and landscape level:** The strategic integration of legumes into farming practices increases planned biodiversity through **crop rotation** that breaks pest and disease cycles and improves soil fertility, reducing the need for synthetic fertilizers and **crop diversification/intercropping** that optimizes land and nutrient use efficiency.
- **Enhanced associated diversity:** Through entering into a symbiotic relationship with *Rhizobia* bacteria, legumes stimulate overall soil biological activity, increase microbial biomass, and promote beneficial bacterial communities and overall **soil microbial diversity**. Legumes also attract diverse insect populations, including pollinators, provide habitat, shelter, and alternative food sources for arthropod predators and parasitoids (natural enemies), thus supporting **diversity of associated flora and fauna, including natural enemies**.

Crop production and efficiency

- **Higher yields:** Integrating legumes can significantly increase crop yields, sometimes by as much as 30–35% compared to sole cropping systems.
- **Improved water efficiency:** Legumes enhance a system's ability to use water more efficiently.
- **Reduced pest and disease pressure:** Intercropping legumes can help suppress pests and diseases, leading to lower yield losses.
- **Reduced input costs:** By providing natural fertility and improving plant health, legumes can reduce the reliance on, and costs associated with external inputs like chemical fertilizers and pesticides.

Resilience and sustainability

- **Climate change adaptation:** Legume integration can make cropping systems more resilient to climate variability through various ecological processes that improve soil health and resource use.
- **Erosion control:** The ground cover provided by legumes helps protect the soil from erosion.
- **Sustainability:** The combined effects on soil health, yield, and input reduction make legume integration a more sustainable agricultural practice.

Currently, many farmers are not completely convinced to adopt and introduce legume crops into their crop rotation systems, despite the different advantages that could be obtained (Allam et al., 2023). One of the main challenges and barriers to the integration of legume crops into cropping systems is lack of adequate information and knowledge on specificities of different legume crops and their effects on production, resilience and the environment. The aim of this meta-analysis is to fill in this knowledge gap and identify (i) the **beneficial effect of legume crops** integration into cropping systems, and (ii) the **barriers to crop diversification** and crop rotation (***Figure 1***).

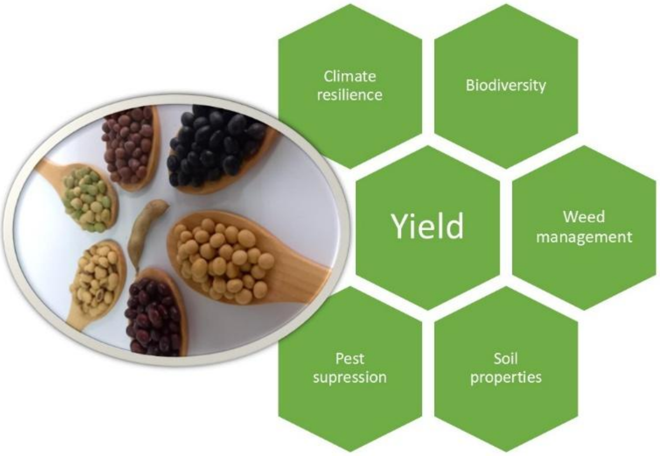

Figure 1. Specific impact-related key words used for meta-analysis

2. Literature review and analysis

This section provides a general overview of the methods and the review approach, whereas detailed methodological decisions and potential adjustments were made for each ecosystem service. A detailed description of the methods is then provided in **Chapter 3** for each service separately.

Literature search was conducted for peer-reviewed publications using Scopus (http://www.scpous.com), for studies that examined the effects of different legume cropping systems on selected ecosystem services, namely yield, climate resilience, associated biodiversity, pest suppression, weed management and soil properties. These were embedded into the general task and then translated into PICO elements (***Table 1***) and finally into keywords.

Table 1. Translation of task aim into PICO elements[1]

Task aim: Identification of benefits[3] from legumes inclusion[2] into cropping systems[1]. […] the impact of various legume management strategies[4] (e.g., cropping system/crop diversification, cultivation practices, crop rotation) and local site conditions[4] (landscape context, soil and climate) […] The outcome of this Task will be a report: […] on the beneficial effect[3] of legume crops integration[2] into cropping systems[1]	
Population[1]	Arable cropping systems
Intervention[2]	Legume inclusion into rotation
Control	No legumes in rotation
Outcome[3]	Associated biodiversity Yield (stability in crop rotation) Soil quality, soil health Climate resilience Pest suppression Positive and negative effects: weed pressure
Geographic scope	Europe

Search comprised publications from 2016 to 2025, with the exception of studies on associated biodiversity where publications before 2016 were also included (Figure 1). The baseline search keywords used were as follows: (legum* OR alfalfa OR lucerne OR chickpea* OR clover* OR fava* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "medicago sativa" OR "cicer arietinum" OR trifolium OR "vicia faba" OR "lens culinaris" OR "lupinus genus” OR "pisum sativum" OR "glycine max" OR "vicia sp.") AND ("cropping system*" OR "crop diversification" OR "cultivation practice*" OR "crop rotation" OR "crop management" OR "crop production" OR "crop stability") AND (“field*”) with the addition of the variations of the above-mentioned specific key words. The eligibility criteria for inclusion of the searched articles are presented in Table 2. Publications were retained during the selection process based on the PRISMA procedure.

Table 2. Eligibility criteria.

	Eligible	**Not eligible**
Population	arable cropping systems	agroforestry, plantations or silviculture
Intervention	legume inclusive cropping systems	
All legume crops possible	non-rotational studies	
Control	cropping systems without legumes	
Outcome	varying depending on the ecosystem service, for details see **Chapter 3**	
Geographic scope	HEU countries, list of HEU countries: https://research-and-innovation.ec.europa.eu/statistics/framework-programme-facts-and-figures/horizon-europe-country-profiles_en + Morocco, Egypt, Switzerland	non-HEU countries excluded
Study type	open air field trials under normal site conditions	pot or greenhouse trials models or simulation studies rigged fields, such as heavily disease- or pest-infested sites"
Document types	articles reporting primary data, book chapters, books, data sets	reviews or meta-analysis, preprints
Language	English	

3. Effects of legume integration into cropping systems

Effects of different legume cropping systems on yield, climate resilience, associated biodiversity, pest suppression, weed management and soil properties were analysed and described separately for each specific key word.

3.1 Yield

3.1.1 Methods

Research Question:
What is the effect of legume integration into cropping systems on yield stability?

Software:

Data extraction and synthesis was conducted with Excel.

Keywords

Keywords and additional Scopus settings have been implemented according to the eligibility criteria described in ***Table 2***, with search strings as described in ***Annex 1, Table 1***. Search was implemented in Scopus in November 2025.

Specific eligibility criteria

The specific eligibility criteria given in ***Table 3*** and ***Table 4*** have been applied during the screening process. A paper was deemed eligible for the next step if all questions were answered with yes. In the title and abstract screening phase papers were also taken into the next round if a question could be answered with "unsure".

Table 3. Specific eligibility criteria for yield stability for the title, key word and abstract screening.

Criteria	Key element
Arable cropping systems	Population
Inclusion of legumes in rotation (any legume crop)	Intervention/Exposure
Yield stability or variability over time	Outcome
Open-air field trials under normal site conditions	Study type
Primary research articles, books, book chapters, datasets	Document type
English	Language
Does the report contain side-by-side comparisons of legume and non-legume crop rotations?	Comparator

Table 4. Specific eligibility criteria for yield stability for full-text screening.

Criteria	Key element
Yield stability or variability over time	Outcome
Open-air field trials under normal site conditions	Study type
HEU and HEU-associated countries (plus Morocco, Egypt, Switzerland)	Geography
Primary research articles, books, book chapters, datasets	Document type
2016–2026	Year
Does the report contain side-by-side comparisons of legume and non-legume crop rotations?	Intervention/Exposure
Are yield data reported for the same (subsequent) crop for intervention and comparator?	Study desing
Are crop rotation(s) tested/compared?	Comparator
Arable cropping system	Population

Data extraction

Data were extracted on the individual studies level. Thus, multiple database entries (=studies) can stem from the same paper, as it might report results from several trials and/or several combinations of treatments and comparisons that are eligible for our research question. The following study level information were extracted: Country/Location, trial information (e.g. duration, design, treatment details), soil information, information on pesticide and fertiliser use, tested and comparator rotation description and biodiversity numbers (incl. indicator), significance testing and results (if available), additional descriptive information from the results and discussion section of the study on the comparison of the two rotations.

3.1.2 Results

Out of 244 publications screened (2016–2025), only 6 field studies met the criteria for assessing legume integration effects on yield stability in crop rotation. These trials were mostly in Canada (3), Germany (2), and Poland (1), ranging from short-term (4 years) to long-term (30 years) field rotations (***Table 5***). All compared cropping systems *with vs. without legumes* under realistic farm conditions. The legumes examined included grain legumes soybean, lentil, field peas, faba bean but forage legumes as alfalfa and red clover typically in rotation with cereals. Non-legume controls were usually continuous cereal monocultures or cereal-based rotations without legumes. Trials often had additional management factors (e.g. fertilization), but all provided direct comparisons isolating the legume rotation effect. No extreme soil conditions were present, ensuring results are broadly applicable. The most frequent reasons why an article was excluded during full-text screening is because: 1) the report didn't contain side-by-side comparisons of legume and non-legume crop rotations (71 excluded); 2) The yield data didn't report for the same (subsequent) crop for intervention and comparator (51 excluded); 3) No available data or reference to yield stability (37). The PRISMA flow chart is given in ***Annex 2, Figure 1***.

Table 5. Overview of the eligible reports for yield stability in crop rotation (N=6).

Report	Trial Design						
Reference	**Location**	**Total trial duration (years)**	**Treatments tested**	**Experimental trial design**	**Replications**	**Legume species**	**pH**
Wijata et al. (2025)	Poland	30	crop rotation and fertilization	randomized block design	4	red clover	6.03-6.44
Wang et al. (2025)	Canada	4	7 rotational crops x three 2-year wheat rotation systems as the succeeding wheat phases	factorial randomized complete block design	4	soybean, lentil, field peas, faba bean	7.2-8.2
St. Luce et al. (2020)	Canada	28	crop rotations	randomized complete block design	3	lentil green manure, field pea	6.5
Macholdt and Honermeier (2019)	Germany	25	crop rotation systems (CRSs), three mineral nitrogen (N) fertilization treatments and the varying annual weather conditions (AWCs)	strip-plot design	3	field bean	6.9
Beres et al. (2018)	Canada	22	effects of rotational diversity on cereals	randomized complete block design	4	field pea	-
Götze et al. (2018)	Germany	13	effects of rotational diversity	block design	2	alfalfa	6.9

Incorporating legumes into crop rotations generally enhances yield stability compared to rotations without legumes (***see Annex 3, Table 1***). Several field studies report that legume-inclusive systems exhibit lower interannual yield variability and more consistent performance than cereal-only sequences. For example, rotations that integrate pulses (such as peas or field beans) tend to fall into a favourable high-yield, low-variability category, outperforming less diverse rotations on stability metrics. In long-term trials, wheat yields were most stable when a legume was included: adding a field bean phase produced the lowest yield variance and highest stability, whereas cereal-only rotations showed significantly greater yield fluctuation. Likewise, introducing a perennial legume break crop has been shown to dampen yield fluctuations, as seen with alfalfa in intensive sugar beet systems (substantially reducing the coefficient of variation of sugar yield). Overall, the evidence indicates that adding legumes to rotations can buffer the system against yield swings, leading to more reliable year-to-year crop production.

The magnitude of stability gains from legumes often depends on management and environmental conditions. Nutrient availability is one key factor: one study noted that under manure-only fertilization, a clover-inclusive rotation was actually *less stable* than a non-legume rotation, suggesting that legumes alone may not supply sufficient nitrogen each season for optimal stability. By contrast, under high fertility (full NPK inputs), the same legume rotation achieved the highest yield stability, indicating that adequate supplemental nutrients allow legumes to fully contribute to consistent yields. This implies a synergistic effect where legumes improve stability most when their nitrogen contribution complements, rather than replaces, external nutrient supply.

Climate and rotation design also modulate yield stability outcomes. Legume benefits can be tempered by extreme weather: for instance, a lentil green manure–based rotation maintained near-average stability overall but underperformed in unusually dry or hot years, revealing vulnerability to drought stress. In terms of crop sequencing, greater rotational diversity and longer intervals between identical crops inherently promote stability. Rotations with a two-year or longer gap before repeating the same crop showed markedly lower yield variability and higher mean yields than more frequent cropping cycles. Even in shorter rotations, a strategically placed legume break can stabilize yields. For example, inserting alfalfa into a sugar beet rotation (with sugar beet grown every other year) mimicked the effects of a longer rotation by dramatically improving yield stability (sugar beet yield CV 7% with alfalfa vs. 34% under continuous sugar beet). These findings highlight that the context, soil fertility management, climatic conditions, and rotation length plays a crucial role in realizing the stability advantages of legumes.

Notable positive examples

- **Pea in high-diversity rotation**: A three-year high-diversity sequence (canola – triticale – field pea) achieved the highest yields coupled with the lowest yield variability. This legume-inclusive rotation fell into the most favourable stability group (high yield, low coefficient of variation), outperforming rotations lacking the legume phase (Wijata et al., 2025).
- **Field bean boosting stability:** Long-term trials showed that integrating field bean into cereal rotations markedly improved yield stability. Rotations with a field bean crop produced the most stable wheat grain yields, significantly reducing yield variance relative to continuous cereals or cereal-only rotations. Notably, the field bean rotations maintained high stability even as overall yields increased (Macholdt and Honermeier, 2019).
- **Alfalfa in sugar beet rotation:** Introducing alfalfa as a break crop greatly enhanced stability in a sugar beet rotation. In a system with sugar beet grown every two years, the legume-inclusive rotation had a white sugar yield CV near 7%, indicating very stable yields, whereas a continuous sugar beet

monoculture (no legume) saw much higher yield variability (CV ~34%). The alfalfa as a break crop not only improved stability but also supported above-average sugar yields (Götze et al., 2017).

- **Undersown clover for stable wheat:** In a four-year rotation experiment, adding undersown red clover led to the lowest stability variance for subsequent wheat yields. Under full fertilizer input, the clover-enhanced rotation had the best stability rank (most consistent yields), slightly outperforming the top non-legume rotation under the same nutrient conditions. This example underscores legumes' capacity to stabilize grain yields when nutrient needs are met (St. Luce et al., 2020).

3.2 Pest suppression

3.2.1 Methods

Research Question:
What is the effect of legume integration into cropping systems on pest suppression?

Software:
Data extraction and synthesis was conducted with Excel.

Keywords
Keywords and additional Scopus settings have been implemented according to the eligibility criteria described in ***Table 2***, with search strings as described in ***Annex 1, Table 2***. Search was implemented in Scopus in June 2025.

Specific eligibility criteria
The eligibility criteria given in ***Table 6*** and ***Table 7*** have been applied during the screening process. A paper was deemed eligible for the next step if all questions were answered with yes. In the title and abstract screening phase papers were also taken into the next round if a question could be answered with "unsure".

Table 6. Specific eligibility criteria for pest suppression for the title, key word and abstract screening.

Criteria	Key element
Is the report about arable cropping systems (no agroforestry)?	Population
Is it an open-air field trial (no greenhouse, laboratory, or modelling-only studies)?	Trial Setting
Is pest control or pest suppression an assessed outcome?	Outcome
Are legumes part of the cropping system as intercrops, rotation components, or cover crops?	Intervention/Exposure
Is it a report of primary research (no review or synthesis)?	Document Type
Is the report about arable cropping systems (no agroforestry)?	Population
Is it an open-air field trial (no greenhouse, laboratory, or modelling-only studies)?	Trial Setting

Table 7.Specific eligibility criteria for pest suppression for full-text screening

Criteria	Key element
Is it a report of primary research (no review or meta-analysis)?	Document Type
Is the site under normal field conditions (no artificial pest release)?	Trial Setting
Are legume-based and non-legume systems directly compared under identical management?	Comparator

Are pest population or natural enemy metrics comparable (e.g., counts, incidence, predation rates)?	Outcome
Are experimental durations sufficient to capture pest population dynamics (>1 growing season)?	Study Design
Are same climatic and management conditions applied to control and legume treatments?	Study Design
Does the crop system allow isolation of the legume effect (no confounding companion factors)?	Intervention
Is it a report of primary research (no review or meta-analysis)?	Document Type
Is the site under normal field conditions (no artificial pest release)?	Trial Setting

Data Extraction

Data were extracted on the individual studies level. Thus, multiple database entries (=studies) can stem from the same paper, as it might report results from several trials and/or several combinations of treatments and comparisons that are eligible for our research question. The following study level information were extracted: Country/Location, trial information (e.g. duration, design, treatment details), information on soil treatment (herbicide, fungicide), tested and comparator rotation description and pest suppression indicators, significance testing and results (if available), additional descriptive information from the results and discussion section of the study on the comparison of the two rotations.

3.2.2 Results

From 87 (published 2016 and later) retrieved via Scopus, only 5 papers were tested in a direct comparison the effect of legume inclusion into the crop rotation on associated pest suppression. The PRISMA flow chart is in ***Annex 2, Figure 2***. It is not present a main region where eligible trials have been conducted, they are from France, Finland, Germany, and Belgium (see ***Table 8***). The total duration of the trials ranged from two to nine years. Most trials tested intercrop treatments, just two tested rotation treatments. The trials were laid out either in a block or split-plot design with three to four repetitions. No site had extreme soil conditions.

Table 8.Overview of the eligible reports for associated pest suppression (N=5).

Report	Trial Design					
Reference	**Location**	**Trial duration (years)**	**Treatments tested**	**Experimental replications**	**Treatments included**	**Key findings related to pest control and crop performance**
Jalli et al. (2021)	Jokioinen, Finland	13	blocks of eight field plots	4 replicates	crop rotation: wheat monoculture, 2-yr rotation (turnip rape, wheat, barley), 4-yr rotation (including pea), under no-tillage and ploughing	crop rotation increased spring wheat yield, especially in diverse and no-till systems; crop rotation reduced plant diseases and affected weed species; no effect on wheat midge levels; integration of legumes and cereals beneficial for yield and disease reduction
Puliga et al. (2022)	Gembloux, Belgium	2	randomised complete block design	4 spatial replicates	winter wheat, winter pea, and wheat-pea mixed intercropping, different long-term organic matter management regimes	mixed wheat-pea intercrop increased generalist predator activity and predation rates compared with wheat monocrop; pea supported intermediate

						predator activity; no effect found of organic matter management on biocontrol potential
Jarvinen et al. (2023)	Finland	2	randomized block design	3-4 replicates	strip intercropping spring turnip rape and faba bean vs monocultures	intercropping reduced specialist turnip rape pest abundance; maintained or increased ratio of generalist arthropod predators to pests; no difference in total predator abundance; temporal shifts in predator assemblage observed
Hatt and Dring (2024)	Germany	3	split-split plot field experiment	4 replicated blocks	intercropping faba bean-wheat and bread seed poppy-barley, wildflower strips vs control field margin	intercropping reduced aphid and predator colonization compared to sole cropping; wildflower strips enhanced aphid predation nearby; intercropping suppressed weeds without significantly reducing crop yield; weed flowers supported natural enemies, indicating functional biodiversity benefit
Mansion-Vaquié et al. (2019)	Lyon, France	2015–2017	plot design	5 field sites (split-plot design)	wheat cultivar mixtures (Renan, Pireneo, Mix), with/without white clover intercrop	intraspecific wheat cultivar mixture did not consistently reduce aphids; intercropping with clover reduced aphid numbers and infestation rates variably by year; wheat yield and nitrogen content slightly reduced by clover intercropping; effect of diversification on aphids depended on year and plant traits.

In terms of positive effects, all five studies included at least some positive outcomes in the context of pest suppression or related ecosystem service delivery, although effects were generally inconsistent and often dependent on crop species, year, and local context (see ***Annex 3, Table 2***). The only rotation study, Jalli et al. (2021), demonstrated that a four-year crop rotation (CR4) including a pea legume phase led to a statistically significant reduction in wheat root and leaf diseases, recording an associated 21 percent increase in yield when compared with continuous monoculture.

Intercropping studies revealed more heterogeneous pattern. Hatt and Dring (2025) found that intercropping faba bean with wheat resulted in reduced aphid colonization rates. Additionally, the land equivalent ratio for faba bean-wheat intercrops confirmed an overall enhancement of productivity. A clearer effect was reported by Järvinen et al. (2023), where strip intercropping with faba bean significantly reduced specialist turnip rape pests in both years of the study. Predator activity relative to pest abundance increased significantly in 2019, although the effect was not reproduced in 2020. Similarly, Puliga et al. (2023) observed that wheat - pea intercrops, and the barley phase following pea, significantly enhanced the activity density of generalist predators, although predator-to-pest ratios showed mixed results depending on the specific comparison. In the clover–wheat system studied by Mansion-Vaquié et al. (2019), pest suppression outcomes were strongly year- and cultivar-dependent. While clover sometimes reduced aphid numbers or infestation rates, many comparisons showed no significant differences relative to wheat monoculture. Notably, wheat yield was consistently and significantly reduced under clover intercropping, underscoring the trade-offs that can arise from interspecific competition even when pest-related benefits are present.

Taking all systems into account, Jalli et al. (2021) provided clear and robust evidence for legume-enhanced pest suppression: the CR4, four-year rotation with pea delivered the most consistent yield and disease suppression, standing out as a recommended cropping system for northern European grain production. Integrating legumes into longer and more diverse crop rotations, as exemplified by the CR4 model, appears optimal for suppressing soil-borne pathogens and providing yield stability. The use of legume intercrops in combination with further functional diversity, such as wildflower strips or multi-species mixtures, may also accentuate biocontrol services. However, practitioners need to closely monitor and manage potential yield competition, particularly in systems with high legume or cereal density.

In summary, across the five records analysed, most documented positive effects of legumes in supporting pest suppression and related ecosystem services, with only two studies reporting notable negative impacts, generally linked to yield reductions or context-dependent pest pressures. Integrated and spatially diversified legume agroecosystems offer the greatest ecological return, although future research should focus on addressing remaining knowledge gaps in crop diversity, non-target pest impacts, and biodiversity outcomes.

Notable positive examples

- **Inclusion of a pea legume phase in the four-year crop rotation:** Four-year rotation with pea led to a statistically significant reduction in wheat root and leaf diseases, recording an associated 21 percent increase in yield when compared with continuous monoculture (Jalli et al., 2021).
- **Faba bean strips intercrop:** Intercropping faba bean-wheat and bread seed poppy-barley reduced aphid and predator colonization compared to sole cropping without significantly reducing crop yield (Hatt and Dring, 2024).

3.3 Weed suppression

3.3.1 Methods

Research Question:
What is the effect of legume integration into cropping systems on weed pressure?

Software:
Data extraction and synthesis was conducted with Excel.

Keywords
Keywords and additional Scopus settings have been implemented according to the eligibility criteria described in ***Table 2***, with search strings as described in ***Annex 1, Table 3***. Search was implemented in Scopus in September 2025.

Specific eligibility criteria

The eligibility criteria given in ***Table 9*** and ***Table 10*** have been applied during the screening process. A paper was deemed eligible for the next step if all questions were answered with yes. In the title and abstract screening phase papers were also taken into the next round if a question could be answered with "unsure".

Table 9.Specific eligibility criteria for weed pressure for the title, key words and abstract screening.

Criteria	Key element
Is the report about arable cropping systems (i.e. no agroforestry?)	Population
Is it an open-air field trial (i.e. no greenhouse, no modelling studies only)	Trial setting
Is the site under normal conditions (i.e. no rigged field)?	Trial setting
Are crop rotation(s) tested/compared?	Comparator
Is the effect on weed pressure measurable?	Outcome
Is it a report of primary research (i.e. no review studies or meta-analysis)	Document Type

Table 10.Specific eligibility criteria for weed pressure for the full-text screening

Criteria	Key element
Is it a report of primary research (i.e. no review studies or meta-analysis, no overview or synthesis studies)?	Document Type
Is the site under normal conditions (i.e. no rigged field)?	Trial Setting
Is it an open-air field trial (i.e. no greenhouse, no modelling studies only)?	Trial Setting
Is the report about arable cropping systems (i.e. no agroforestry)?	Population
Does the report contain side-by-side comparisons of legume and non-legume pre-crop rotations with the same main crop?	Intervention/Exposure
Are weed data reported (i.e. weed dry biomass, density, cover percentage) or can be calculated?	Outcome
Are weed data reported for the same (subsequent) crop for intervention and comparator?	Study Design
Is the legume system compared with a non-legume control under the same initial climatic conditions, soil properties, and main crop management practices?	Study Design

Data Extraction

Data were extracted on the individual studies level. Thus, multiple database entries (=studies) can stem from the same paper, as it might report results from several trials and/or several combinations of treatments and comparisons that are eligible for our research question. The following study level information were extracted: Country/Location, trial information (e.g. duration, design, treatment details), soil information, information on pesticide and fertiliser use, tested and comparator description (including legume-inclusive vs. legume-free crop rotations and legume-based intercropping vs. intercropping without legumes), weed-related data, significance testing and statistical outcomes (when available), as well as further descriptive information from the results and discussion sections concerning the comparison of the respective cropping systems.

3.3.2 Results

From 420 records retrieved via Scopus (published from 2016 to 2025), N=16 articles met the eligibility criteria for assessing the effect of legume integration on weed pressure across different cropping systems.

The most frequent reasons for excluding an article during full-text screening were: 1) weed data either not reported or not quantifiable, i.e. reported only qualitatively without dry biomass, density, or cover estimates; 2) the report did not contain side-by-side comparisons of legume and non-legume rotations with the same main crop; 3) confounding between legume effects and other management factors (e.g. fertilization or tillage) without proper control; or 4) impossible extract data by graphs through the commonly used tools. The PRISMA flow chart is in ***Annex 2, Figure 3***.

The majority of eligible trials have been conducted in EU, particularly Italy, Spain, Lithuania, Poland, Sweden, Germany, Finland, and one additional study from Turkey (see ***Table 11***). Most studies were carried out in open-field on-station trials, although several participatory on-farm trials were also included, reflecting practical relevance of experiments carried out under real farming conditions. The total duration of the trials ranged from one to thirteen years and covered a wide range of legume integration strategies, including cover crops (e.g. vetch, squarrose clover), living mulches (e.g. white clover, subterranean clover), cereal–legume intercrops (e.g. pea–barley, lentil–wheat, faba bean–wheat), and full crop rotations where legumes acted as main or pre-crop. Across the included studies, the integration of legumes generally showed a favourable effect on weed suppression. Approximately two-thirds of the studies reported a clear reduction in weed biomass, density or cover percentage compared to non-legume controls, suggesting that well-established legumes can effectively compete for light and resources. However, the overall response was not entirely uniform. In roughly one-third of cases, the suppressive effect was context-dependent, with species such as pea or clover showing limited competitiveness when grown in pure stands but becoming markedly more effective in mixtures or when intercropped with vigorous companion crops. Only a small minority of studies reported mixed or even negative effects, typically under conditions where legumes failed to establish sufficiently or where crop residues were poorly managed, allowing weeds to re-emerge. Overall, the evidence indicates that weed suppression is not an inherent property of legumes but rather a function of their ability to rapidly cover the soil, generate substantial biomass, and maintain continuous competitive pressure throughout the growing season.

Table 11.Overview of the eligible report for weed pressure (N=16).

Report	**Trial Design**					**Weed pressure**
Reference	**Location**	**Total trial duration**	**Trial Design**	**Treatments Tested**	**Legume Species**	**Effect on Weed**
Dorado et al., 2025	Madrid, Spain	8 years	comparison of three cropping systems under different management intensities	no-till barley vs reduced-input rotations with pea vs organic system with fallow–legume–barley	pea	Negative
Raimondi et al., 2025	Sassari, Italy	3 years	randomized complete block design testing intercropping in cardoon	cardoon grown alone vs intercropped with rocket, camelina, or hairy vetch	hairy vetch	Positive
Çağlar et al., 2025	Turkey (Ankara, Manisa)	1 growing season	randomized block design	vetch and ryegrass mixtures ranging from pure vetch to pure ryegrass	common vetch	Mixed (strong only in grass-

			with gradient mixture ratios			dominant mixtures)
Tavoletti et al., 2023	Ancona, Italy	2 years	split-plot design testing nitrogen × cropping pattern	sole barley, sole pea, and barley–pea mixtures under different nitrogen application levels	pea	Positive
Abou Chehade et al., 2023	Pisa, Italy	2 years	factorial design testing cover crop × termination method	rye, squarrose clover, and mixtures terminated by roller-crimper or green manure incorporation	squarrose clover	Mixed (strong only when used in mixture)
Abou Chehade et al., 2021	Pisa, Italy	1 growing season	split-plot design (tillage × cover crop species × termination)	rye, squarrose clover, and mixtures used as mulch under conventional tillage vs no-tillage	squarrose clover	Positive
Jalli et al., 2021	Jokioinen, Finland	13 years	3 rotation types × 2 tillage systems, 4 replicates	1) spring wheat monoculture; 2) spring turnip rape → spring wheat → spring barley; 3) spring turnip rape → spring barley → field pea. Each under ploughing and no-tillage.	pea	Negative
Marcinkevičienė et al., 2021	Vytautas Magnus University Agriculture Academy, Lithuania	3 years	randomized complete block design	sole, binary, and trinary crops including white clover with caraway	white clover	Mixed (suppression improved only in later years)
Cannon et al., 2020	2 sites (Cirencester,Gloucestershire), UK	2 years	randomized complete block design sole crop/bicrop × drilling pattern	Faba bean–wheat vs sole crops in broadcast/alternate-row layouts	faba bean	Positive
Diacono et al., 2018	Metaponto, Italy	2 years	factorial design (cover-crop termination x organic fertilization treatments)	barley, vetch, and mixtures used as cover crops; terminated by roller-crimper or incorporated as green manure	vetch (in mixture)	Mixed (mixture suppressive; pure vetch unstable across years)
Wanic et al., 2018	Olsztyn, Poland	3 years	factorial design (winter wheat subspecies x preceding crops	wheat/spelt grown after pea vs after oilseed rape vs after cereal	pea (as pre-crop)	Positive
Gawęda et al., 2018)	Lublin, Poland	4 years	randomized block design (rotation × tillage)	winter wheat grown after soybean vs after rapeseed under conventional vs no-till	soybean (as pre-crop)	Positive
Woźniak & Soroka, 2018	Lublin, Poland	3 years	complete subblocks	rotations with pea vs cereal monoculture under	pea (as pre-crop)	Positive

			(rotation × tillage)	conventional tillage, reduced tillage, no-tillage		
Caballero et al., 2017	2 sites (Baldomar, Sant Antolí) Spain	3 years	randomized complete block (8 integrated weed management strategies x site)	rotations including sunflower/pea with different herbicide timings	field pea (in rotation)	Mixed (suppression depended on herbicide timing)
Masilionytė et al., 2017	Joniškėlis, Lithuania	7 years	randomized complete block design (rotation x post-harvest cover crops)	lupine + radish vs mustard (+ buckwheat) as cover crops	narrow-leafed lupine (in mixture)	Mixed (less suppressive than mustard options)
Costanzo and Bàrberi, 2016	Pisa, Italy	3 years	two-factor randomized complete block (cultivar x living mulch presence/absence)	wheat grown with subterranean clover living mulch vs control	subterranean clover	Positive

Across the 16 field- studies reviewed (see ***Annex 3, Tables 3 and 4***), legume integration into arable systems generally exerted a suppressive effect on weeds, although the magnitude and consistency of the response varied depending on crop type and management practices. The clearest and most consistent suppressive outcomes were observed when legumes were used as cover crops or mulches with sufficient biomass accumulation prior to termination. Hairy vetch emerged as one of the most reliable suppressive species, especially when intercropped or used as a winter cover crop (Raimondi et al., 2025; Çağlar et al., 2025; Diacono et al., 2018), with reported reductions in weed biomass reaching up to 80% compared to non-legume controls. Similar trends were observed for squarrose clover and subterranean clover, whose suppressive strength increased markedly when used in mixtures with grasses or cereals (Abou Chehade et al., 2021, 2023; Costanzo and Bàrberi, 2016). In studies where termination was performed too early or residues were incorporated rather than retained as surface mulch, weed control efficacy declined sharply despite equivalent legume biomass (Diacono et al., 2018; Abou Chehade et al., 2021), highlighting the importance of soil coverage and residue persistence in mediating suppression.

When legumes were used as living mulch under main crops, the results were mostly positive, but dependent on the context. For instance, in Italy, Costanzo and Bàrberi (2016) found that subterranean clover in durum wheat consistently reduced dicotyledonous weeds without penalizing yields. Moreover, green manure mixtures of hairy vetch and clover also effectively suppressed weeds under reduced or no tillage conditions (Abou Chehade et al., 2021, 2023). However, under unfavourable establishment conditions or early interruption, the suppression effects weakened, confirming that biomass accumulation and canopy persistence are key factors in weed control.

Intercropping trials further confirmed the suppressive capacity of legumes when sown together with cereals or industrial crops rather than alone. Either pea or beans intercropped with wheat or barley consistently reduced weed abundance compared to grain legumes as sole crop, leveraging rapid canopy closure and complementary use of resources (Tavoletti et al., 2023; Cannon et al., 2020). Similarly, hairy vetch intercropped with cardoon or ryegrass improved suppression compared to pure stands (Raimondi et al., 2025; Çağlar et al., 2025). Where legumes were the main crops, weed suppression was often weaker or inconsistent (Çağlar et al., 2025).

Evidence from crop rotations reinforced the suppressive role of legumes across seasons, though responses were more variable. In Spain, pea-based reduced-input rotations showed higher in-season weed density during the legume crop growth but reduced weed infestations in subsequent barley crops (Dorado et al., 2025). Similar effects were observed in Poland, where wheat or spelt following pea or soybean exhibited lower weed densities than after non-legume crops (Wanic et al., 2018; Gawęda et al., 2018; Woźniak and Soroka, 2018). In Lithuania, rotations including white clover or lupine also influenced weed dynamics, though effects due to cover crop composition and seasonal conditions (Marcinkevičienė et al., 2021; Masilionytė et al., 2017).

A minority of studies reported negative or mixed outcomes, typically associated with low establishment, unfavourable termination timing, or insufficient soil cover. For instance, in Spain and Lithuania, legume-based covers provided a fewer suppression when managed under suboptimal conditions or mixed with less competitive species (Caballero et al., 2017; Masilionytė et al., 2017).

Overall, the evidence from the 16 studies indicates that legumes suppress weeds most effectively when three conditions are met: (1) rapid establishment leading to dense ground cover, (2) residue persistence maintained through minimal soil disturbance, and (3) complementary pairing with competitive cereals or grasses. Legume cover crops such as vetch and clover were the most reliable suppressors across cropping systems, whereas grain legumes (e.g., peas, lentils, soybeans) showed more variable effects that also depended on their proportion within the intercrop and upon the trials' experimental design. Long-term experiments also suggest that legumes not only reduce weed biomass but can also stabilize weed communities by preventing the dominance of highly competitive species. Thus, rather than removing weeds entirely, inserting legumes into cropping systems reduce weed specialization leading toward less aggressive weed communities, promoting the establishment of a more balanced flora, particularly in diversified or low-input systems.

In conclusion, diversifying cropping systems through the integration of legumes is a promising strategy for reducing dependence on herbicides, particularly when they are legume-based designed. Their suppression capacity is greatest when all legumes ecosystem services are efficiently exploited i.e., covering the soil, intercepting light, and occupying ecological niches, rather than serving solely as sources of nitrogen. When used in this way, legumes can serve as keystone species in ecological weed management, contributing to resilient and sustainable agricultural systems.

Notable positive examples

- **Hairy vetch intercropped or used as a winter cover crop:** Reducing weed biomass up to 80% compared to non-legume controls (Raimondi et al., 2025; Çağlar et al., 2025; Diacono et al., 2018).
- **Squarrose clover and subterranean clover in mixtures with grasses or cereals:** High weed suppression strength (Abou Chehade et al., 2021, 2023; Costanzo and Bàrberi, 2016).

3.4 Soil health and quality

3.4.1 Methods

Research Question:
What is the effect of legume integration into cropping systems on soil health and soil quality?

Software:
Data extraction and synthesis was conducted with Excel.

Keywords
Keywords and additional Scopus settings have been implemented according to the eligibility criteria described in ***Table 2***, with search strings as described in ***Annex 1, Table 4***. Search was implemented in Scopus in June 2025.

Specific eligibility criteria
The eligibility criteria given in ***Table 12*** and ***Table 13*** have been applied during the screening process. A paper was deemed eligible for the next step if all questions were answered with yes. In the title and abstract screening phase papers were also taken into the next round if a question could be answered with "unsure".

Table 12.Specific eligibility criteria for associated biodiversity for the title, key word and abstract screening.

Criteria	Key element
Is it a report of primary research (i.e. excludes review, meta-analysis, modelling, or overview studies)?	Document Type
Is the trial conducted under field conditions (i.e. no greenhouse, lysimeter, or pot studies)?	Trial Setting
Is the site under normal agronomic conditions (i.e. no artificially rigged or degraded soils)?	Trial Setting
Is the study focused on arable cropping systems (i.e. excludes grasslands, orchards, or agroforestry)?	Population
Does the study include a legume-based system compared directly with a non-legume control (pre-crop or rotation)?	Intervention/Exposure
Are soil health or soil quality parameters measured directly (i.e. physical, chemical, or biological soil indicators)?	Outcome

Table 13.Specific eligibility criteria for associated biodiversity for the full-text screening.

Criteria	Key element
Is it a report of primary research (i.e. no review studies or meta-analysis, no overview or synthesis studies)?	Document Type
Is the site under normal conditions (i.e. no rigged field)?	Trial Setting
Is it an open-air field trial (i.e. no greenhouse, no modelling studies only)?	Trial Setting
Is the report about arable cropping systems (i.e. no agroforestry)?	Population
Are crop rotation/rotations tested?	Intervention/Exposure
Is the effect of soil health/soil quality measurable?	Outcome
Is it a report of primary research (i.e. no review studies or meta-analysis, no overview or synthesis studies)?	Study Design
Is the site under normal conditions (i.e. no rigged field)?	Study Design

Data Extraction:

Data were extracted on the individual studies level. Thus, multiple database entries (=studies) can stem from the same paper, as it might report results from several trials and/or several combinations of treatments and comparisons that are eligible for our research question. The following study level information were extracted: Country/Location, trial information (e.g. duration, design, treatment details), soil information, information on pesticide and fertiliser use, tested and comparator rotation description and biodiversity numbers (incl. indicator), significance testing and results (if available), additional descriptive information from the results and discussion section of the study on the comparison of the two rotations.

3.4.2 Results

Out of 75 publications screened (2016–2025), only 7 field studies met the criteria for assessing legume integration effects on soil health and quality. These trials were mostly in Canada (3), Italy (2), and Spain (2), ranging from short-term (1–3 years) to long-term (5–17 years) field rotations (***Table 14***). All compared cropping systems *with vs. without legumes* under realistic farm conditions. The legumes examined included grain legumes like pea, faba bean, soybean, typically in rotation with cereals. Non-legume controls were usually continuous cereal monocultures or cereal-based rotations without legumes. Trials often had additional management factors (e.g. tillage intensity or organic vs. conventional practices), but all provided direct comparisons isolating the legume rotation effect. No extreme soil conditions were present, ensuring results are broadly applicable. The most frequent reasons why an article was excluded during full-text screening is because: i) legumes were not part of crop rotation schemes or even present on the studies; ii) pot experiments or not field experiments or conducted in greenhouse; iii) unfavourable experimental site conditions. The PRISMA flow chart is in ***Annex 2, Figure 4***.

Table 14.Overview of the eligible report for soil health and quality (N=7).

Report	Trial Design				Soil	
Reference	**Location**	**Total trial duration**	**Treatments tested**	**Replications**	**Texture (wording as provided in the reference)**	**pH**
Lavergne et al., 2025a	Quebec, Canada	2019-2021	farm management practices x Crop rotation	3	30.4% clay, 30.6% sand, 39.0 silt	Mean 6.2 (range 5.1–7.3)
Nascimento et al., 2025	Leida, Spain	2019-2022	fertilizer treatment x crop rotation	3	clay loam (38% sand, 34% silt and 28% clay)	8.3
Lavergne et al., 2025b	Quebec, Canada	2019-2021	intensive cropping systems under organic management x crop rotation	3	Fine, Medium, and Coarse (classified from sand, silt, and clay content following Moebius-Clune et al., 2016).	NA
Carrascosa et al., 2024	Spain, Santomera, Murcia	2022	short term crop rotation x intercropping	6	clay-loam	8.1
Stagnari et al., (2020)	Mosciano Sant'Angelo, Italy	2010-2017	tillage practices x crop sequences	3	23% sand, 45% silt, 32% clay	8
Agomoh et al., (2020)	Woodslee, Canada	2001-2018	crop rotation	4	clay loam	ranged from 5.8 to 6.9

Landi et al., (2018)	Vercelli, Italy	2010-2015	crop rotation x farming system	NA	27.22-35.44% sand, 52.84-62.76% silt and 9.17-11.77% clay	4.89-5.75

Improved soil organic matter and nutrient availability

Across these studies, legume-inclusive rotations generally maintained or enhanced soil organic matter and fertility relative to rotations lacking legumes. In Spain, for example, a pea–wheat rotation clearly outperformed a cereal-only sequence. Soils following pea had significantly higher microbial biomass and far less loss of soil organic carbon (SOC) over time. The pea rotation mitigated SOC decline by 78% compared to a wheat-only rotation (Nascimento et al., 2025).

Similarly, a study of 90 organic fields in Canada found that greater crop diversity, often achieved by including soybean and cover crops in rotation, was strongly associated with improved soil structure and carbon levels (Lavergne et al., 2025a). In that study, fields with high diversity indices showed better aggregate stability and moisture retention, indicating legumes contributed to building soil physical health despite intensive organic management. Total soil nitrogen (TN) tended to follow SOC trends. Several legume systems modestly increased or preserved TN relative to non-legume controls. However, results varied with management, where heavy tillage was used, the gains in SOC from legumes were less pronounced (Lavergne et al., 2025a).

A long-term trial in Italy (7 years) reported no significant difference in SOC or total N between continuous wheat and a wheat–faba bean rotation, suggesting that other factors (e.g. tillage or drought) can override rotation benefits in the short term (Stagnari et al., 2020). Overall, though, the inclusion of legumes has shown positive effects on soil carbon and nutrients, helping to replenish organic matter inputs and biological nitrogen fixation into cropping systems.

Biological soil health improvements

Legume integration consistently boosted biological indicators of soil health. Microbial activity and soil fauna benefited from legume presence across diverse contexts. In a rotation trial in Spain, soil enzyme activities (β-glucosidase, phosphatase, urease, dehydrogenase) were significantly higher under rotations including pea (and cowpea intercrops) compared to a non-legume control, reflecting enhanced microbial nutrient cycling due to legumes in the system (Carrascosa-Robles et al., 2024). Likewise, when pea was grown before wheat, the subsequent wheat crop saw only a minimal drop in soil microbial biomass carbon during residue decomposition (an 86% smaller decrease than observed without a preceding legume), indicating that pea residues helped sustain microbial communities (Nascimento et al., 2025).

Soil fauna also responded positively to legumes. In an organic rice system in Italy, introducing a soybean phase before the rice crop greatly increased beneficial nematode populations (Landi et al., 2018). Key soil food web metrics such as the Basal Index and Channel Index were significantly higher under the soybean-inclusive rotation. Bacterivorous and fungivorous nematodes, for instance, increased by 200–300% compared to a conventional rice system without legumes (Landi et al., 2018). This suggests that legumes, when introduced during organic conversion, can stimulate soil biodiversity and foster more active nutrient cycling networks.

Not all biological groups responded strongly, for instance, a study on Canadian organic farms reported no significant differences in earthworm abundances between fields with a maize–soybean–cereal rotation and adjacent fields without cropping, implying that earthworm communities were maintained regardless of the soybean crop (Lavergne et al., 2025b). However, overall trends indicate that legumes, by providing high-quality residues and root exudates, tend to enrich soil biota more effectively than cereal-only systems do.

While positive effects dominated, a few studies reported negative or mixed outcomes under certain conditions. Importantly, only 2 of the 7 studies documented any clear negative impacts of legumes on soil health, and these were context-specific trade-offs rather than general trends. Agomoh et al. (2019) conducted a 17-year field trial in Canada comparing monoculture winter wheat with three legume-inclusive rotation schemes: soybean–winter wheat (S–WW), corn–soybean–winter wheat (C–S–WW), and winter wheat–soybean–soybean (WW–S–S). The study found that total soil carbon and nitrogen stocks were significantly lower in the diversified rotations than in the wheat monoculture. Total carbon declined from 27 g kg^{-1} in continuous wheat to 22–23 g kg^{-1} in the legume-based rotations, and total nitrogen dropped from 2.7 to 2.2 g kg^{-1}. These reductions, most evident in legume rotations including red clover, suggest that elevated N inputs from legumes accelerated microbial SOM turnover. Although crop productivity increased under the legume-inclusive rotations, the study highlights a potential trade-off between yield gains and long-term soil carbon retention when high-N legumes like red clover are used without sufficient carbon return. This represents the only included study in the review to report a statistically significant negative effect of legumes on soil C and N stocks.

Another nuanced outcome came from the organic rice study in Italy. despite overall improvements in soil biology, the legume (soybean) rotation had higher levels of plant-parasitic nematodes than an integrated (legume-free) system, suggesting that the organic legume system initially lacked predators to control certain pests (Landi et al., 2018). Additionally, soil structure indicators in that organic legume system (e.g. nematode maturity and structure indices) were lower than in the non-legume reference, pointing to a more disturbed soil food web during the early years of conversion (Landi et al., 2018). These findings illustrate that legume benefits might come with short-term costs, such as flushes of nutrient mineralization or temporary imbalances in soil biota, especially in systems with abrupt management changes. It’s also worth noting that some trials observed no significant change in certain soil parameters with legumes (e.g. the faba bean rotation showing no SOC increase in Stagnari et al. (2020), and earthworm counts remaining steady in Lavergne et al., 2025b). Such neutral results indicate that legume effects can be subtle or require longer-term accumulation under specific conditions.

Notable positive examples

Several “model” legume rotations emerged with outstanding benefits.

- **A pea–wheat rotation** highlighted by Nascimento et al. (2025) showed that pea as a precursor crop substantially improved short-term soil C and microbial biomass without any evident downsides. This rotation achieved a clear win for soil quality, greatly slowing SOC decline and boosting microbial indicators compared to continuous wheat.
- **Adding a legume phase into a Mediterranean vegetable rotation** also yielded rapid benefits. For example, including pea into a purslane rotation raised soil enzyme levels within one season

(Carrascosa-Robles et al., 2024). This quick increase in enzymes underlines how fast legumes can improve soil biological functioning even in intensive vegetable systems.

These examples showcase the potential of specific legume species: pea stands out for building soil organic matter and fertility in rotations, and soybean stands out for stimulating soil biological activity and nutrient turnover. Integrating such legumes in rotations can thus be considered a best-practice model for enhancing different facets of soil health.

3.5 Associated biodiversity

3.5.1 Methods

Research Question:
What is the effect of legume integration into cropping systems on associated above-ground biodiversity?

Software:
Data handling and screening was conducted using CADIMA. Data extraction and synthesis was conducted with Excel.

Keywords
Keywords and additional Scopus settings have been implemented according to the eligibility criteria described in ***Table 2***, with search strings as described in ***Annex 1, Table 5***. Due to very low number of eligible studies, the search has been expanded additionally to studies before 2016 (all other settings though have been kept similarly) with the hope to increase the number of eligible hits --> in the process the two searches have undergone the same analysis but have kept as separate datasets (“2016+”, “before 2016”) in order to ensure compliance and coherence within overall task. Search was implemented in Scopus in June 2025.

Specific eligibility criteria
The eligibility criteria given in ***Table 15*** and ***Table 16*** have been applied during the screening process. A paper was deemed eligible for the next step if all questions were answered with yes. In the title and abstract screening phase papers were also taken into the next round if a question could be answered with “unsure”.

Table 15.Specific eligibility criteria for associated biodiversity for the title and abstract screening.

Criteria	Key element
Is the report about arable cropping systems (i.e. no agroforestry?)	Population
Is it an open-air field trial (i.e. no greenhouse, no modelling studies only)?	Trial setting
Is the site under normal conditions (i.e. no rigged field)?	Trial setting
Are crop rotation(s) tested/compared?	Comparator
Is the effect on above-ground biodiversity measured (i.e. no soil diversity and no studies solely focussing on individual species (abundance))?	Outcome
Is it a report of primary research (i.e. no review studies or meta-analysis)?	Document Type

Table 16.Specific eligibility criteria for associated biodiversity for the full-text screening.

Criteria	Key element

Is it a report of primary research (i.e. no review studies or meta-analysis, no overview or synthesis studies)?	Document Type
Is the site under normal conditions (i.e. no rigged field)?	Trial Setting
Is it an open-air field trial (i.e. no greenhouse, no modelling studies only)?	Trial Setting
Is the report about arable cropping systems (i.e. no agroforestry)?	Population
Does the report contain side-by-side comparisons of legume and non-legume pre-crop rotations with the same main crop?	Intervention/Exposure
Are species richness or diversity indices reported or can be calculated?	Outcome
Are biodiversity data reported for the same (subsequent) crop for intervention and comparator?	Study Design
Are the initial climatic conditions, soil properties, and main crop management practices the same in both rotations?	Study Design

Data Extraction

Data were extracted on the individual studies level. Thus, multiple database entries (=studies) can stem from the same paper, as it might report results from several trials and/or several combinations of treatments and comparisons that are eligible for our research question. The following study level information were extracted: Country/Location, trial information (e.g. duration, design, treatment details), soil information, information on pesticide and fertiliser use, tested and comparator rotation description and biodiversity numbers (incl. indicator), significance testing and results (if available), additional descriptive information from the results and discussion section of the study on the comparison of the two rotations.

3.5.2 Results

From 372 (published 2016 and later), and 275 records (published before 2016) retrieved via Scopus, only N=6, and respectively N=1 article were tested in a direct comparison the effect of legume inclusion into the crop rotation on associated above-ground biodiversity. The most frequent reasons why an article was excluded during full-text screening is because: 1) the report did not contain side-by-side comparisons of legume and non-legume rotations with the same main crop; 2) biodiversity data were not reported for the same (subsequent) crop; 3) species richness or diversity indices were nor reported or could ne not calculated based on the provided information, instead many studies only reported weed abundance, biomass or provided a list of the most dominant species, but not full species lists; or 4) the initial climatic conditions, soil properties or main crop management practices were not the same in both rotations so that the legume effect could not undoubtedly be extrapolated. The PRISMA flow chart is in ***Annex 2, Figures 5 and 6***.

The majority of eligible trials have been conducted in Eastern Europe, namely Poland and Serbia (see ***Table 17***). One trial has been conducted in Spain. This study is also the only eligible report published before 2016. The total duration of the trials ranged from three to eleven years. Most trials tested several treatments, the majority crop rotations in combination with tillage regimes. Thus, more than one study/case per report is existing (total: n= 55). Th trials were laid out either in a block or split plot design with three to four repetitions. No site had extreme soil conditions.

All articles exclusively studied arable flora diversity (weeds) as an indicator for associated biodiversity. Except for Wanic et al. (2018), who calculated a range of different biodiversity indices, all studies described arable flora biodiversity by means of species richness (see ***Table 6 in Annex 3***). Legumes under study were pea (n=17 cases), vetch and soybean. There were tested in rotation with cereals and were compared against crop rotations of continuous cereal rotations (wheat, spelt, barley, maize) or rotations of oilseed-cereal. One eligible trial (Simić et al. 2020) also tested different cover crops. Arable flora species richness across the eligible studies ranged from two to 22 different species (mean: 12.7) in rotations without legumes and from six to 26 different species (mean: 12.9) in rotations with legumes.

Table 17.Overview of the eligible report for associated biodiversity (N=7).

Report	Trial Design				Soil	
Reference	**Location**	**Total trial duration**	**Treatments tested**	**Replica-tions**	**Texture (wording as provided in the reference)**	**pH**
Woźniak (2020)	Lublin, Poland	2007-2018	tillage x crop rotation; measured at cereal heading and tillering stage	3	24.5% silt, 13.7% dust	7.4
Wanic et al. (2018)	Olsztyn, Poland	2011-2016	wheat subspecies x crop rotation; measured at cereal heading and tillering stage	4	silty fine clay	slightly acidic
Simić et al. (2020)	Belgrade, Serbia	2011-2016	cover crops	4	47% clay and silt, 53% sand	7.8
Woźniak & Soroka (2018)	Lublin, Poland	2007-2017	crop rotation x tillage	3	sandy loam	7.2
Gawęda et al. (2018)	Lublin, Poland	2014-2017	pre-crop x tillage	3	sandy loam	7.7
Simić et al. (2016)	Belgrade, Serbia	2009-2012	crop rotation x weed management	4	47 % clay and silt, 53 % sand	7.8

Simić et al. (2020) tested the effect of different cover crops, including vetch, versus non-leguminous crops and no cover cropping on arable flora richness in the proceeding maize crop. Of the five species tested, common vetch was the most effective at suppressing weeds in general, which in this case also resulted in a reduced number of species and individual counts, as well as both fresh and dry biomass. The studies of Wanic et al. (2018) and Woźniak (2020) compared associated biodiversity in response to crop rotations at two cereal growth stages. Here, diversity responses were not uniform. In wheat and spelt, self-succession decreased diversity at the tillering stage. At the heading stage, wheat showed its highest associated biodiversity, while spelt showed its lowest diversity and evenness. Dominance of arable flora species remained largely unchanged across pre-crops (Wanic et al., 2018). In spring barley, arable flora species richness varied across stages: there were more species after pea than wheat at tillering (BBCH 23-24), but the opposite occurred at milk maturity (BBCH 73-74) (Woźniak, 2020). The trial of Woźniak & Soroka (2018) showed that rotations that including pea supported a richer weed flora than cereal monoculture. This is consistent Simić et al. (2016) explanation of their results, that continuous monocropping fosters the dominance of “problem” species, whereas diversified rotations distribute advantage across years and tend to even associated biodiversity. Dorado et al. (1999) also found out that many of the arable flora species that respond best to crop rotation are winter annuals, whose life cycles coincide with those of crops such as barley and vetch. This helps to explain the significant effects of crop rotation observed in such systems.

In conclusion, the studies overall show the tendency that crop rotations with legumes compared to the ones without legumes do shape weed communities. However, *no consistent effect direction of legume* *inclusion into the rotations across trials was found* (see ***Table 6 in Annex 3***); In some cases, species richness was higher after legumes, while in others it was not. Similarly, the comparison rotation that was selected did not demonstrate a distinct pattern. This suggests that other factors are at play, indicating the need for further research.

3.6 Climate resilience

3.6.1 Methods

Research Question:
What is the effect of legume integration into cropping systems on climate resilience?

Software:
Data extraction and synthesis was conducted with Excel.

Keywords
Keywords and additional Scopus settings have been implemented according to the eligibility criteria described in ***Table 2***, with search strings as described in ***Annex 1, Table 6***. Search was implemented in Scopus in September 2025.

Specific eligibility criteria
The eligibility criteria given in ***Table 18*** and ***Table 19*** have been applied during the screening process. A paper was deemed eligible for the next step if all questions were answered with yes. In the title and abstract screening phase papers were also taken into the next round if a question could be answered with "unsure".

Table 18.: Specific eligibility criteria for climate resilience for the title, key word and abstract screening.

Criteria	Key element
Is the report about arable cropping systems (i.e. no agroforestry?)	Population
Is it an open-air field trial (i.e. no greenhouse, no modelling studies only)?	Trial setting
Is the site under normal conditions (i.e. no rigged field)?	Trial setting
Are crop rotation(s) tested/compared?	Comparator
Is the effect on climate resilience measurable?	Outcome
Is it a report of primary research (i.e. no review studies or meta-analysis)?	Document Type

Table 19.Specific eligibility criteria for climate resilience for the full-text screening.

Criteria	Key element
Is it a report of primary research (i.e. no review studies or meta-analysis, no overview or synthesis studies)?	Document Type
Is the site under normal conditions (i.e. no rigged field)?	Trial Setting
Is it an open-air field trial (i.e. no greenhouse, no modelling studies only)?	Trial Setting
Is the report about arable cropping systems (i.e. no agroforestry)?	Population
Does the report contain side-by-side comparisons of legume and non-legume pre-crop rotations with the same main crop?	Intervention/Exposure
Are climate resilience related data reported (i.e. GHG emissions, N_2O emissions, yield stability in dry years) or can be calculated?	Outcome

Are climate resilience related data reported for the same (subsequent) crop for intervention and comparator?	Study Design
Is the legume system compared with a non-legume control under the same initial climatic conditions, soil properties, and main crop management practices?	Study Design

Data Extraction

Data were extracted on the individual studies level. Thus, multiple database entries (=studies) can stem from the same paper, as it might report results from several trials and/or several combinations of treatments and comparisons that are eligible for our research question. The following study level information were extracted: Country/Location, trial information (e.g. duration, design, treatment details), soil information, information on pesticide and fertiliser use, tested and comparator rotation description and climate resilience related data, significance testing and results (if available), additional descriptive information from the results and discussion section of the study on the comparison of the two rotations.

3.6.2 Results

From 601 records retrieved via Scopus (published from 2016 to 2025), N=6 articles met the eligibility criteria for assessing the effect of legume integration on climate resilience across different cropping systems. The most frequent reasons why an article was excluded during full-text screening is because: 1) the report dealt with application of different modelling systems and prediction models for climate resilience; or 2) confounding between legume effects and other management factors (e.g. fertilization or tillage) without proper control. The PRISMA flow chart is in ***Annex 2, Figure 7***.

All trials have been conducted in EU, particularly Italy, France, Germany, Latvia, Sweden, United Kingdom and Denmark (see ***Table 20***). All studies were carried out in open-field on-station trials. The total duration of the trials ranged from one to over forty years and covered a wide range of legume integration strategies, including cover crops (e.g. hairy vetch, common vetch, crimson clover, squarrose clover), and full crop rotations where legumes acted as main or pre-crop. Across the included studies, the integration of legumes generally showed a favourable effect on climate resilience. Most of the studies reported positive effect on climate resilience parameters of perennial legume crops, including reduced GHG emissions, increased carbon soil sequestration and yield stability in dry years. In some cases, negative effect, particularly of grain legumes, on N_2O emissions was reported. Generally, the studies highlighted the need for strategic selection of legume crops as they can improve nutrient cycling and mitigate environmental impacts, but also increase N_2O emissions, necessitating careful management.

Table 20.Overview of the eligible report for climate resilience (N=6).

Report	**Trial Design**					**Weed pressure**
Reference	**Location**	**Total trial duration**	**Trial Design**	**Treatments Tested**	**Legume Species**	**Effect**
Fiorini et al., 2025	Gabbioneta-Binanuova, Italy	3 years	Comparison of nine cropping systems	Soybean-rye+hairy vetch -sunflower- rye+hairy vetch -maize; Soybean- ray+tillage radish -sunflower- ray+tillage radish -maize; Soybean-hairy vetch+tillage radish -sunflower-hairy vetch+tillage radish -maize; Soybean-rye+hairy vetch+tillage	Hairy vetch, common vetch, crimson clover and squarrose clover	**Positive:** Hairy vetch monoculture on annual soil carbon sequestration **Negative**: Hairy vetch monoculture

				radish -sunflower- rye+hairy vetch+tillage radish -maize; Soybean-rye+ hairy vetch+common vetch +radish+black oat +common oat+crimson clover+squarrose clover-sunflower- rye+ hairy vetch+common vetch +radish+black oat +common oat+crimson clover+squarrose clover -maize		on increased N_2O emissions.
Skovgaard Andersen et al., 2025	Taastrup, Denmark	1 year	Comparison of two leguminous CC species– hairy vetch and crimson clover and from two non-leguminous CC species– oilseed radish and winter rye	Spring barley-fallow; Spring barley-hairy vetch; Spring barley-crimson clover; Spring barley-oilseed radish; Spring barley-winter rye	Hairy vetch and crimson clover	**Neutral:** No significant effect on N_2O emissions
Vaziritabar et al., 2025	Giessen, Germany	36 years	Long-term experiments (LTEs) with different pre-crops	Maize-winter wheat-winter ray-spring barley; Summer oat-winter wheat-winter ray-spring barley; Field bean-winter wheat-winter ray-spring barley; Crimson clover- winter wheat-winter ray-spring barley; Hairy vetch-winter wheat-winter rye-spring barley	Field bean, crimson clover and hairy vetch	**Positive:** Perennial legumes promote higher winter wheat and spring barley yields in dry years
Valujeva et al., 2023	Peterlauki, Latvia	5 years	Comparison of four cropping systems in reduced and conventional tillage	Winter wheat-winter wheat-winter rapeseed-winter wheat-winter wheat – reduced and conventional tillage; Winter rapeseed-spring barley-field beans-winter wheat-spring rapeseed - reduced and conventional tillage; Field beans-winter wheat-winter rapeseed-spring barley-field beans - reduced and conventional tillage; Spring barley-field beans- winter wheat-winter rapeseed-spring barley - reduced and conventional tillage	Field bean	**Positive:** Reduction of N_2O emission from clay soils
Reckling et al., 2022	Lanna, Stenstugu, and Säby, Sweden; Tulloch, Scotland;	Over 40 years (SE); 24 years	LTEs with different cropping systems	(SE) Oilseed crop-winter wheat-spring oat-spring barley + undersown ley-red clover/grass ley -red clover/grass ley; Oilseed	Red clover, clover, winter pea	**Positive:** Perennial legumes on environmental adaptability of

	Auzeville, France	(UK); 12 yeas (FR)		crop -winter wheat-spring oat-spring barley+undersown ley grass ley; Oilseed crop-winter wheat-spring oat-spring barley-spring wheat-slack fallow (UK) Clover/grass ley-clover/grass ley-clover/grass ley-oat-swede-undersown oat; Clover/grass ley-clover/grass ley-clover/grass ley-clover/grass ley-oat-undersown oat (FR) Durum wheat-sorghum-sunflower; Durum wheat-sunflower-winter pea/winter faba bean	and winter faba bean	cereal crops; **Negative:** Grain legumes yield reduction of cereals in high yielding environments
Plaza-Bonilla et al., 2018	Auzeville, France	6 years	Two 3-year rotation cycles	Sorghum-sunflower–durum wheat; Sunflower-winter pea–durum wheat; Sunflower-spring pea–durum wheat; Sorghum-vetch cover crop-sunflower-rye+vetch cover crop—durum wheat; Sunflower-mustard cover crop-winter pea-mustard cover crop–durum wheat; Sunflower-spring pea-mustard cover crop–durum wheat-mustard cover crop	Winter and spring pea, vetch in mixture as cover crop	**Positive:** Reduction in external and on-site emissions related to N fertilizers **Negative:** Introduction into low input crop rotations led to SOC losses

Yield stability

Although diversifying European cropping systems by legume introduction can improve the performance of cereals by increasing productivity and environmental adaptability, Reckling et al. (2022) fond that their effects on cereal yield stability can be inconsistent. The authors studied diversification through (i) introduction of perennial leys (red clover and clover), (ii) increasing the proportion of ley in the rotation, (iii) varying the order in which crops are positioned in the rotation, (iv) introduction of grain legumes (winter pea and winter faba bean), and (v) introduction of cover crops. For those five diversification measures tested in their study, they concluded that (i) diversification through perennial grass and legume crop mixtures outperformed systems without leys with higher environmental adaptability of the cropping systems with perennial leys, especially in low-input systems, (ii) diversification through the length of the perennial ley did not affect yield stability or environmental adaptability and that (iii) diversification through the integration of grain legumes indicated increased yields in lower-yielding years compared to the system without the grain legume. However, they also observed that the inclusion of grain legumes tended to reduce yields of cereals in high yielding environments.

In their study, Vaziritabar et al. (2025) found that in long-term crop rotation, green fallow generally outperforms bare fallow, grain legumes, and cereals in crop yield, nitrogen use efficiency, and soil health. Climate-smart rotations with clover or vetch green fallows increased soil nitrogen availability and enhanced the performance of subsequent crops, including cereals. Furthermore, in dry years, the impact of green fallow was higher particularly for winter wheat and spring barley compared to oat and maize as pre-crops.

GHG emissions

Valujeva et al. (2023) investigated the combination of environmental and management factors reducing N_2O, CO_2, and CH_4 emissions from clay soil in temperate climates. They observed lower average N_2O emissions and CH_4 assimilation in crop rotation systems including field beans, along with the highest average GHG emission budget indicating the potential of this grain legume for reducing N_2O emission from clay soils. The authors indicated that additional research is needed to investigate the effects of field beans on reducing CO_2 emissions, increasing carbon sequestration and CH_4 assimilation. Furthermore, their study indicated that the volumes of GHG emissions were also significantly influenced by the interaction of environmental and management factors, where precipitation is the most significant factor in the interaction with other environmental factors, soil tillage, and crop residues for N_2O and CO_2 emissions, while CH_4 emissions were influenced by the interaction of air temperature with other environmental factors, soil tillage, and crop residues.

Contrasting results were observed by Fiorini et al. (2025) who measured N_2O emissions and soil health indicators to assess the environmental impact of cover crops, and where another legume crop, hairy vetch, increased N_2O emissions. However, this legume in mixture with rye balanced high N input, moderated N_2O emissions, and strong C sequestration. In study of Skovgaard Andersen et al. (2025), who investigated the effect of two leguminous (crimson clover and hairy vetch) and two non-leguminous (oilseed radish and winter rye) cover crops on N_2O emissions upon spring tillage on a sandy loam soil, the same legume crop did not significantly elevate N_2O emissions, indicating a trade-off between fertility and greenhouse gas emissions.

Soil organic carbon

Plaza-Bonilla et al. (2018) aimed to quantify the C footprint of six low-input arable cropping systems resulting from the combination of three levels of grain legume introduction in a 3-year and the use of cover crops or bare fallow between cash crops, covering two rotation cycles. They considered external emissions, on-site emissions and soil organic carbon (SOC) stock changes. The authors observed that introducing grain legumes in crop rotation reduced external emissions by lowering synthetic nitrogen fertilizer use but led to SOC losses, increasing the overall carbon footprint in systems without cover crops, but that legume cover crops mitigated SOC losses, reducing the carbon footprint significantly. This further supports overall observation that although important in enhancing soil health and sustainability in agricultural systems, legume crops should be selected strategically, as they can improve nutrient cycling and mitigate environmental impacts, but also increase N_2O emissions, necessitating careful management.

Notable positive examples

- **Hairy vetch-rye mixture as cover crop:** The rye and vetch mixture combined high biomass production and soil C sequestration with moderate N_2O emissions, making it a promising option for balancing productivity and sustainability (Fiorini et al., 2025).

4. Potential barriers to legume integration into cropping systems

There is no shortage of data demonstrating that diversified cropping systems integrating legume crops can sustain high levels of productivity with fewer external inputs and lower externalities compared to more simplified systems. Similarly, data exist indicating diverse cropping systems have greater capacity to buffer against and adapt to weather extremes associated with climate change (Mortensen and Smith, 2020). Nevertheless, crop divarication practices are not widespread in Europe due to encompassing economic, knowledge-based, logistical, environmental, and policy-related challenges, hindering the adoption by farmers (Smith et al., 2018).

Through the meta-analysis, we have also identified several barriers for full exploitation of the be beneficial effect of legume integration into cropping systems:

- **Yield–stability trade-off with legume pre-crops:** In some cases, legumes improved yield at the cost of stability. For instance, in their study Wang et al. (2025) found that legume pre-crops (e.g. soybean, lentil) boosted subsequent wheat yields but also amplified yield fluctuations between years, whereas a non-legume break crop (canola) produced more stable wheat yields (though without the initial yield boost from the legume). This illustrates a trade-off where pursuing higher yields via legumes can increase interannual variability.
- **High variability in pea-containing rotation:** In study of Wang et al. (2025) a rotation including field pea (wheat–canola–wheat–pea) exhibited the poorest yield stability among tested systems. Its Finlay–Wilkinson regression slope (>1.3) indicated that yields in this legume-inclusive rotation were highly sensitive to environmental variations (i.e. above-average variability), even though its average yield was relatively high. This example shows that not all legume rotations inherently stabilize yields; certain pulse crops in specific sequences may introduce variability.
- **Legume under low inputs less stable:** Under low-input conditions, legumes did not always confer stability. In a manure-fertilized comparison, the rotation with red clover was less stable than a manure-based cereal rotation, as evidenced by a higher yield variance (poorer stability) in the legume treatment. Without sufficient external nutrients, the legume's contribution to yield stability appeared to be limited, indicating that sole reliance on legume-derived nitrogen can be a vulnerability in stability terms (St. Luce et al., 2020).
- **Bare fallow rotations more stable:** Some of the most stable rotations in the papers analysed were those without any legumes, using fallow periods instead. For example, rotations like fallow–wheat–wheat maintained very steady yields (regression slopes < 1, denoting low sensitivity to year-to-year environmental changes) but at the expense of lower overall productivity. This highlights a trade-off: strategies that maximized stability (such as regular fallow or continuous cereals with low responsiveness) often did so by forgoing the yield gains that legumes or additional crops would provide (Béres et al., 2018).
- **Inconsistent pest suppression:** In the clover–wheat system studied by Mansion-Vaquié et al. (2019), pest suppression outcomes were strongly year- and cultivar-dependent. While clover sometimes reduced aphid numbers or infestation rates, many comparisons showed no significant differences relative to wheat monoculture. Notably, wheat yield was consistently and significantly reduced under clover intercropping, underscoring the trade-offs that can arise from interspecific competition even when pest-related benefits are present.

- **Lower total soil carbon and nitrogen stocks:** Agomoh et al. (2019) conducted a 17-year field trial in Canada comparing monoculture winter wheat with three legume-inclusive rotation schemes: soybean–winter wheat (S–WW), corn–soybean–winter wheat (C–S–WW), and winter wheat–soybean–soybean (WW–S–S). The study found that total soil carbon and nitrogen stocks were significantly lower in the diversified rotations than in the wheat monoculture. These reductions, most evident in legume rotations including red clover, suggest that elevated N inputs from legumes accelerated microbial SOM turnover. Plaza-Bonilla et al. (2018) also observed that introducing grain legumes in crop rotation reduced external emissions by lowering synthetic nitrogen fertilizer use but led to SOC losses, increasing the overall carbon footprint in systems without cover crops. Although crop productivity increased under the legume-inclusive rotations, those studies highlight a potential trade-off between yield gains and long-term soil carbon retention when high-N legumes like red clover are used without sufficient carbon return.

5. Recommendations for improving legume integration into cropping systems

Generally, meta-analysis showed that integrating legume crops into cropping systems had beneficial effects on soil fertility and boosted sustainability by fixing atmospheric nitrogen, enriching organic matter, and improving soil structure and water retention. These benefits included reduced reliance on synthetic fertilizers, natural pest suppression, and better resource use efficiency, which led to higher crop yields and greater resilience to environmental challenges. For full exploitation of the beneficial effects of legume crops in diverse cropping systems following recommendations could be made:

- **Diversify rotations with legumes:** Incorporate leguminous crops into rotation schedules to reduce yield variability. Evidence from multiple studies indicates that adding peas, beans, clovers, or other legumes tends to lower the coefficient of variation of yields, moving the system toward a more stable output profile compared to strictly non-legume rotations. Greater rotational diversity that includes a legume can thus buffer against annual yield swings.
- **Ensure adequate fertility inputs:** Pair legume integration with appropriate nutrient management. While legumes fix nitrogen, they may not fully meet crop nitrogen demand each year. Trials show that a legume-inclusive rotation realized its full stability benefits only when supplemented with sufficient fertilization. To maintain stable yields, provide manure or mineral fertilizer as needed so that nutrient shortfalls do not undermine the legume's positive effect.
- **Match legume choice to the environment**: Select legume species and management practices suited to local climate conditions to safeguard stability. In drought-prone or extreme environments, consider drought-tolerant legumes or additional moisture conservation measures, as legume benefits to yield stability can diminish under severe heat or water stress. Aligning the legume choice (e.g., deep-rooted perennials in dry areas) with environmental constraints will help ensure more consistent yields.
- **Use legumes as strategic break crops:** Leverage legumes as rotation break crops to enhance stability of subsequent cereals or cash crops. Deep-rooted or multi-year legumes like alfalfa can disrupt pest and disease cycles and enrich soil nitrogen, which in turn steadies the yields of following crops. Even short rotations saw markedly improved stability when a legume break was included. Thus, introducing

a legume at key points in the rotation is recommended to bolster resilience and consistency in production.

- **Extend rotation length for both yield stability and pest suppression:** Avoid very short, repetitive crop sequences. Where possible, adopt longer rotations (with at least a two-year gap before the same crop recurs) and include a legume within that cycle. Rotations spanning three or more distinct crops – ideally with a legume among them – have been shown to achieve both higher yield stability and greater yields than tighter monocultures or two-year systems. Therefore, extending the rotation length and diversifying crop types can synergize with legume integration to maximize stability benefits without sacrificing productivity.
- **Ensure adequate biomass return to soil:** To maximize the soil quality benefits of legumes, ensure adequate biomass return to soil (e.g. by using cover crops or residue retention) and consider pairing legume integration with practices like minimal tillage and diverse rotations.
- **Choose legume crops and cropping system according to needs:** Depending on the needs choose legume crops for nitrogen fixation to improve soil fertility, pest and disease suppression, and enhanced resource-use efficiency. Choose cropping system accordingly. Choose legume based on soil conditions, climate, and the target benefits, such as increasing yields, reducing fertilizer use, or improving overall soil health, for instance.

Those recommendations and their practical application in crop diversification systems create an effective roadmap for full exploitation of beneficial effects of legume integration into cropping systems (**Figure 2**):

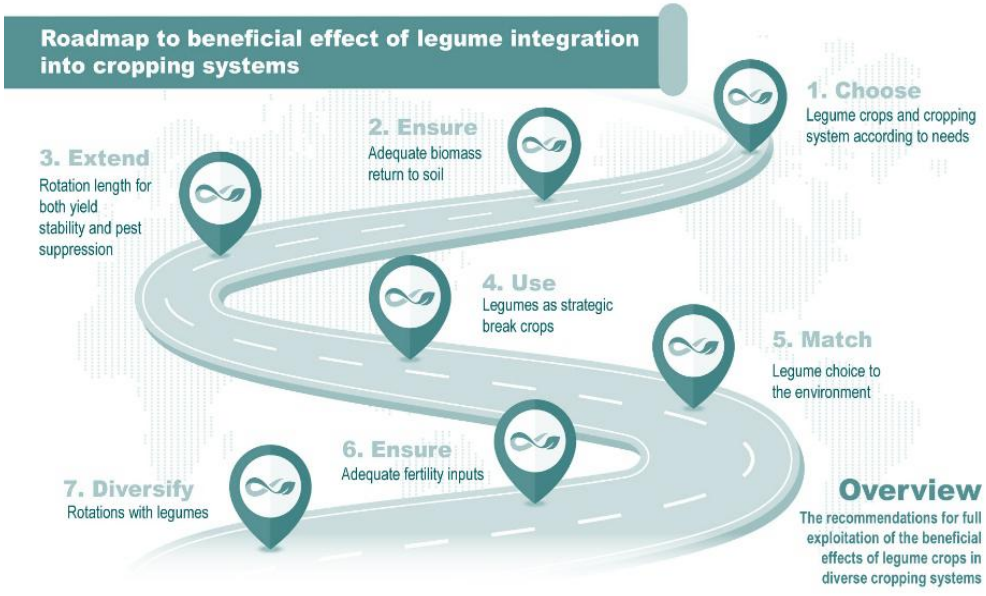

Figure 2: Roadmap to beneficial effects of legume integration into cropping systems

6. Future research directions

The meta-analysis conducted showed that there are research gaps to be filled in regarding beneficial effects of legume crops integration into cropping systems.

Beneficial effects of legume crops

Except for pest suppression (**Section 3.3**), there was limited number of publications dealing with other legume effect studies. This especially stands for associated biodiversity and climate resilience. In studies related to the associated biodiversity were primarily dealing with weed biodiversity, with information on insect, especially pollinators lacking (**Section 3.5**). Climate resilience was only secondary focus of the most studies analysed, with yield as a main indicator followed by GHG emissions (**Section 3.6**). This indicates the need for more studies regarding those two aspects of legume crop role in cropping systems, particularly on insect and pollinators for biodiversity and context and methodology for climate resilience. Besides that, future long-term studies are also needed to monitor how legume-driven soil improvements evolve over time and to refine recommendations – for instance, optimizing cover crop termination and diversifying legume species – so that the positive effects on soil health consistently outweigh any drawbacks (**Section 3.4**).

Geographic scope

Meta-analysis revealed limited geographic scope of the studies on beneficial effect of legume crops in cropping systems. The research analysed was conducted in only 15 out of 51 HEU and Associated Countries (**Figure 3**).

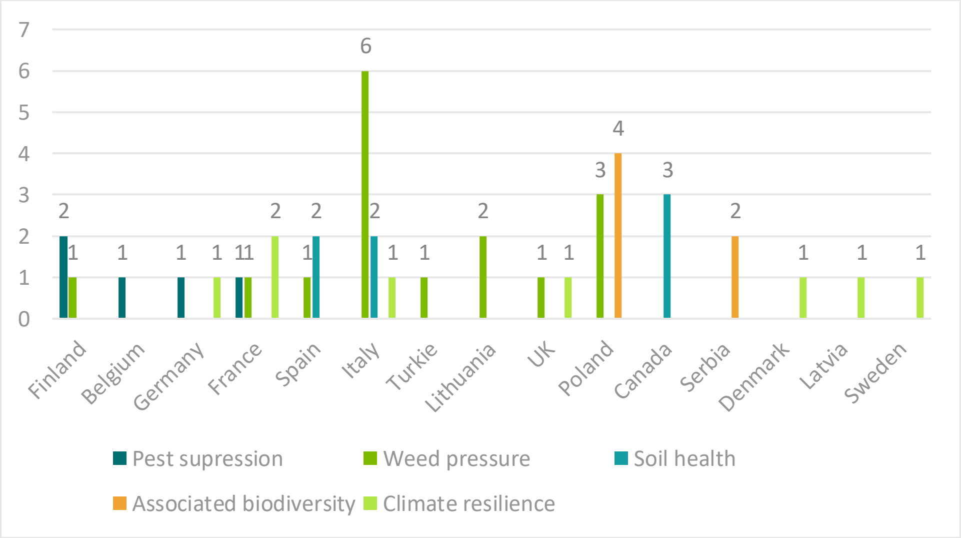

Figure 3: Meta-analysis geographic scope

Studies across different European regions have consistently shown that while the integration of legumes generally reduces nitrous oxide emissions and nitrogen fertilizer use, the economic and specific environmental impacts are highly site-specific (Reckling et al., 2020). Besides low number of countries represented, meta-analysis has shown that most of the studies were conducted in South-West, West and Northern Europe, with Central, East and South-East Europe being underrepresented. Since effective integration of legume crops into cropping systems needs region-specific guidance and solutions, more research is needed in those and other less covered regions to maximize benefits of legume crops and address local challenges

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Annex 1: Search strings

Table 1: Yield

Search string	Results	Date	Comments
(TITLE-ABS-KEY (legum* OR alfalfa OR lucerne OR chickpea* OR clover* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "medicago sativa" OR "cicer arietinum" OR trifolium OR "vicia faba" OR "lens culinaris" OR "lupinus" OR "pisum sativum" OR "glycine max" OR "vicia")) AND (TITLE-ABS-KEY ("crop rotation" OR "cropping system" OR "crop* rotation*" OR "crop* sequence*" OR "sequential crop*" OR "successive crop*" OR "sequence* of crops" OR "ley farming" OR "sequence* of plant species")) AND (TITLE-ABS-KEY (field*)) AND (TITLE-ABS-KEY ("yield stability" OR "yield stability analysis" OR "yield trend*" OR "yield ratio" OR "yield response*" OR "production potential" OR "stable yield*" OR "yield ability" OR "crop productivity" OR "agricultural productivity" OR "stability index" OR "stability value" OR "relative yield" OR "average yield" OR "productivity" OR "yield stagnation" OR "yield stability index" OR "yield increas*" OR "yield persistence" OR "constancy of agricultural yield" OR "yield over years" OR "yield variance" OR "yield development" OR "yield level" OR "temporal yield stability")) AND PUBYEAR > 2015 AND PUBYEAR < 2026 AND (EXCLUDE (AFFILCOUNTRY , "United States") OR EXCLUDE (AFFILCOUNTRY , "China") OR EXCLUDE (AFFILCOUNTRY , "Australia") OR EXCLUDE (AFFILCOUNTRY , "Brazil") OR EXCLUDE (AFFILCOUNTRY , "Argentina") OR EXCLUDE (AFFILCOUNTRY , "India") OR EXCLUDE (AFFILCOUNTRY , "Japan") OR EXCLUDE (AFFILCOUNTRY , "Pakistan") OR EXCLUDE (AFFILCOUNTRY , "Ethiopia") OR EXCLUDE (AFFILCOUNTRY , "Kenya") OR EXCLUDE (AFFILCOUNTRY , "Nigeria") OR EXCLUDE (AFFILCOUNTRY , "South Africa") OR EXCLUDE (AFFILCOUNTRY , "Iran") OR EXCLUDE (AFFILCOUNTRY , "Mexico") OR EXCLUDE (AFFILCOUNTRY , "Russian Federation") OR EXCLUDE (AFFILCOUNTRY , "Zimbabwe") OR EXCLUDE (AFFILCOUNTRY , "Bangladesh") OR EXCLUDE (AFFILCOUNTRY , "Ghana") OR EXCLUDE (AFFILCOUNTRY , "Indonesia") OR EXCLUDE (AFFILCOUNTRY , "Uganda") OR EXCLUDE (AFFILCOUNTRY , "Burkina Faso") OR EXCLUDE (AFFILCOUNTRY , "Costa Rica") OR EXCLUDE (AFFILCOUNTRY , "Jordan") OR EXCLUDE (AFFILCOUNTRY , "Saudi Arabia") OR EXCLUDE (AFFILCOUNTRY , "Philippines") OR EXCLUDE (AFFILCOUNTRY , "South Korea") OR EXCLUDE (AFFILCOUNTRY , "Benin") OR EXCLUDE (AFFILCOUNTRY , "Chile") OR EXCLUDE (AFFILCOUNTRY , "Malaysia") OR EXCLUDE (AFFILCOUNTRY , "Sri Lanka") OR EXCLUDE (AFFILCOUNTRY , "Syrian Arab Republic") OR EXCLUDE (AFFILCOUNTRY , "Thailand") OR EXCLUDE (AFFILCOUNTRY , "Tanzania") OR EXCLUDE (AFFILCOUNTRY , "Uruguay") OR EXCLUDE (AFFILCOUNTRY , "Viet Nam") OR EXCLUDE (AFFILCOUNTRY , "Cameroon") OR EXCLUDE (AFFILCOUNTRY , "Colombia") OR EXCLUDE (AFFILCOUNTRY , "Malawi") OR EXCLUDE (AFFILCOUNTRY , "Taiwan") OR EXCLUDE (AFFILCOUNTRY , "Cambodia") OR EXCLUDE (AFFILCOUNTRY , "Madagascar") OR EXCLUDE (AFFILCOUNTRY , "Nepal") OR EXCLUDE (AFFILCOUNTRY , "Peru") OR EXCLUDE (AFFILCOUNTRY , "Swaziland") OR EXCLUDE (AFFILCOUNTRY , "Algeria") OR EXCLUDE (AFFILCOUNTRY , "Azerbaijan") OR EXCLUDE (AFFILCOUNTRY , "Cuba") OR EXCLUDE (AFFILCOUNTRY , "Democratic Republic Congo") OR EXCLUDE (AFFILCOUNTRY , "Ecuador") OR EXCLUDE (AFFILCOUNTRY , "Georgia") OR EXCLUDE (AFFILCOUNTRY , "Iraq") OR EXCLUDE (AFFILCOUNTRY , "Kazakhstan") OR EXCLUDE (AFFILCOUNTRY , "Palestine") OR EXCLUDE (AFFILCOUNTRY , "Paraguay") OR EXCLUDE (AFFILCOUNTRY , "Puerto Rico") OR EXCLUDE (AFFILCOUNTRY , "Rwanda") OR EXCLUDE (AFFILCOUNTRY , "Uzbekistan")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "dp") OR LIMIT-TO (DOCTYPE , "bk")) AND (LIMIT-TO (LANGUAGE , "English"))	244	2025-11-6	2016+

Table 2: Pest suppression

Search string	Results	Date	Comments
(TITLE-ABS-KEY ((legum* OR alfalfa OR lucerne OR chickpea* OR clover* OR fava* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "medicago sativa" OR "cicer arietinum" OR trifolium OR "vicia faba" OR "lens culinaris" OR "pisum sativum" OR "glycine max" OR vicia OR bean OR sulla))	149	2025-06-19	2016+

AND TITLE-ABS-KEY (("pest suppression" OR "pest control" OR "pest management")) AND TITLE-ABS-KEY (("field experiment" OR "field trial" OR "field study")) AND NOT TITLE-ABS-KEY ((greenhouse OR "growth chamber" OR pot OR "pot experiment" OR "pot trial"))) AND PUBYEAR > 2015 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ch")) AND (LIMIT-TO (LANGUAGE , "English")) AND (EXCLUDE (AFFILCOUNTRY , "China") OR EXCLUDE (AFFILCOUNTRY , "India") OR EXCLUDE (AFFILCOUNTRY , "Brazil") OR EXCLUDE (AFFILCOUNTRY , "Kenya") OR EXCLUDE (AFFILCOUNTRY , "Australia") OR EXCLUDE (AFFILCOUNTRY , "Egypt") OR EXCLUDE (AFFILCOUNTRY , "Switzerland") OR EXCLUDE (AFFILCOUNTRY , "South Africa") OR EXCLUDE (AFFILCOUNTRY , "Pakistan") OR EXCLUDE (AFFILCOUNTRY , "Ghana") OR EXCLUDE (AFFILCOUNTRY , "Nigeria") OR EXCLUDE (AFFILCOUNTRY , "Japan") OR EXCLUDE (AFFILCOUNTRY , "Indonesia") OR EXCLUDE (AFFILCOUNTRY , "Saudi Arabia") OR EXCLUDE (AFFILCOUNTRY , "Taiwan") OR EXCLUDE (AFFILCOUNTRY , "Morocco") OR EXCLUDE (AFFILCOUNTRY , "Malawi") OR EXCLUDE (AFFILCOUNTRY , "Iraq") OR EXCLUDE (AFFILCOUNTRY , "Ethiopia") OR EXCLUDE (AFFILCOUNTRY , "Uruguay") OR EXCLUDE (AFFILCOUNTRY , "Tanzania") OR EXCLUDE (AFFILCOUNTRY , "Mexico") OR EXCLUDE (AFFILCOUNTRY , "Cuba") OR EXCLUDE (AFFILCOUNTRY , "Cameroon") OR EXCLUDE (AFFILCOUNTRY , "Argentina") OR EXCLUDE (AFFILCOUNTRY , "Zambia") OR EXCLUDE (AFFILCOUNTRY , "Yemen") OR EXCLUDE (AFFILCOUNTRY , "Togo") OR EXCLUDE (AFFILCOUNTRY , "Sri Lanka") OR EXCLUDE (AFFILCOUNTRY , "South Korea") OR EXCLUDE (AFFILCOUNTRY , "Niger") OR EXCLUDE (AFFILCOUNTRY , "Nepal") OR EXCLUDE (AFFILCOUNTRY , "Mali") OR EXCLUDE (AFFILCOUNTRY , "Malaysia") OR EXCLUDE (AFFILCOUNTRY , "Iran") OR EXCLUDE (AFFILCOUNTRY , "Democratic Republic Congo") OR EXCLUDE (AFFILCOUNTRY , "Colombia") OR EXCLUDE (AFFILCOUNTRY , "Burkina Faso") OR EXCLUDE (AFFILCOUNTRY , "Benin") OR EXCLUDE (AFFILCOUNTRY , "Bangladesh"))			

Table 3: Weed suppression

Search string	Results	Date	Comments
(TITLE-ABS-KEY (legume* OR alfalfa OR lucerne OR chickpea* OR clover* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "medicago sativa" OR "cicer arietinum" OR trifolium OR "vicia faba" OR "lens culinaris" OR "lupinus" OR "pisum sativum" OR "glycine max" OR "vicia")) AND (TITLE-ABS-KEY ("cropping system*" OR "crop diversification" OR "cultivation practice*" OR "crop rotation*")) AND (TITLE-ABS-KEY ("weed pressure" OR "weed abundance" OR “weed diversity” OR "weed species" OR "weed plant*" OR "field weed" OR "arable weed" OR "arable flora" OR "arable vegetation" OR weed*)) AND (TITLE-ABS-KEY ("field trial*" OR "field experiment*" OR "field study*" OR "on-farm trial*" OR "on-farm experiment*")) AND (AFFILCOUNTRY ("Austria" OR "Belgium" OR "Bulgaria" OR "Croatia" OR "Cyprus" OR "Czech Republic" OR "Denmark" OR "Estonia" OR "Finland" OR "France" OR "Germany" OR "Greece" OR "Hungary" OR "Ireland" OR "Italy" OR "Latvia" OR "Lithuania" OR "Luxembourg" OR "Malta" OR "Netherlands" OR "Poland" OR "Portugal" OR "Romania" OR "Slovakia" OR "Slovenia" OR "Spain" OR "Sweden" OR "United Kingdom" OR "Albania" OR "Armenia" OR "Bosnia and Herzegovina" OR "Faroe Islands" OR "Georgia" OR "Iceland" OR "Israel" OR "Kosovo" OR "Moldova" OR "Montenegro" OR "North Macedonia" OR "Norway" OR "Serbia" OR "Tunisia" OR "Turkey" OR "Ukraine" OR "Switzerland" OR "Egypt" OR "Morocco")) AND (PUBYEAR > 2015) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "bk") OR LIMIT-TO (DOCTYPE , "dp")) AND (LIMIT-TO (LANGUAGE , "English"))	420	2025-09	2016+

Table 4: Soil health

Search string	Results	Date	Comments
(TITLE-ABS-KEY (legum* OR alfalfa OR lucerne OR chickpea* OR clover* OR fava* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "Medicago sativa" OR "Cicer arietinum" OR trifolium OR "Vicia faba" OR "Lens culinaris" OR "Lupinus spp." OR "Pisum sativum" OR "Glycine max" OR "Vicia spp.") AND TITLE-ABS-KEY ("microbial diversity" OR "bacterial diversity" OR "arbuscular mycorrhizal fungi (AMF)	75	2025-09-29	2016 +

diversity" OR "soil fauna diversity" 8OR "nematode diversity" OR "arthropod diversity" OR "collembolan diversity" OR "acari diversity" OR "earthworm diversity" OR "microfauna diversity" OR "mesofauna diversity" OR "macrofauna diversity" OR microbes OR bacteria OR fungi OR microorganism* OR "soil fauna" OR "soil biota" OR "soil organism*" OR nematode* OR collembola OR acari OR termite* OR earthworm* OR "Soil microbial diversity" OR "plant--soil interactions" OR "soil health indicator*" OR "soil physical propert*" OR "soil chemistry") AND TITLE-ABS-KEY ("field*") AND TITLE-ABS-KEY ("soil health" OR "soil quality" OR "soil biodiversity")) AND PUBYEAR > 2015 AND PUBYEAR < 2026 AND (EXCLUDE (AFFILCOUNTRY , "China") OR EXCLUDE (AFFILCOUNTRY , "United States") OR EXCLUDE (AFFILCOUNTRY , "Brazil") OR EXCLUDE (AFFILCOUNTRY , "India") OR EXCLUDE (AFFILCOUNTRY , "Australia") OR EXCLUDE (AFFILCOUNTRY , "Pakistan") OR EXCLUDE (AFFILCOUNTRY , "Indonesia") OR EXCLUDE (AFFILCOUNTRY , "Saudi Arabia") OR EXCLUDE (AFFILCOUNTRY , "Argentina") OR EXCLUDE (AFFILCOUNTRY , "Viet Nam") OR EXCLUDE (AFFILCOUNTRY , "South Africa") OR EXCLUDE (AFFILCOUNTRY , "Nigeria") OR EXCLUDE (AFFILCOUNTRY , "Japan") OR EXCLUDE (AFFILCOUNTRY , "Mexico") OR EXCLUDE (AFFILCOUNTRY , "Malaysia") OR EXCLUDE (AFFILCOUNTRY , "South Korea") OR EXCLUDE (AFFILCOUNTRY , "Senegal") OR EXCLUDE (AFFILCOUNTRY , "Kenya") OR EXCLUDE (AFFILCOUNTRY , "Iran") OR EXCLUDE (AFFILCOUNTRY , "Chile") OR EXCLUDE (AFFILCOUNTRY , "Uruguay") OR EXCLUDE (AFFILCOUNTRY , "Ghana") OR EXCLUDE (AFFILCOUNTRY , "Democratic Republic Congo") OR EXCLUDE (AFFILCOUNTRY , "Bangladesh") OR EXCLUDE (AFFILCOUNTRY , "United Arab Emirates") OR EXCLUDE (AFFILCOUNTRY , "Thailand") OR EXCLUDE (AFFILCOUNTRY , "Tanzania") OR EXCLUDE (AFFILCOUNTRY , "Taiwan") OR EXCLUDE (AFFILCOUNTRY , "Singapore") OR EXCLUDE (AFFILCOUNTRY , "Russian Federation") OR EXCLUDE (AFFILCOUNTRY , "Qatar") OR EXCLUDE (AFFILCOUNTRY , "Oman") OR EXCLUDE (AFFILCOUNTRY , "Niger") OR EXCLUDE (AFFILCOUNTRY , "New Zealand") OR EXCLUDE (AFFILCOUNTRY , "Mali") OR EXCLUDE (AFFILCOUNTRY , "Malawi") OR EXCLUDE (AFFILCOUNTRY , "Jordan") OR EXCLUDE (AFFILCOUNTRY , "Iraq") OR EXCLUDE (AFFILCOUNTRY , "Hong Kong") OR EXCLUDE (AFFILCOUNTRY , "Ethiopia") OR EXCLUDE (AFFILCOUNTRY , "Colombia") OR EXCLUDE (AFFILCOUNTRY , "Cameroon")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "dp") OR LIMIT-TO (DOCTYPE , "bk")) AND (LIMIT-TO (LANGUAGE , "English"))			

Table 5: Associated biodiversity

Search string	Results	Date	Comments
(TITLE-ABS-KEY (("cropping system*" OR "crop diversification" OR "cultivation practice*" OR "crop rotation" OR "cropping practice*")) AND TITLE-ABS-KEY ((legum* OR alfalfa OR lucerne OR chickpea* OR clover* OR fava* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "medicago sativa" OR "cicer arietinum" OR trifolium OR "vicia faba" OR "lens culinaris" OR "pisum sativum" OR "glycine max" OR "vicia sp." OR bean OR sulla)) AND TITLE-ABS-KEY (("plant* number" OR "plant* specie*" OR "wild flower*" OR "wildflower*" OR "segetal plant*" OR "segetal flora" OR "segetal specie*" OR "segetal weed*" OR "segetal" OR "field herb*" OR "wild herb*" OR "arable herb*" OR "herbs" OR "weed* specie*" OR "weed* plant*" OR "field weed*" OR "arable weed*" OR "weeds" OR weed* OR "arable weed* vegetation" OR "weed* abundance" OR "arable flora" OR "arable vegetation" OR "flora*" OR "vascular plant*" OR "flor* *diversity" OR species OR richness OR vegetation OR "species diversity" OR "biodiversity" OR "biological diversity" OR "associated *diversity" OR "unplanned *diversity" OR "shannon" OR "shannon ind*" OR "shannon weaver ind*" OR "shannon wiener ind*" OR "invertebrate*" OR "mesofauna" OR "macrofauna" OR "insect*" OR "pollinator*" OR "*bee" OR "*bees" OR "wasp*" OR "butterfly" OR "butterflies" OR "moth*" OR "*flies" OR "*fly" OR "beetle*" OR "Coleoptera" OR "Carabid*" OR "bug*" OR "spider*" OR "Arachnida" OR "vertebrate*" OR "bird*" OR "mammal*" OR "fauna*" OR pollinator* OR "grasshopper*" OR cricket* OR orthoptera OR "arthropod*" OR "Hymenoptera" OR taxa OR "taxonomic group*" OR amphibian* OR reptile* OR dragonfl* OR damselfl*)) AND TITLE-ABS-KEY ("field*")) AND PUBYEAR > 2015 AND PUBYEAR < 2026 AND (EXCLUDE (AFFILCOUNTRY,"United States") OR EXCLUDE (AFFILCOUNTRY,"China") OR EXCLUDE (AFFILCOUNTRY,"Australia") OR EXCLUDE (AFFILCOUNTRY,"Brazil") OR EXCLUDE (AFFILCOUNTRY,"Argentina") OR EXCLUDE (AFFILCOUNTRY,"India") OR EXCLUDE (AFFILCOUNTRY,"Japan") OR EXCLUDE (AFFILCOUNTRY,"Pakistan") OR	372	2025-06-13	2016 +

EXCLUDE (AFFILCOUNTRY,"Ethiopia") OR EXCLUDE (AFFILCOUNTRY,"Kenya") OR EXCLUDE (AFFILCOUNTRY,"Nigeria") OR EXCLUDE (AFFILCOUNTRY,"South Africa") OR EXCLUDE (AFFILCOUNTRY,"Iran") OR EXCLUDE (AFFILCOUNTRY,"Mexico") OR EXCLUDE (AFFILCOUNTRY,"Russian Federation") OR EXCLUDE (AFFILCOUNTRY,"Zimbabwe") OR EXCLUDE (AFFILCOUNTRY,"Bangladesh") OR EXCLUDE (AFFILCOUNTRY,"Ghana") OR EXCLUDE (AFFILCOUNTRY,"Indonesia") OR EXCLUDE (AFFILCOUNTRY,"Uganda") OR EXCLUDE (AFFILCOUNTRY,"Burkina Faso") OR EXCLUDE (AFFILCOUNTRY,"Costa Rica") OR EXCLUDE (AFFILCOUNTRY,"Jordan") OR EXCLUDE (AFFILCOUNTRY,"Saudi Arabia") OR EXCLUDE (AFFILCOUNTRY,"Philippines") OR EXCLUDE (AFFILCOUNTRY,"South Korea") OR EXCLUDE (AFFILCOUNTRY,"Benin") OR EXCLUDE (AFFILCOUNTRY,"Chile") OR EXCLUDE (AFFILCOUNTRY,"Malaysia") OR EXCLUDE (AFFILCOUNTRY,"Sri Lanka") OR EXCLUDE (AFFILCOUNTRY,"Syrian Arab Republic") OR EXCLUDE (AFFILCOUNTRY,"Thailand") OR EXCLUDE (AFFILCOUNTRY,"Tanzania") OR EXCLUDE (AFFILCOUNTRY,"Uruguay") OR EXCLUDE (AFFILCOUNTRY,"Viet Nam") OR EXCLUDE (AFFILCOUNTRY,"Cameroon") OR EXCLUDE (AFFILCOUNTRY,"Colombia") OR EXCLUDE (AFFILCOUNTRY,"Malawi") OR EXCLUDE (AFFILCOUNTRY,"Taiwan") OR EXCLUDE (AFFILCOUNTRY,"Cambodia") OR EXCLUDE (AFFILCOUNTRY,"Madagascar") OR EXCLUDE (AFFILCOUNTRY,"Nepal") OR EXCLUDE (AFFILCOUNTRY,"Peru") OR EXCLUDE (AFFILCOUNTRY,"Swaziland") OR EXCLUDE (AFFILCOUNTRY,"Algeria") OR EXCLUDE (AFFILCOUNTRY,"Azerbaijan") OR EXCLUDE (AFFILCOUNTRY,"Cuba") OR EXCLUDE (AFFILCOUNTRY,"Democratic Republic Congo") OR EXCLUDE (AFFILCOUNTRY,"Ecuador") OR EXCLUDE (AFFILCOUNTRY,"Georgia") OR EXCLUDE (AFFILCOUNTRY,"Iraq") OR EXCLUDE (AFFILCOUNTRY,"Kazakhstan") OR EXCLUDE (AFFILCOUNTRY,"Palestine") OR EXCLUDE (AFFILCOUNTRY,"Paraguay") OR EXCLUDE (AFFILCOUNTRY,"Puerto Rico") OR EXCLUDE (AFFILCOUNTRY,"Rwanda") OR EXCLUDE (AFFILCOUNTRY,"Uzbekistan")) AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"ch") OR LIMIT-TO (DOCTYPE,"dp") OR LIMIT-TO (DOCTYPE,"bk")) AND (LIMIT-TO (LANGUAGE,"English"))			
((TITLE-ABS-KEY (("cropping system*" OR "crop diversification" OR "cultivation practice*" OR "crop rotation" OR "cropping practice*")) AND TITLE-ABS-KEY ((legum* OR alfalfa OR lucerne OR chickpea* OR clover* OR fava* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "medicago sativa" OR "cicer arietinum" OR trifolium OR "vicia faba" OR "lens culinaris" OR "pisum sativum" OR "glycine max" OR "vicia sp." OR bean OR sulla)) AND TITLE-ABS-KEY (("plant* number" OR "plant* specie*" OR "wild flower*" OR "wildflower*" OR "segetal plant*" OR "segetal flora" OR "segetal specie*" OR "segetal weed*" OR "segetal" OR "field herb*" OR "wild herb*" OR "arable herb*" OR "herbs" OR "weed* specie*" OR "weed* plant*" OR "field weed*" OR "arable weed*" OR "weeds" OR weed* OR "arable weed* vegetation" OR "weed* abundance" OR "arable flora" OR "arable vegetation" OR "flora*" OR "vascular plant*" OR "flor* *diversity" OR species OR richness OR vegetation OR "species diversity" OR "biodiversity" OR "biological diversity" OR "associated *diversity" OR "unplanned *diversity" OR "shannon" OR "shannon ind*" OR "shannon weaver ind*" OR "shannon wiener ind*" OR "invertebrate*" OR "mesofauna" OR "macrofauna" OR "insect*" OR "pollinator*" OR "*bee" OR "*bees" OR "wasp*" OR "butterfly" OR "butterflies" OR "moth*" OR "*flies" OR "*fly" OR "beetle*" OR "Coleoptera" OR "Carabid*" OR "bug*" OR "spider*" OR "Arachnida" OR "vertebrate*" OR "bird*" OR "mammal*" OR "fauna*" OR pollinator* OR "grasshopper*" OR cricket* OR orthoptera OR "arthropod*" OR "Hymenoptera" OR taxa OR "taxonomic group*" OR amphibian* OR reptile* OR dragonfl* OR damselfl*)) AND TITLE-ABS-KEY ("field*"))) AND NOT ((TITLE-ABS-KEY (("cropping system*" OR "crop diversification" OR "cultivation practice*" OR "crop rotation" OR "cropping practice*")) AND TITLE-ABS-KEY ((legum* OR alfalfa OR lucerne OR chickpea* OR clover* OR fava* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "medicago sativa" OR "cicer arietinum" OR trifolium OR "vicia fava" OR "lens culinaris" OR "pisum sativum" OR "glycine max" OR "vicia sp." OR bean OR sulla)) AND TITLE-ABS-KEY (("plant* number" OR "plant* specie*" OR "wild flower*" OR "wildflower*" OR "segetal plant*" OR "segetal flora" OR "segetal specie*" OR "segetal weed*" OR "segetal" OR "field herb*" OR "wild herb*" OR "arable herb*" OR "herbs" OR "weed* specie*" OR "weed* plant*" OR "field weed*" OR "arable weed*" OR "weeds" OR weed* OR "arable weed* vegetation" OR "weed* abundance" OR "arable flora" OR "arable vegetation" OR "flora*" OR "vascular plant*" OR "flor* *diversity" OR species OR richness OR vegetation OR "species diversity" OR "biodiversity" OR "biological diversity" OR "associated *diversity" OR "unplanned *diversity" OR "shannon" OR "shannon ind*" OR "shannon weaver ind*" OR "shannon wiener ind*" OR	275	2025-06-26	Before 2016

"invertebrate*" OR "mesofauna" OR "macrofauna" OR "insect*" OR "pollinator*" OR "*bee" OR "*bees" OR "wasp*" OR "butterfly" OR "butterflies" OR "moth*" OR "*flies" OR "*fly" OR "beetle*" OR "Coleoptera" OR "Carabid*" OR "bug*" OR "spider*" OR "Arachnida" OR "vertebrate*" OR "bird*" OR "mammal*" OR "fauna*" OR pollinator* OR "grasshopper*" OR cricket* OR orthoptera OR "arthropod*" OR "Hymenoptera" OR taxa OR "taxonomic group*" OR amphibian* OR reptile* OR dragonfl* OR damselfl*)) AND TITLE-ABS-KEY ("field*")) AND PUBYEAR > 2015 AND PUBYEAR < 2026) AND (EXCLUDE (AFFILCOUNTRY , "United States") OR EXCLUDE (AFFILCOUNTRY , "China") OR EXCLUDE (AFFILCOUNTRY , "Australia") OR EXCLUDE (AFFILCOUNTRY , "Brazil") OR EXCLUDE (AFFILCOUNTRY , "Argentina") OR EXCLUDE (AFFILCOUNTRY , "India") OR EXCLUDE (AFFILCOUNTRY , "Japan") OR EXCLUDE (AFFILCOUNTRY , "Pakistan") OR EXCLUDE (AFFILCOUNTRY , "Ethiopia") OR EXCLUDE (AFFILCOUNTRY , "Kenya") OR EXCLUDE (AFFILCOUNTRY , "Nigeria") OR EXCLUDE (AFFILCOUNTRY , "South Africa") OR EXCLUDE (AFFILCOUNTRY , "Iran") OR EXCLUDE (AFFILCOUNTRY , "Mexico") OR EXCLUDE (AFFILCOUNTRY , "Russian Federation") OR EXCLUDE (AFFILCOUNTRY , "Zimbabwe") OR EXCLUDE (AFFILCOUNTRY , "Bangladesh") OR EXCLUDE (AFFILCOUNTRY , "Ghana") OR EXCLUDE (AFFILCOUNTRY , "Indonesia") OR EXCLUDE (AFFILCOUNTRY , "Uganda") OR EXCLUDE (AFFILCOUNTRY , "Burkina Faso") OR EXCLUDE (AFFILCOUNTRY , "Costa Rica") OR EXCLUDE (AFFILCOUNTRY , "Jordan") OR EXCLUDE (AFFILCOUNTRY , "Saudi Arabia") OR EXCLUDE (AFFILCOUNTRY , "Philippines") OR EXCLUDE (AFFILCOUNTRY , "South Korea") OR EXCLUDE (AFFILCOUNTRY , "Benin") OR EXCLUDE (AFFILCOUNTRY , "Chile") OR EXCLUDE (AFFILCOUNTRY , "Malaysia") OR EXCLUDE (AFFILCOUNTRY , "Sri Lanka") OR EXCLUDE (AFFILCOUNTRY , "Syrian Arab Republic") OR EXCLUDE (AFFILCOUNTRY , "Thailand") OR EXCLUDE (AFFILCOUNTRY , "Tanzania") OR EXCLUDE (AFFILCOUNTRY , "Uruguay") OR EXCLUDE (AFFILCOUNTRY , "Viet Nam") OR EXCLUDE (AFFILCOUNTRY , "Cameroon") OR EXCLUDE (AFFILCOUNTRY , "Colombia") OR EXCLUDE (AFFILCOUNTRY , "Malawi") OR EXCLUDE (AFFILCOUNTRY , "Taiwan") OR EXCLUDE (AFFILCOUNTRY , "Cambodia") OR EXCLUDE (AFFILCOUNTRY , "Madagascar") OR EXCLUDE (AFFILCOUNTRY , "Nepal") OR EXCLUDE (AFFILCOUNTRY , "Peru") OR EXCLUDE (AFFILCOUNTRY , "Swaziland") OR EXCLUDE (AFFILCOUNTRY , "Algeria") OR EXCLUDE (AFFILCOUNTRY , "Azerbaijan") OR EXCLUDE (AFFILCOUNTRY , "Cuba") OR EXCLUDE (AFFILCOUNTRY , "Democratic Republic Congo") OR EXCLUDE (AFFILCOUNTRY , "Ecuador") OR EXCLUDE (AFFILCOUNTRY , "Georgia") OR EXCLUDE (AFFILCOUNTRY , "Iraq") OR EXCLUDE (AFFILCOUNTRY , "Kazakhstan") OR EXCLUDE (AFFILCOUNTRY , "Palestine") OR EXCLUDE (AFFILCOUNTRY , "Paraguay") OR EXCLUDE (AFFILCOUNTRY , "Puerto Rico") OR EXCLUDE (AFFILCOUNTRY , "Rwanda") OR EXCLUDE (AFFILCOUNTRY , "Uzbekistan")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "dp") OR LIMIT-TO (DOCTYPE , "bk")) AND (LIMIT-TO (LANGUAGE , "English"))			

Table 6: Climate resilience

Search string	Results	Date	Comments
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Annex 2: PRISMA flow charts

Figure 3. Prisma flow charts for yield stability in crop rotation

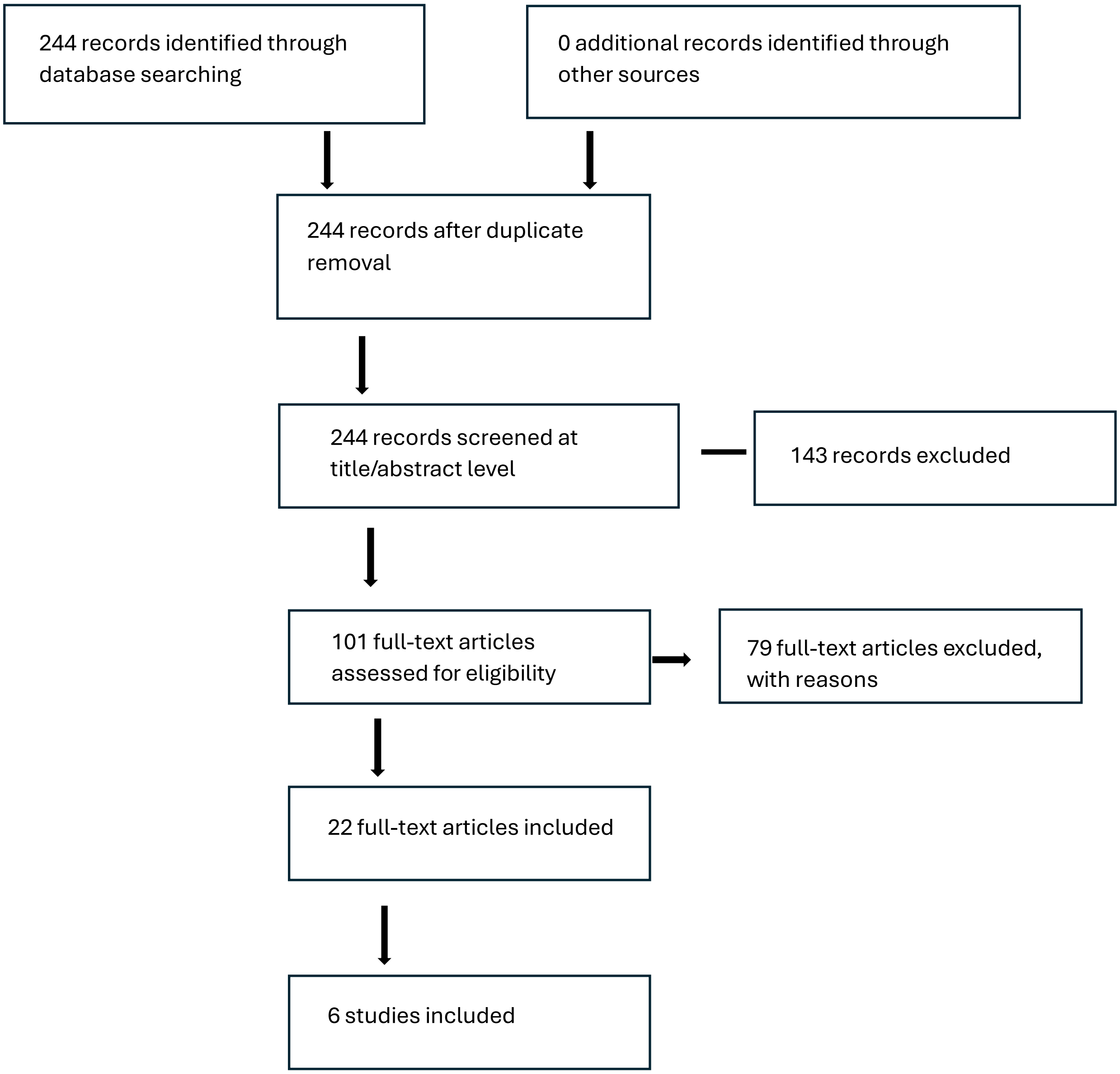


Figure 4. Prisma flow charts for pest suppression

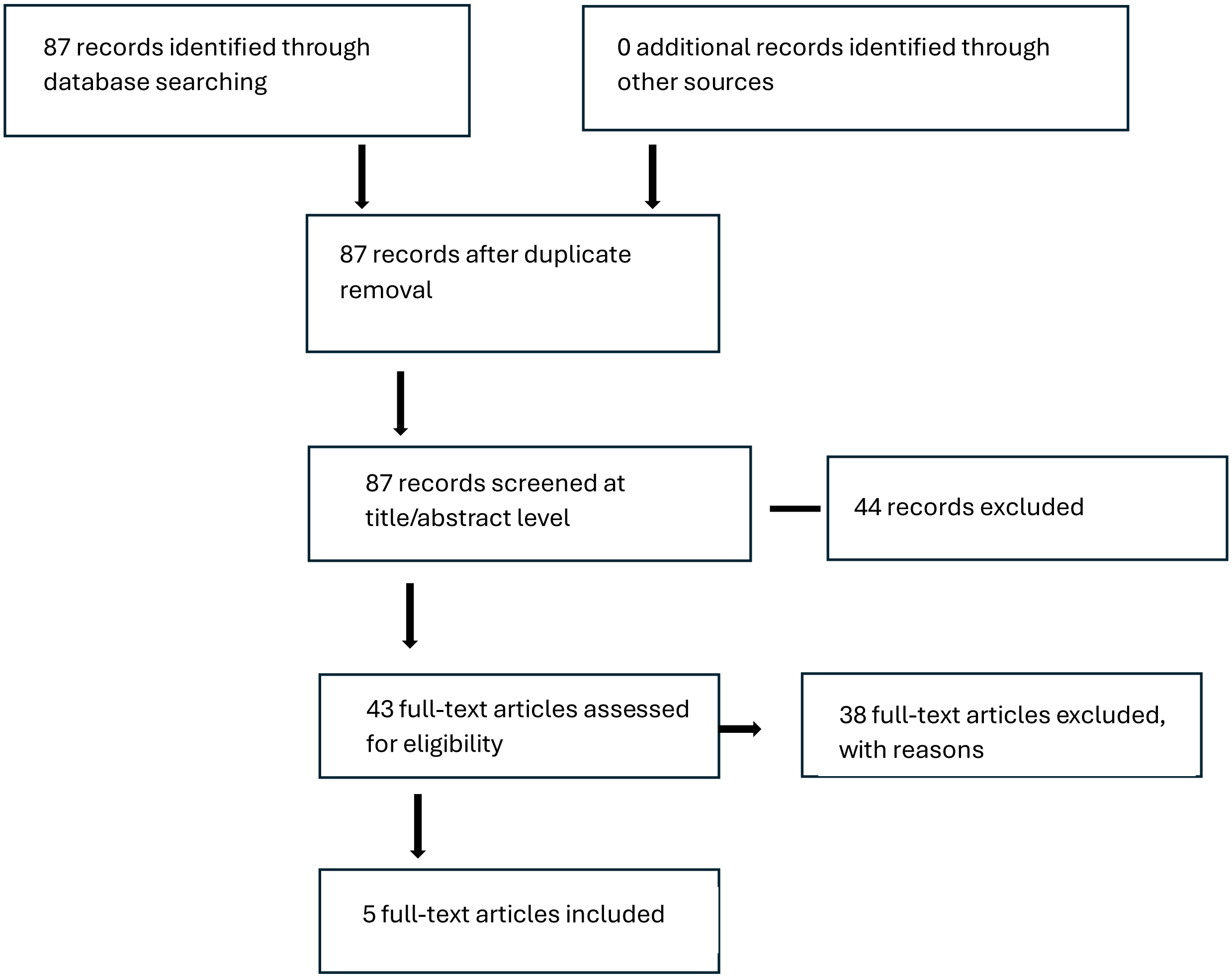


Figure 5. Prisma flow charts for weed suppression

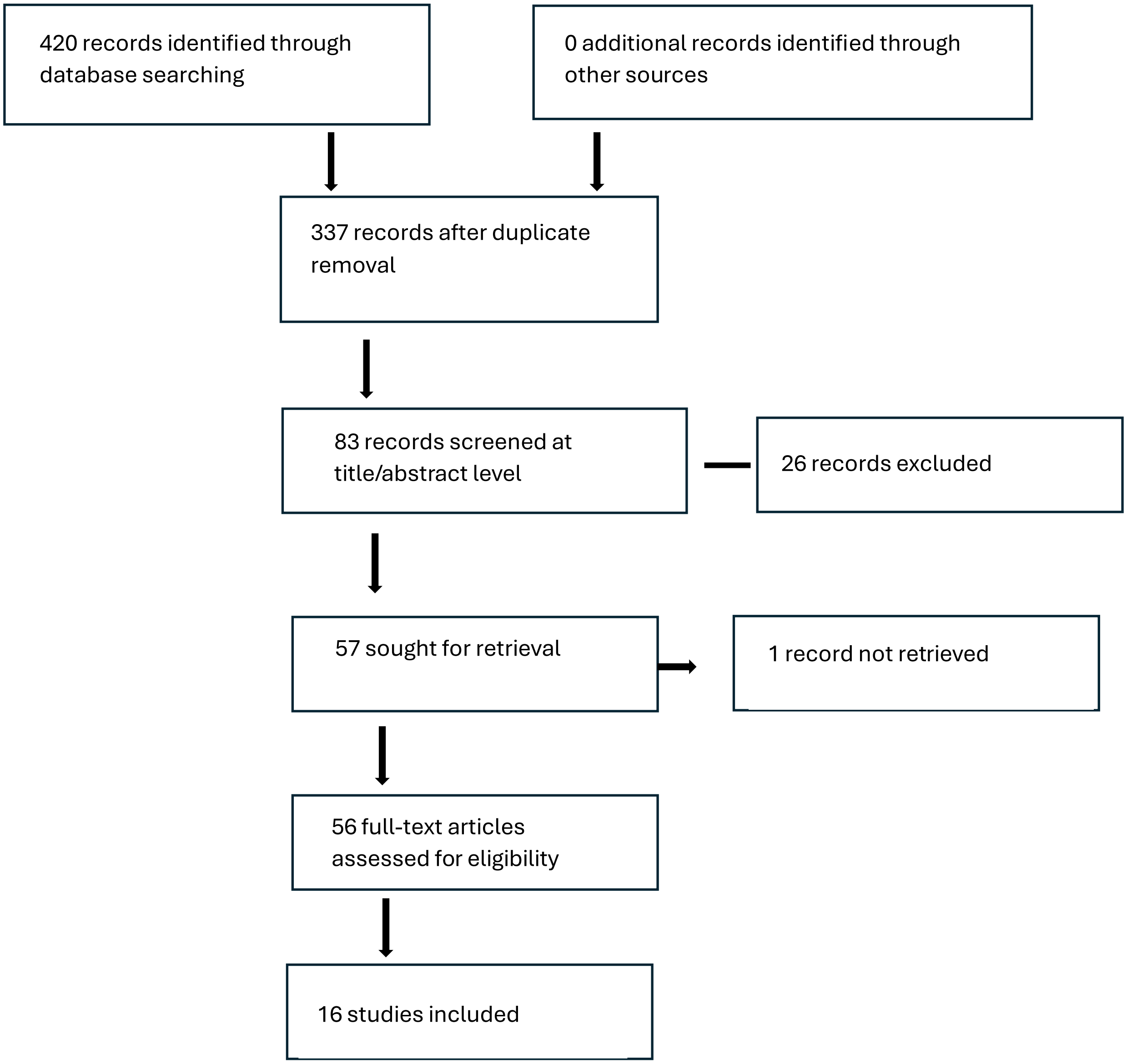


Figure 6. Prisma flow charts for soil health

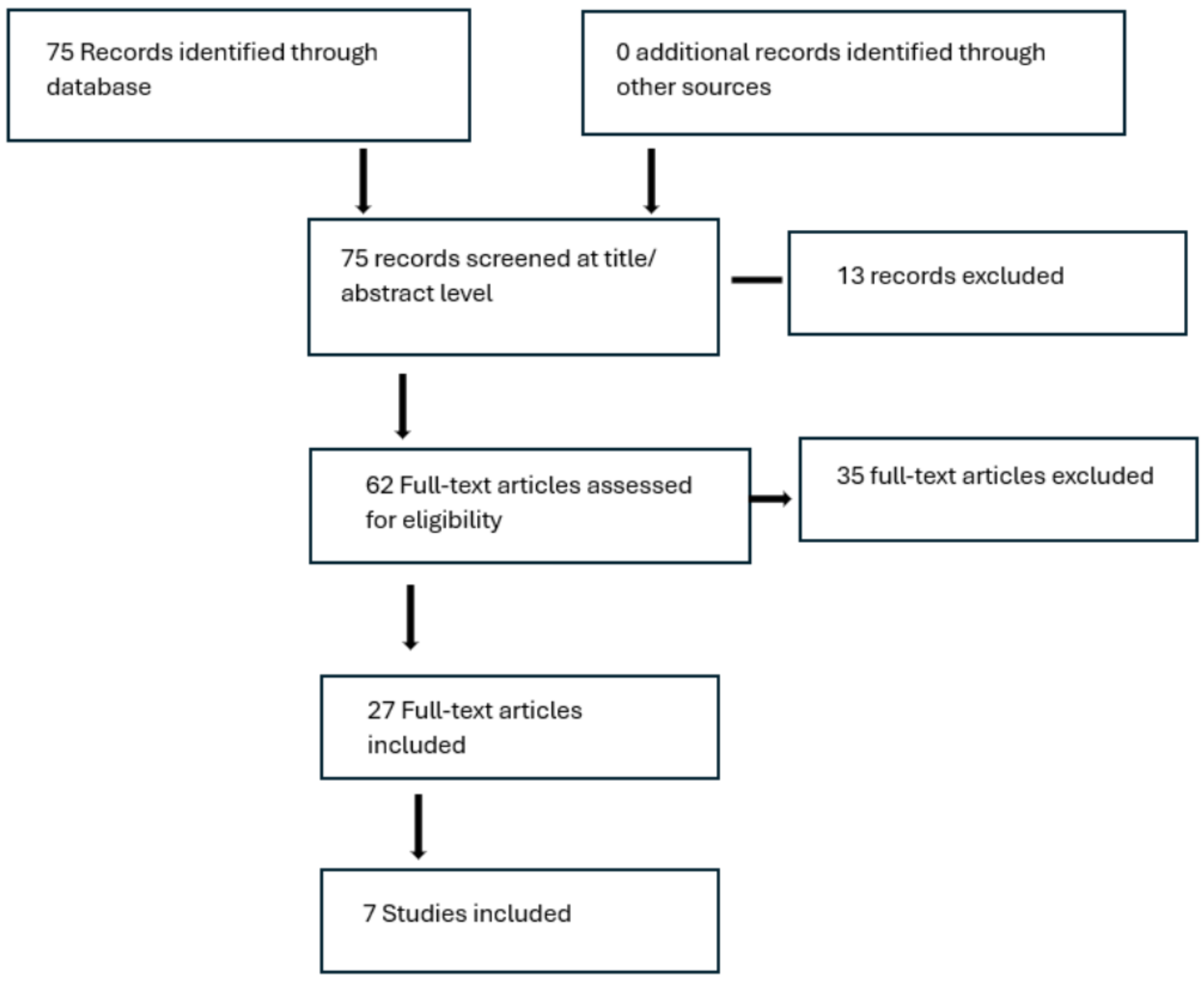
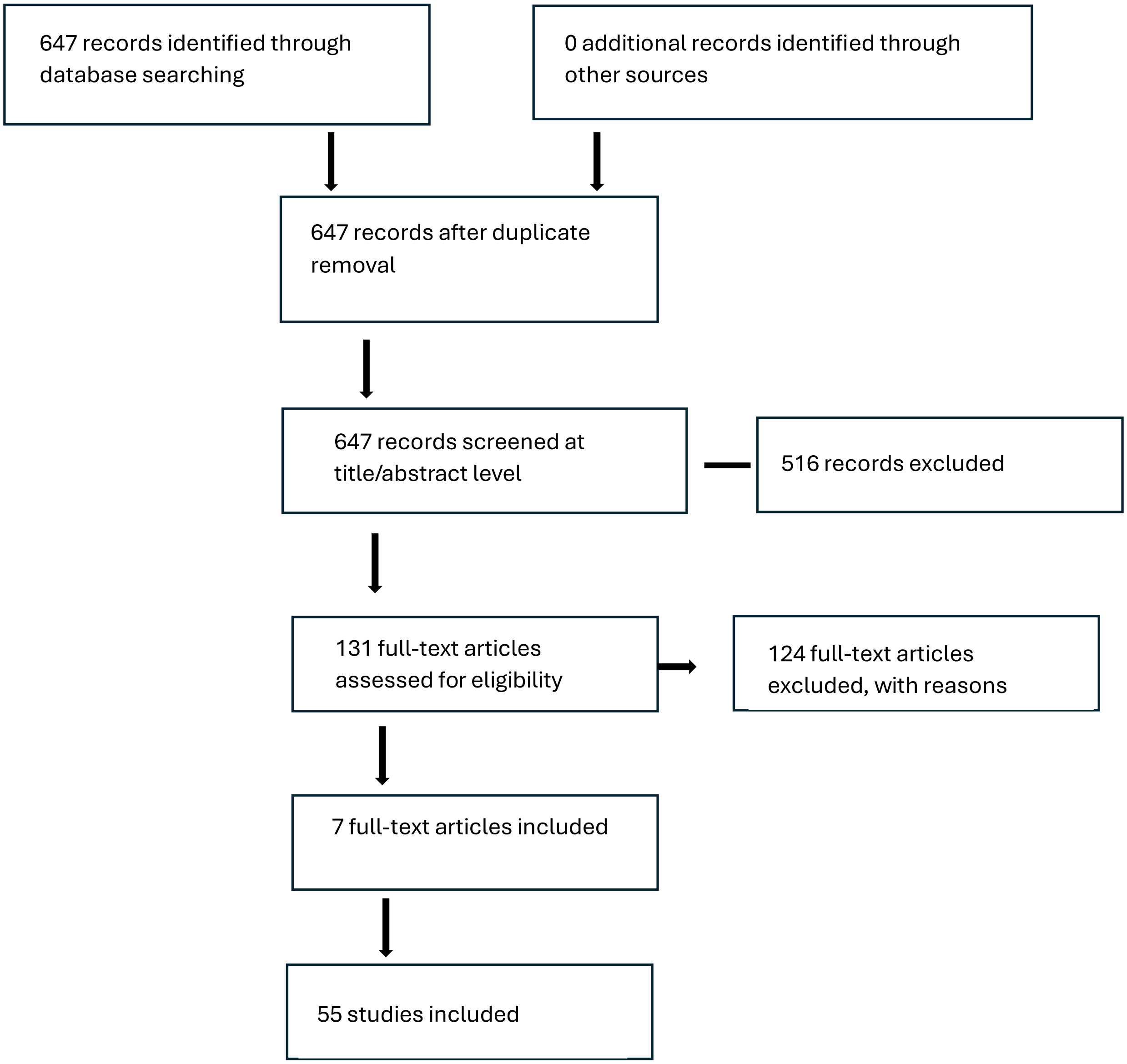
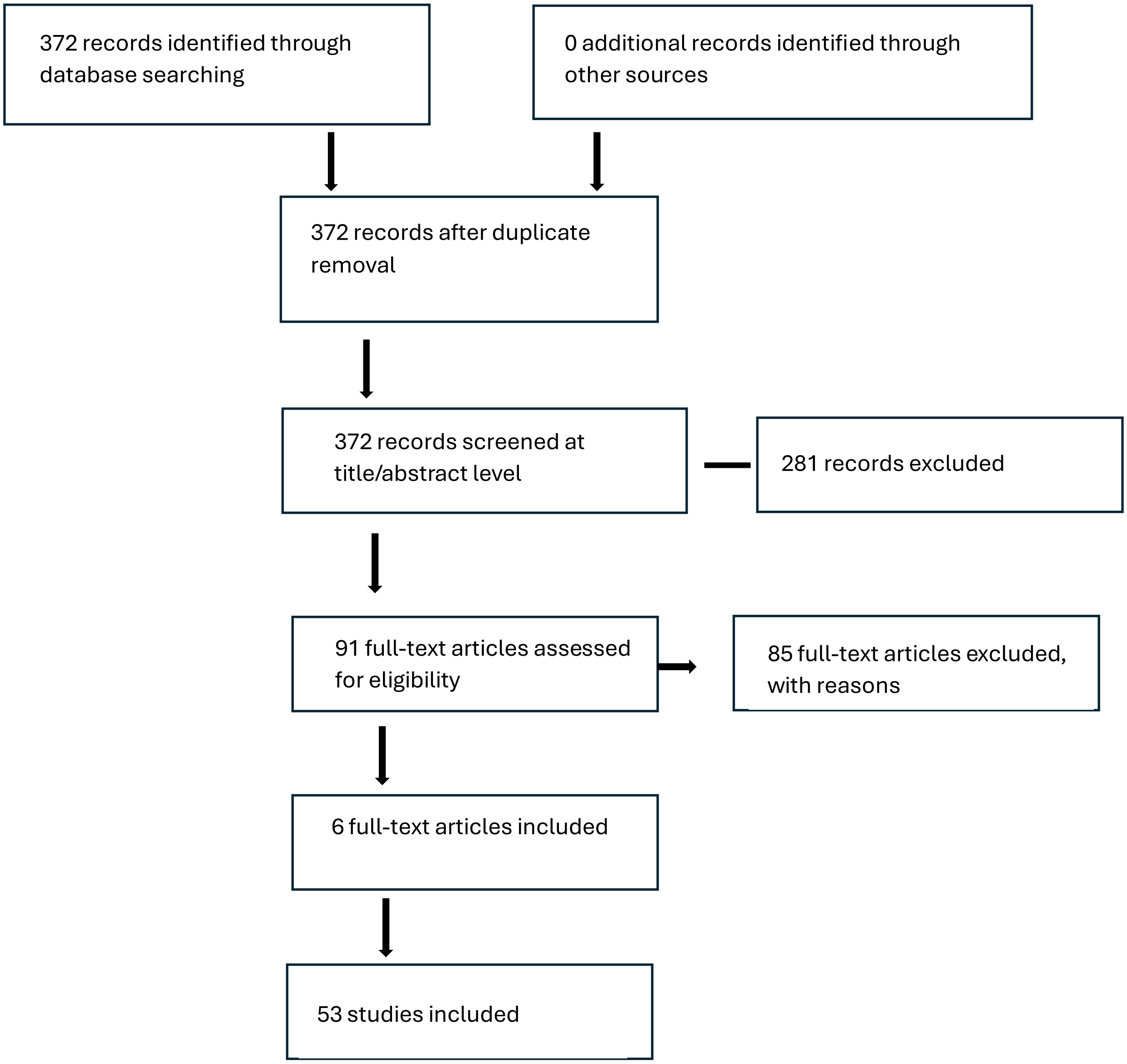


Figure 7. Prisma flow charts for associated biodiversity

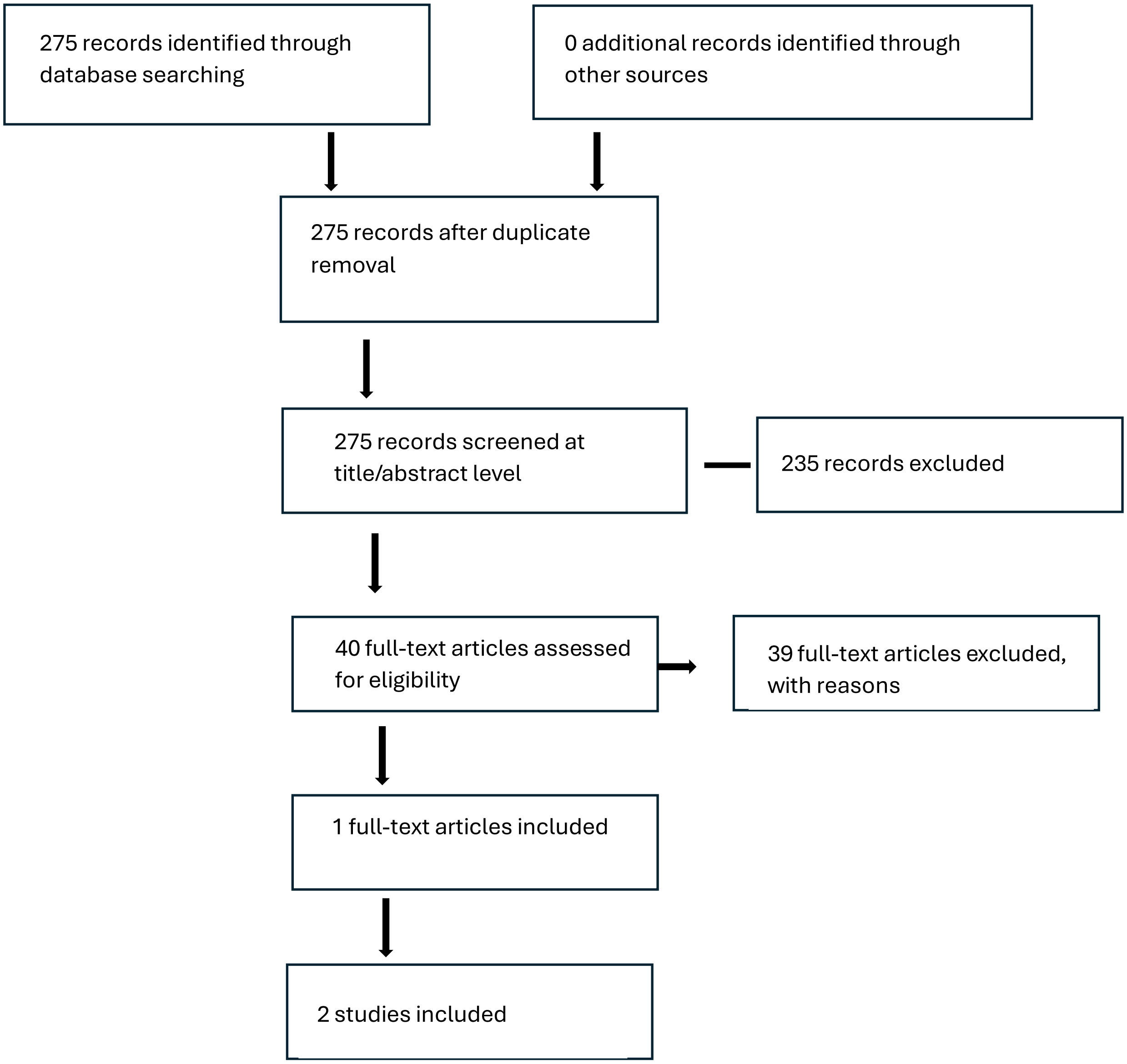
Merged dataset



2016+


372 records identified through database searching
0 additional records identified through other sources
372 records after duplicate removal
372 records screened at title/abstract level
281 records excluded
91 full-text articles assessed for eligibility
85 full-text articles excluded, with reasons
6 full-text articles included
53 studies included

Before 2016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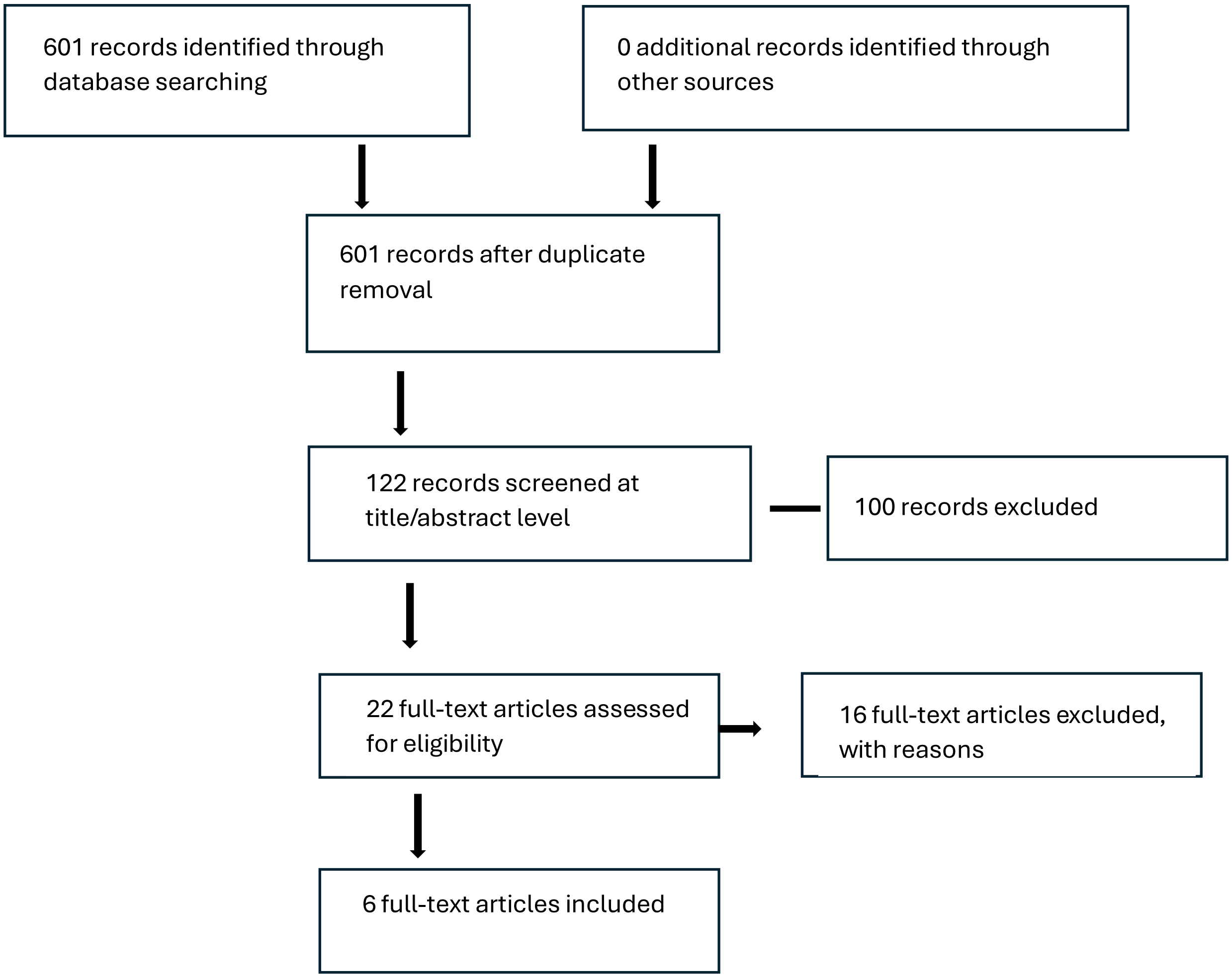
0 additional records identified through other sources
275 records after duplicate removal
275 records screened at title/abstract level
235 records excluded
40 full-text articles assessed for eligibility
39 full-text articles excluded, with reasons
1 full-text articles included
2 studies included

Figure 8.Prisma flow charts for climate resilience



Annex 3: Overviews

Table 1: Yield

Paper	Yield Stability Parameter	Control	Treatment	Effect		Differences	
Reference	**Yield unit**	**Without legume Rotation**	**With legume Rotation**	**Positive**	**Negative**	**Differences significant?**	**Significance test**
Wijata et al. (2025)	Sum of Shukla Stability Variance	sugar beet- spring barley-winter rapeseed- winter wheat	sugar beet- spring barley with undersown red clover- red clover- winter wheat	With full NPK, legume rotation had the lowest stability variance rank sum for wheat (sum=5, the most stable), slightly better than the best non-legume treatment (sum=7). Non-legume rotation: Under manure-only, stability was better (rank sum=9) than the legume rotation with manure (sum=13) – i.e. the legume rotation was less stable when only manure was used. In both rotations, the unfertilized control was least stable (highest σ²; rank sums 16 vs 13).		-	-
Wang et al. (2025)	Yield variability (CV)	WW (winter wheat) -WW, hard red spring wheat (HRSW)-WW, WW-HRSW	7 rotational crops (soybean, lentil, field peas, faba bean, canola, flax, and oats)		Legume pre-crops did not consistently improve yield stability; they boosted yield but often increased yield fluctuation between years/sites. Non-legume canola gave more stable yields in later wheat despite no first-year boost. Overall, legume rotations traded some stability for higher yields in this study	-	-
		fallow-wheat-wheat (F-W-W), fallow-wheat-wheat-wheat (F-W-	lentil green manure-wheat-wheat (GM-W-W),		W–C–W–P displayed the lowest stability (grain slope 1.32;	F–W–W, F–W–W–W,	Finlay–Wilkinson

St. Luce, M. et al. (2020)	Finlay–Wilkinson regression slope	W-W), continuous wheat (ContW)	wheat-canola-wheat-field pea (W-C-W-P).		protein slope 1.37), becoming highly variable across environments despite high average yields. GM–W–W stability close to 1 but tended to underperform in dry/hot years, revealing vulnerability to climatic stress. F–W–W & F–W–W–W maintained the most stable performance (slopes < 1) but at lower yield levels.	ContW, W–C–W–P (slope significantly ≠ 1). GM–W–W (slope not significantly different from 1).	slope tests ($p < 0.05$)
Macholdt, J. et al. (2019)	Variation coefficient of eco-valence (%) for grain yield	**CRS1**: Winter rye-Winter wheat-Winter barley-Spring oat, **CRS2**: Winter rye (+ S*+ G**)-Winter wheat-Winter barley-(+ S + G)-Spring oat **CRS3**: Oilseed rape (+ S) -Winter wheat -Winter barley (+ S + G) -Spring oat **CRS4**: Sugar beet (+ G)-Winter wheat-Winter barley (+ S + G)-Spring oat (+ S + G) G = green manure, S= Straw manure	**CRS5:** Field bean (+ S)-Winter wheat-Winter barley (+ S + G)-Spring oat (+ S + G) **CRS6**: Field bean (+ S)-Winter wheat-Winter barley (+ S + G)-Silage maize	CRS6 showed the highest grain yield stability in N1 (4.69) and N2 (4.68), whereas CRS1 and CRS2 were characterized by the highest eco-valence values, indicating low grain yield stability. CRS5 showed moderate eco-valence values with a markedly better grain yield stability in N2 than in N0. *N0 = without N; N1 = 40 + 40 kg N ha^{-1}; N2 = 60 + 40 + 60 kg N ha^{-1}		-	-
	GGE biplot (combined evaluation of yield performance and yield stability)			CRS1–2 (cereal-heavy): lowest yields and least stable. CRS3–4 (oilseed rape / sugar beet): intermediate yield and stability. CRS5–6 (field bean): highest and most stable wheat yields. *field bean as the preceding crop (CRS5–6) showed better grain yield performance under conditions without N fertilization.		-	-
	risk analysis (grain yield > 6 t ha^{-1} [%})			Probability that wheat yield exceeds 6 t ha^{-1} was highest in legume rotations, especially		-	-

				at high N (N2): – CRS5: 19% (N0), 73% (N1), 78% (N2); –CRS6: 14% (N0), 66% (N1), 75% (N2); *vs* cereal rotations CRS1–2 with only 2–5% (N0) and 44–56% (N2). Over all N levels, CRS5–6 had the greatest overall probability of outperforming the long-term mean (5.51 t ha^{-1}).		
Beres, B.L et al. (2018)	variability (Coefficient of Variation, CV %)	low diversity rotations (LDR): -continuous triticale (T-T_LDR) -triticale-wheat (T-W_LDR) -triticale-canola (T-C_MDR)	Moderate diversity rotations (MDR): -(triticale-field pea (T-P_MDR) -triticale: field pea intercrop (T- in P_MDR)) high diversity rotation (HDR): -canola-triticale-field pea (C-T-P_HDR))	Including a pea phase increased yield stability and shifted rotations toward lower CV values. The 3-year rotation C–T–P_HDR showed the highest yield and the lowest variability, occupying the most favorable stability group (Group I: high yield, low CV). Legume-inclusive rotations (T–P_MDR, T-in-P_MDR) had lower CV and more stable performance than cereal-only rotations.		
Götze, P. et al. (2018)	Coefficient of variation (CV, %) of white sugar yield	SB monoculture (CI = 0; 100% SB) – CV = 34.1% (WW–SB–SB)–SB (CI = 0) – CV = 16.6% (SB–WW–SB)–SB (CI = 0) – CV = 9.8% (WW–WW–SB)–SB (CI = 0) – CV = 12.4%	Alf–WW–SB–WW)–SB (CI = 1) – CV = 7.2% (WW–SB–Alf–WW)–SB (CI = 2) – CV = 7.1% (WW–Alf–WW)–SB (CI = 3) – CV = 9.7% (WW–Alf–Alf–WW)–SB (CI = 4) – CV = 10.0%	Cropping interval ≥ 2 years: higher yield stability and higher yield.Rotations with CI ≥ 2 years had lower CV and lower ecovalence while also achieving higher white sugar yields than rotations with CI 0–1 year. Integration of alfalfa (legume) improved stability at short		For all crop rotation fields, slopes b were not significantly different from 1, indicating average sensitivity to environmental conditions

	(SB–SB–WW)–SB (CI = 1) – CV = 6.4% (GM)–SB (grain maize–SB, CI = 1) – CV = 12.2% (SB–WW–WW)–SB (CI = 2) – CV = 6.4% (Pot–WW)–SB (potato–wheat–SB, CI = 2) – CV = 4.7% *SB = sugar beet, WW = winter wheat, GM = grain maize, Pot = potato, Alf=Alfalfa CI = *cropping interval* (years between two sugar beet crops) CI = 0, sugar beet every year CI = 1, sugar beet every 2 years CI = 2, sugar beet every 3 years	interval: At CI = 1, the legume rotation (Alf–WW–SB–WW)–SB combined above-average white sugar yield with high yield stability (CV 7.2%), whereas SB monoculture at CI = 0 had both lowest yield and highest CV (34.1%).

Table 2: Pest suppression

Reference	Chemical crop protection	Pest control indicators	Year	Without legume		With legume		Differences significant?	Significance test
				Rotation/intercropping	Pest suppression outcome	Rotation/intercropping	Pest suppression outcome		
Jalli et al. (2021)	Herbicides, fungicides, insecticides	Stem and root disease index	n/a	CR1: continuous spring wheat monoculture	22.1	CR4: 4-year rotation including pea legume as pre-crop for wheat	18.9	yes	ANOVA
		Leaf blotch disease severity	n/a		29.5		23.7	yes	
		Wheat midge kernel damage (%)	n/a		3.3		3.1	no	
		Spring wheat yield (kg/ha)	n/a		3615		4381	yes	
		Stem and root disease index	n/a	CR2: 2-year rotation including spring wheat and turnip rape/barley	20.5	CR4: 4-year rotation including pea legume as pre-crop for wheat	18.9	no	ANOVA
		Leaf blotch disease severity	n/a		25.2		23.7	no	

		Wheat midge kernel damage (%)	n/a		3.3		3.1	no	
		Spring wheat yield (kg/ha)	n/a		4142		4381	yes	
Hatt & Dring (2025)	Organic, no pesticides	Aphid colonization rate	2021	Wheat	0.37	Faba bean-wheat	0.29	no	Linear mixed model (ANOVA)
		Grain yield	2021		2568		2211	no	
Mansion-Vaquié et al. (2019)[1]		Cumulative aphids/tiller[2]	Average 2016 2017	Monoculture: Wheat (Renan cv)	150	Intercrop wheat-clover	188	no yes	Tukey-adjusted Estimated Marginal Mean
			Average 2016 2017	Monoculture: Wheat (Pireneo cv)	182		206	no	
			Average 2016 2017	Monoculture: Wheat (Mix cv)	177		163	yes no	
		Number aphids/tiller[2]	2016	Monoculture: Wheat (Renan cv)	1.76	Intercrop wheat-clover	2.87	no	
			2017		2.98		1.91	yes	
			2016	Monoculture: Wheat (Pireneo cv)	3.75		3.23	no	
			2017		3.78		1.99	yes	
			2016	Monoculture: Wheat (Mix cv)	2.82		1.85	yes	
			2017		3.41		3.29	no	
		% tillers infested (peak)[1]	2016	Monoculture: Wheat (Renan cv)	68	Intercrop wheat-clover	57	no	
			2017		53		39	yes	
			2016	Monoculture: Wheat (Pireneo cv)	70		68	no	
			2017		63		53	yes	
			2016	Monoculture: Wheat (Mix cv)	65		60	no	
			2017		63		54	no	
		Yield (t/ha)	2016	Monoculture: Wheat (Renan cv)	2.91	Intercrop wheat-clover	2.40	yes	LMM, Tukey HSD
			2017		4.43		4.03	yes	
			2016	Monoculture: Wheat (Pireneo cv)	2.45		2.16	yes	
			2017		4.78		4.15	yes	
			2016	Monoculture: Wheat (Mix cv)	2.37		2.32	yes	
			2017		4.55		4.20	yes	

		Grain N (g/kg)	2016	Monoculture: Wheat (Renan cv)	18.22	Intercrop wheat-clover	17.60	yes	LMM, Tukey HSD
			2017		16.73		16.72		
			2016	Monoculture: Wheat (Pireneo cv)	19.00		17.00	yes	
			2017		18.33		16.89	yes	
			2016	Monoculture: Wheat (Mix cv)	19.72		17.32	yes	
			2017		18.00		16.73	yes	
Järvinen et al. (2023)	None in 2019; 2020: lambda-cyhalothrin only for turnip rape seedlings	Total abundance of turnip rape pests	2019	Monoculture spring turnip rape	66.4	Strip intercropping (50:50 strips, turnip rape/faba bean)	30.9	yes	
		Total abundance of turnip rape pests	2020		15.7		7.9	yes	
		Predator/pest ratio	2019	Monoculture spring turnip rape	1.8	Strip intercropping (50:50 strips, turnip rape/faba bean)	6.8	yes	
		Predator/pest ratio	2020		6.3		10.6	no	
Puliga et al. (2023)	Conventional; herbicide in wheat/pea, mechanical in mix, no insect/fungicide in 2019, full suite in 2020	Activity density of generalist predators	2019	J monocrop	11.4	Wheat+Pea intercrop	24.7	yes	Type III Chi-squared test
		Activity density of generalist predators	2020	Barley after wheat	11.5	Barley after pea	22.7	yes	
				Barley after wheat+pea	11.4	Barley after pea	22.7	yes	
				Barley after what	11.5	Barley after wheat+pea	11.4	no	
		Predator/pest ratio	2019	Monoculture spring turnip rape	1.8	Strip intercropping (50:50 strips, turnip rape/faba bean)	6.8	yes	
		Predator/pest ratio	2020		6.3		10.6	no	
	Comments: ^{1} = The precise numerical data for cumulative aphid numbers, number aphids per tiller, and percentage of tillers infested in Mansion-Vaquié et al. (2019) are not provided as raw table values in the paper, but the estimation are made visually by measuring bar/point heights using WebPlotDigitizer v4.6. program								

Table 3: Weed suppression – Crop rotations with legumes vs. crop rotations without legumes

Paper	Weed unit	Control		Treatment		Legume use	Differences	
	Weed biomass ($g\ m^{-2}$) or weed density ($pt\ m^{-2}$) or weed cover (%)	Without legume		With legume				
Reference		Rotation	weed outcome	Rotation	weed outcome	Main crop or cover crop	Significant differences?	Significance test
Dorado et al., 2025	Weed biomass	barley-barley	0.28	field pea- barley	3.03	Main crop	no	Bonferroni test, $p \leq 0.05$
		barley-barley	3.58	field pea- barley	1.54		no	
		barley-barley	1.03	field pea- barley	44.00		no	
		barley-barley	1.29	field pea- barley	11.16		no	
		barley-barley	0.28	Fallow - grain legume - barley	21.62		yes	
		barley-barley	3.58	Fallow - grain legume - barley	41.15		yes	
		barley-barley	1.03	Fallow - grain legume - barley	123.59		yes	
		barley-barley	1.29	Fallow - grain legume - barley	139.51		yes	
Jalli et al., 2021	Weed density	spring wheat monoculture	85	spring wheat—spring turnip rape—spring barley—field pea	100	Main crop	no	LSD test, $p \leq 0.05$
		spring wheat/spring turnip rape – spring wheat/spring barley	115	spring wheat—spring turnip rape—spring barley—field pea	100		no	
		spring wheat monoculture	95	spring wheat—spring turnip rape—spring barley—field pea	170		yes	
		spring wheat/spring turnip rape – spring wheat/spring barley	180	spring wheat—spring turnip rape—spring barley—field pea	170		yes	
		spring wheat monoculture	160	spring wheat—spring turnip rape—spring barley—field pea	160		no	
		spring wheat/spring turnip rape – spring wheat/spring barley	200	spring wheat—spring turnip rape—spring barley—field pea	160		no	
		spring wheat monoculture	120	spring wheat—spring turnip rape—spring barley—field pea	410		yes	
		spring wheat/spring turnip rape – spring wheat/spring barley	350	spring wheat—spring turnip rape—spring barley—field pea	410		yes	
		spring wheat monoculture	190	spring wheat—spring turnip rape—spring barley—field pea	410		yes	
		spring wheat/spring turnip rape – spring wheat/spring barley	210	spring wheat—spring turnip rape—spring barley—field pea	410		yes	

		spring wheat monoculture	200	spring wheat—spring turnip rape—spring barley—field pea	280		no	
		spring wheat/spring turnip rape – spring wheat/spring barley	320	spring wheat—spring turnip rape—spring barley—field pea	280		no	
		spring wheat monoculture	100	spring wheat—spring turnip rape—spring barley—field pea	300		yes	
		spring wheat/spring turnip rape – spring wheat/spring barley	220	spring wheat—spring turnip rape—spring barley—field pea	300		yes	
		spring wheat monoculture	60	spring wheat—spring turnip rape—spring barley—field pea	220		yes	
		spring wheat/spring turnip rape – spring wheat/spring barley	130	spring wheat—spring turnip rape—spring barley—field pea	220		yes	
Wanic et al., 2018	Weed density	Wheat-Wheat	109	Peas-Wheat	134	Main crop	no	Tukey's test, p ≤0.05
		Wheat-Wheat	140	Peas-Wheat	160		no	
		Wheat-Wheat	148	Peas-Wheat	79		yes	
		Oliseed rape-Wheat	130	Peas-Wheat	134		no	
		Oliseed rape-Wheat	177	Peas-Wheat	160		no	
		Oliseed rape-Wheat	89	Peas-Wheat	79		yes	
		Spelt-Spelt	74	Peas-Spelt	97		no	
		Spelt-Spelt	160	Peas-Spelt	35		yes	
		Spelt-Spelt	274	Peas-Spelt	165		yes	
		Oliseed rape-Spelt	114	Peas-Spelt	97		no	
		Oliseed rape-Spelt	88	Peas-Spelt	35		yes	
		Oliseed rape-Spelt	180	Peas-Spelt	165		no	
	Weed biomass	Wheat-Wheat	237	Peas-Wheat	107		yes	
		Wheat-Wheat	84.7	Peas-Wheat	60.8		yes	
		Wheat-Wheat	181.2	Peas-Wheat	104.7		yes	
		Oliseed rape-Wheat	183.4	Peas-Wheat	107		yes	
		Oliseed rape-Wheat	94	Peas-Wheat	60.8		yes	
		Oliseed rape-Wheat	158.7	Peas-Wheat	104.7		yes	
		Spelt-Spelt	103.7	Peas-Spelt	134.3		yes	
		Spelt-Spelt	85.3	Peas-Spelt	46.7		no	

		Spelt-Spelt	243.1	Peas-Spelt	183.3		yes	
		Oliseed rape-Spelt	129.3	Peas-Spelt	134.3		no	
		Oliseed rape-Spelt	80.3	Peas-Spelt	46.7		yes	
		Oliseed rape-Spelt	231.4	Peas-Spelt	183.3		yes	
Gawęda et al., 2018	Weed density	Winter rapeseed-Wheat	32.8	Soybean-Wheat	19.3	Main crop	yes	Tukey's test, p ≤ 0.05.
		Winter rapeseed-Wheat	14.5	Soybean-Wheat	8.9		yes	
		Winter rapeseed-Wheat	14.9	Soybean-Wheat	11.8		no	
		Winter rapeseed-Wheat	28.5	Soybean-Wheat	16.2		yes	
	Weed biomass	Winter rapeseed-Wheat	8.8	Soybean-Wheat	4.7		yes	
		Winter rapeseed-Wheat	7.5	Soybean-Wheat	3.9		yes	
		Winter rapeseed-Wheat	6.3	Soybean-Wheat	4.6		no	
		Winter rapeseed-Wheat	10.9	Soybean-Wheat	13.3		yes	
Woźniak et al., 2018	Weed density	spring barley - spring wheat durum wheat	38	pea - spring wheat - durum wheat	26.6	Main crops	yes	Tukey's test, p ≤ 0.05.
		spring barley - spring wheat durum wheat	38	pea - spring barley - spring wheat	26.9		yes	
		spring barley - spring wheat durum wheat	102.6	pea - spring wheat - durum wheat	76		yes	
		spring barley - spring wheat durum wheat	102.6	pea - spring barley - spring wheat	68.2		yes	
Rey-Caballero et al., 2017	Weed density	Wheat monocrop + post emergence herbicide	27	wheat–field pea–wheat	20	Main crop	no	Tukey's test, p ≤ 0.05.
		Wheat monocrop + post emergence herbicide rotation	29	wheat–field pea–wheat	20		no	
		Wheat monocrop + early post emergence herbicide timing	20	wheat–field pea–wheat	20		no	
		Wheat monocrop + pre and post emergence herbicide (1st and 3rd year) + only post (2nd year)	3	wheat–field pea–wheat	20		yes	
		Wheat–rapeseed–wheat	27	wheat–field pea–wheat	20		no	
		Wheat–sunflower–wheat	38	wheat–field pea–wheat	20		no	
		Wheat monocrop with ≈1-month sowing delay	9	wheat–field pea–wheat	20		yes	
		Wheat monocrop + post emergence herbicide	18	wheat–field pea–wheat	3		yes	

Wheat monocrop + post emergence herbicide rotation	10	wheat–field pea–wheat	3	yes
Wheat monocrop + early post emergence herbicide timing	10	wheat–field pea–wheat	3	yes
Wheat monocrop + pre and post emergence herbicide (1st and 3rd year) + only post (2nd year)	7	wheat–field pea–wheat	3	no
Wheat–rapeseed–wheat	13	wheat–field pea–wheat	3	yes
Wheat–sunflower–wheat	1	wheat–field pea–wheat	3	no
Wheat monocrop with ≈1-month sowing delay	11	wheat–field pea–wheat	3	yes
Wheat monocrop + post emergence herbicide	29	wheat–field pea–wheat	2	yes
Wheat monocrop + post emergence herbicide rotation	12	wheat–field pea–wheat	2	yes
Wheat monocrop + early post emergence herbicide timing	11	wheat–field pea–wheat	2	yes
Wheat monocrop + pre and post emergence herbicide (1st and 3rd year) + only post (2nd year)	0.2	wheat–field pea–wheat	2	no
Wheat–rapeseed–wheat	4	wheat–field pea–wheat	2	no
Wheat–sunflower–wheat	0.5	wheat–field pea–wheat	2	no
Wheat monocrop with ≈1-month sowing delay	6	wheat–field pea–wheat	2	no
Wheat monocrop + post emergence herbicide	1.5	wheat–field pea–wheat	1.8	no
Wheat monocrop + post emergence herbicide rotation	1.2	wheat–field pea–wheat	1.8	no
Wheat monocrop + early post emergence herbicide timing	0.9	wheat–field pea–wheat	1.8	no
Wheat monocrop + pre and post emergence herbicide (1st and 3rd year) + only post (2nd year)	0.3	wheat–field pea–wheat	1.8	no
Wheat–rapeseed–wheat	2.1	wheat–field pea–wheat	1.8	no
Wheat–sunflower–wheat	1.5	wheat–field pea–wheat	1.8	no
Wheat monocrop with ≈1-month sowing delay	8.3	wheat–field pea–wheat	1.8	no

		Wheat monocrop + post emergence herbicide	0.3	wheat–field pea–wheat	0.3		no	
		Wheat monocrop + post emergence herbicide rotation	0.9	wheat–field pea–wheat	0.3		no	
		Wheat monocrop + early post emergence herbicide timing	0.3	wheat–field pea–wheat	0.3		no	
		Wheat monocrop + pre and post emergence herbicide (1st and 3rd year) + only post (2nd year)	0.3	wheat–field pea–wheat	0.3		no	
		Wheat–rapeseed–wheat	8.9	wheat–field pea–wheat	0.3		yes	
		Wheat–sunflower–wheat	0.3	wheat–field pea–wheat	0.3		no	
		Wheat monocrop with ≈1-month sowing delay	0.3	wheat–field pea–wheat	0.3		no	
		Wheat monocrop + post emergence herbicide	11	wheat–field pea–wheat	4		no	
		Wheat monocrop + post emergence herbicide rotation	11	wheat–field pea–wheat	4		no	
		Wheat monocrop + early post emergence herbicide timing	12	wheat–field pea–wheat	4		no	
		Wheat monocrop + pre and post emergence herbicide (1st and 3rd year) + only post (2nd year)	1	wheat–field pea–wheat	4		no	
		Wheat–rapeseed–wheat	14	wheat–field pea–wheat	4		yes	
		Wheat–sunflower–wheat	12	wheat–field pea–wheat	4		no	
		Wheat monocrop with ≈1-month sowing delay	12	wheat–field pea–wheat	4		yes	

Table 4: Weed suppression – Intercropping with legumes vs. intercropping without legumes

Paper	Weed unit	Control		Treatment		Legume use	Differences	
		Without legume		With legume				
Reference	Weed biomass (g m^{-2}) or weed density (pt m^{-2}) or weed cover (%)	Intercropping and non-legume ref.	weed outcome	Intercropping and legume ref.	weed outcome	Main crop or cover crop	Significant differences?	Significance test
Raimondi et al. (2025)	Weed biomass	Cardoon - Eruca sativa	85	Cardoon - Hairy vetch	90	Main crop	no	Sidak test, p ≤ 0.05
		Cardoon - Camelina sativa	55	Cardoon - Hairy vetch	90		no	

		Cardoon	167.5	Cardoon - Hairy vetch	90		yes	
		Cardoon - Eruca sativa	115	Cardoon - Hairy vetch	150		no	
		Cardoon - Camelina sativa	85	Cardoon - Hairy vetch	150		no	
		Cardoon	305	Cardoon - Hairy vetch	150		no	
Çağlar et al., 2025	Weed biomass	%100 ryegrass	14.7	%100 common vetch	29.8	Cover crop	yes	LSD test, p ≤ 0.05
		%100 ryegrass	14.7	%90 common vetch/ %10 ryegrass	13		no	
		%100 ryegrass	14.7	%80 common vetch/ %20 ryegrass	10.7		yes	
		%100 ryegrass	14.7	%70 common vetch/ %30 ryegrass	9		yes	
		%100 ryegrass	14.7	%60 common vetch/ %40 ryegrass	9.8		yes	
		%100 ryegrass	14.7	%50 common vetch/ %50 ryegrass	13.3		no	
		%100 ryegrass	14.7	%40 common vetch/ %60 ryegrass	15.2		no	
		%100 ryegrass	14.7	%30 common vetch/ %70 ryegrass	19.5		yes	
		%100 ryegrass	14.7	%20 common vetch/ %80 ryegrass	27		yes	
		%100 ryegrass	14.7	%10 common vetch / %90 ryegrass	20.8		yes	
		%100 ryegrass	22.2	%100 common vetch	29.3		no	
		%100 ryegrass	22.2	%90 common vetch/ %10 ryegrass	40.5		no	
		%100 ryegrass	22.2	%80 common vetch/ %20 ryegrass	19.2		no	
		%100 ryegrass	22.2	%70 common vetch/ %30 ryegrass	20.3		no	
		%100 ryegrass	22.2	%60 common vetch/ %40 ryegrass	11.7		yes	
		%100 ryegrass	22.2	%50 common vetch/ %50 ryegrass	25.4		no	
		%100 ryegrass	22.2	%40 common vetch/ %60 ryegrass	22.8		no	

		%100 ryegrass	22.2	%30 common vetch/ %70 ryegrass	25.7		no	
		%100 ryegrass	22.2	%20 common vetch/ %80 ryegrass	30		no	
		%100 ryegrass	22.2	%10 common vetch/ %90 ryegrass	20.2		no	
Tavoletti et al., 2023	Weed biomass	Barley	60.4	Pea3 (pure)	131	Main crop	yes	Tukey's test, p ≤0.05
		Barley	60.4	Pea1 (pure)	120.7		yes	
		Barley	60.4	Mix1—(Pea1–Barley1)	66		no	
		Barley	60.4	Mix3—(Pea3–Barley1)	57		no	
		Barley	60.4	Mix4—(Pea1–Barley1)	55.8		no	
		Barley	60.4	Mix2—(Pea3–Barley1)	51.9		no	
		Barley	60.4	Mix3—(Pea1–Barley1)	47.9		no	
		Barley	60.4	Mix2—(Pea1–Barley1)	45.5		no	
		Barley	60.4	Mix4—(Pea3–Barley1)	43.7		no	
		Barley	60.4	Mix1—(Pea3–Barley1)	40.4		no	
Abou Chehade et al., 2023	weed biomass	Conventional Tillage-Rye	2.7	Conventional Tillage-Squarrose clover	3.1	Cover crop	no	Bonferroni-adjusted post hoc test p ≤0.05
		Conventional Tillage -Control without cover	1.9	Conventional Tillage-mixture	2.9		no	
		Conventional Tillage-Rye	2.7	Conventional Tillage-mixture	2.9		no	
		Conventional Tillage -Control without cover	1.9	Conventional Tillage-Squarrose clover	3.1		no	
		Conventional Tillage-Rye	2.7	No Tillage-Squarrose clover	3.1		no	
		Conventional Tillage -Control without cover	1.9	No Tillage-mixture	2		no	
		Conventional Tillage-Rye	2.7	No Tillage-mixture	2		no	
		Conventional Tillage -Control without cover	1.9	No Tillage-Squarrose clover	3.1		no	
		No Tillage-Rye	3.5	Conventional Tillage-Squarrose clover	3.1		no	
		No Tillage-Control without cover	5.2	Conventional Tillage-mixture	2.9		no	

		No Tillage-Rye	3.5	Conventional Tillage-mixture	2.9		no	
		No Tillage-Control without cover	5.2	Conventional Tillage-Squarrose clover	3.1		no	
		No Tillage-Rye	3.5	No Tillage-Squarrose clover	3.1		no	
		No Tillage-Control without cover	5.2	No Tillage-mixture	2		no	
		No Tillage-Rye	3.5	No Tillage-mixture	2		no	
		No Tillage-Control without cover	5.2	No Tillage-Squarrose clover	3.1		no	
Abou Chehade et al., 2021	weed density	Rye	21.3	Squarrose clover	23	Cover crop	no	Tukey's test, p ≤0.05
		Rye	21.3	Mixture (rye + Squarrose clover)	18.5		no	
		Control without cover	26.7	Squarrose clover	23		yes	
		Control without cover	26.7	Mixture (rye + Squarrose clover)	18.5		yes	
Marcinkevičienė et al., 2021	Weed density	Spring Barley	78.3	Pea	17.5	Main crop	yes	LSD test, p ≤ 0.05
		Spring Barley	78.3	Pea-Caraway	21.7		yes	
		Spring Barley	78.3	Spring Barley-Caraway-White Clover	251.2		yes	
		Spring Barley	78.3	Spring Wheat-Caraway-White Clover	121.7		no	
		Spring Barley	78.3	Pea-Caraway-White Clover	157.1		yes	
		Spring Barley	47.5	Pea	50.4		no	
		Spring Barley	47.5	Pea-Caraway	14.2		yes	
		Spring Barley	47.5	Spring Barley-Caraway-White Clover	1.25		yes	
		Spring Barley	47.5	Spring Wheat-Caraway-White Clover	4.59		yes	
		Spring Barley	47.5	Pea-Caraway-White Clover	3.75		yes	
		Spring Barley	35.4	Pea	74.2		no	
		Spring Barley	35.4	Pea-Caraway	59.6		no	
		Spring Barley	35.4	Spring Barley-Caraway-White Clover	35.4		no	
		Spring Barley	35.4	Spring Wheat-Caraway-White Clover	41.2		no	

Spring Barley	35.4	Pea-Caraway-White Clover	45		no
Spring Wheat	31.7	Pea	17.5		no
Spring Wheat	31.7	Pea-Caraway	21.7		no
Spring Wheat	31.7	Spring Barley-Caraway-White Clover	251.2		yes
Spring Wheat	31.7	Spring Wheat-Caraway-White Clover	21.7		yes
Spring Wheat	31.7	Pea-Caraway-White Clover	157.1		yes
Spring Wheat	28.4	Pea	50.4		no
Spring Wheat	28.4	Pea-Caraway	14.2		no
Spring Wheat	28.4	Spring Barley-Caraway-White Clover	1.25		yes
Spring Wheat	28.4	Spring Wheat-Caraway-White Clover	4.59		yes
Spring Wheat	28.4	Pea-Caraway-White Clover	3.75		yes
Spring Wheat	49.6	Pea	74.2		no
Spring Wheat	49.6	Pea-Caraway	59.6		no
Spring Wheat	49.6	Spring Barley-Caraway-White Clover	35.4		no
Spring Wheat	49.6	Spring Wheat-Caraway-White Clover	41.2		no
Spring Wheat	49.6	Pea-Caraway-White Clover	45		no
Caraway	18.4	Pea	17.5		no
Caraway	18.4	Pea-Caraway	21.7		no
Caraway	18.4	Spring Barley-Caraway-White Clover	251.2		yes
Caraway	18.4	Spring Wheat-Caraway-White Clover	121.7		yes
Caraway	18.4	Pea-Caraway-White Clover	157.1		yes
Caraway	5.42	Pea	50.4		yes
Caraway	5.42	Pea-Caraway	14.2		no
Caraway	5.42	Spring Barley-Caraway-White Clover	1.25		no
Caraway	5.42	Spring Wheat-Caraway-White Clover	4.59		no

Caraway	5.42	Pea-Caraway-White Clover	3.75	no
Caraway	37.1	Pea	74.2	no
Caraway	37.1	Pea-Caraway	59.6	no
Caraway	37.1	Spring Barley-Caraway-White Clover	35.4	no
Caraway	37.1	Spring Wheat-Caraway-White Clover	41.2	no
Caraway	37.1	Pea-Caraway-White Clover	45	no
Spring Barley-Caraway	274.6	Pea	17.5	yes
Spring Barley-Caraway	274.6	Pea-Caraway	21.7	yes
Spring Barley-Caraway	274.6	Spring Barley-Caraway-White Clover	251.2	no
Spring Barley-Caraway	274.6	Spring Wheat-Caraway-White Clover	121.7	yes
Spring Barley-Caraway	274.6	Pea-Caraway-White Clover	157.1	no
Spring Barley-Caraway	9.18	Pea	50.4	yes
Spring Barley-Caraway	9.18	Pea-Caraway	14.2	no
Spring Barley-Caraway	9.18	Spring Barley-Caraway-White Clover	1.25	no
Spring Barley-Caraway	9.18	Spring Wheat-Caraway-White Clover	4.59	no
Spring Barley-Caraway	9.18	Pea-Caraway-White Clover	3.75	no
Spring Barley-Caraway	44.2	Pea	74.2	no
Spring Barley-Caraway	44.2	Pea-Caraway	59.6	no
Spring Barley-Caraway	44.2	Spring Barley-Caraway-White Clover	35.4	no
Spring Barley-Caraway	44.2	Spring Wheat-Caraway-White Clover	41.2	no
Spring Barley-Caraway	44.2	Pea-Caraway-White Clover	45	no
Spring Wheat-Caraway	137.5	Pea	17.5	yes
Spring Wheat-Caraway	137.5	Pea-Caraway	21.7	yes
Spring Wheat-Caraway	137.5	Spring Barley-Caraway-White Clover	251	no
Spring Wheat-Caraway	137.5	Spring Wheat-Caraway-White Clover	121.7	no

		Spring Wheat-Caraway	137.5	Pea-Caraway-White Clover	157.1		no
		Spring Wheat-Caraway	8.33	Pea	50.4		yes
		Spring Wheat-Caraway	8.33	Pea-Caraway	14.2		no
		Spring Wheat-Caraway	8.33	Spring Barley-Caraway-White Clover	1.25		no
		Spring Wheat-Caraway	8.33	Spring Wheat-Caraway-White Clover	4.59		no
		Spring Wheat-Caraway	8.33	Pea-Caraway-White Clover	3.75		no
		Spring Wheat-Caraway	60.4	Pea	74.2		no
		Spring Wheat-Caraway	60.4	Pea-Caraway	59.6		no
		Spring Wheat-Caraway	60.4	Spring Barley-Caraway-White Clover	35.4		no
		Spring Wheat-Caraway	60.4	Spring Wheat-Caraway-White Clover	41.2		no
		Spring Wheat-Caraway	60.4	Pea-Caraway-White Clover	45		no
	Weed biomass	Spring Barley	40.8	Pea	13.1		yes
		Spring Barley	40.8	Pea-Caraway	59.5		no
		Spring Barley	40.8	Spring Barley-Caraway-White Clover	181.8		yes
		Spring Barley	40.8	Spring Wheat-Caraway-White Clover	111.3		no
		Spring Barley	40.8	Pea-Caraway-White Clover	414		yes
		Spring Barley	5.86	Pea	18.3		no
		Spring Barley	5.86	Pea-Caraway	22.1		no
		Spring Barley	5.86	Spring Barley-Caraway-White Clover	15.6		no
		Spring Barley	5.86	Spring Wheat-Caraway-White Clover	34.5		yes
		Spring Barley	5.86	Pea-Caraway-White Clover	21.9		no
		Spring Barley	30.7	Pea	104.4		no
		Spring Barley	30.7	Pea-Caraway	279.8		yes
		Spring Barley	30.7	Spring Barley-Caraway-White Clover	228.3		yes
		Spring Barley	30.7	Spring Wheat-Caraway-White Clover	136.2		yes

Spring Barley	30.7	Pea-Caraway-White Clover	162.7		yes
Spring Wheat	8.67	Pea	13.1		no
Spring Wheat	8.67	Pea-Caraway	59.5		yes
Spring Wheat	8.67	Spring Barley-Caraway-White Clover	181.8		yes
Spring Wheat	8.67	Spring Wheat-Caraway-White Clover	111.3		yes
Spring Wheat	8.67	Pea-Caraway-White Clover	414		yes
Spring Wheat	6.71	Pea	18.3		no
Spring Wheat	6.71	Pea-Caraway	22.1		no
Spring Wheat	6.71	Spring Barley-Caraway-White Clover	15.6		no
Spring Wheat	6.71	Spring Wheat-Caraway-White Clover	34.5		yes
Spring Wheat	6.71	Pea-Caraway-White Clover	21.9		no
Spring Wheat	23.5	Pea	104.4		no
Spring Wheat	23.5	Pea-Caraway	279.8		yes
Spring Wheat	23.5	Spring Barley-Caraway-White Clover	228.3		yes
Spring Wheat	23.5	Spring Wheat-Caraway-White Clover	136.2		yes
Spring Wheat	23.5	Pea-Caraway-White Clover	162.7		yes
Caraway	96	Pea	13.1		yes
Caraway	96	Pea-Caraway	59.5		no
Caraway	96	Spring Barley-Caraway-White Clover	181.8		no
Caraway	96	Spring Wheat-Caraway-White Clover	111.3		no
Caraway	96	Pea-Caraway-White Clover	414		yes
Caraway	29.7	Pea	18.3		no
Caraway	29.7	Pea-Caraway	22.1		no
Caraway	29.7	Spring Barley-Caraway-White Clover	15.6		no
Caraway	29.7	Spring Wheat-Caraway-White Clover	34.5		no

Caraway	29.7	Pea-Caraway-White Clover	21.9	no
Caraway	93.8	Pea	104.4	no
Caraway	93.8	Pea-Caraway	279.8	yes
Caraway	93.8	Spring Barley-Caraway-White Clover	228.3	yes
Caraway	93.8	Spring Wheat-Caraway-White Clover	136.2	no
Caraway	93.8	Pea-Caraway-White Clover	162.7	no
Spring Barley-Caraway	120.6	Pea	13.1	yes
Spring Barley-Caraway	120.6	Pea-Caraway	59.5	no
Spring Barley-Caraway	120.6	Spring Barley-Caraway-White Clover	181.8	no
Spring Barley-Caraway	120.6	Spring Wheat-Caraway-White Clover	111.3	no
Spring Barley-Caraway	120.6	Pea-Caraway-White Clover	414	yes
Spring Barley-Caraway	40.6	Pea	18.3	no
Spring Barley-Caraway	40.6	Pea-Caraway	22.1	no
Spring Barley-Caraway	40.6	Spring Barley-Caraway-White Clover	15.6	no
Spring Barley-Caraway	40.6	Spring Wheat-Caraway-White Clover	34.5	no
Spring Barley-Caraway	40.6	Pea-Caraway-White Clover	21.9	no
Spring Barley-Caraway	111.7	Pea	104.4	no
Spring Barley-Caraway	111.7	Pea-Caraway	279.8	yes
Spring Barley-Caraway	111.7	Spring Barley-Caraway-White Clover	228.3	yes
Spring Barley-Caraway	111.7	Spring Wheat-Caraway-White Clover	136.2	no
Spring Barley-Caraway	111.7	Pea-Caraway-White Clover	162.7	no
Spring Wheat-Caraway	66.7	Pea	13.1	yes
Spring Wheat-Caraway	66.7	Pea-Caraway	59.5	no
Spring Wheat-Caraway	66.7	Spring Barley-Caraway-White Clover	181.8	no
Spring Wheat-Caraway	66.7	Spring Wheat-Caraway-White Clover	111.3	no

		Spring Wheat-Caraway	66.7	Pea-Caraway-White Clover	414		yes	
		Spring Wheat-Caraway	44.3	Pea	18.3		no	
		Spring Wheat-Caraway	44.3	Pea-Caraway	22.1		no	
		Spring Wheat-Caraway	44.3	Spring Barley-Caraway-White Clover	15.6		no	
		Spring Wheat-Caraway	44.3	Spring Wheat-Caraway-White Clover	34.5		no	
		Spring Wheat-Caraway	44.3	Pea-Caraway-White Clover	21.9		no	
		Spring Wheat-Caraway	151.9	Pea	104.4		no	
		Spring Wheat-Caraway	151.9	Pea-Caraway	279.8		no	
		Spring Wheat-Caraway	151.9	Spring Barley-Caraway-White Clover	228.3		no	
		Spring Wheat-Caraway	151.9	Spring Wheat-Caraway-White Clover	136.2		no	
		Spring Wheat-Caraway	151.9	Pea-Caraway-White Clover	162.7		no	
Cannon et al., 2020	Weed biomass	Wheat 56 days after sowing	2.7	beans 56 days after sowing	3.5	Main crop	yes	standard error of the difference (sed)
		Wheat 56 days after sowing	2.7	Beans/Wheat 56 days after sowing	2		yes	
		Wheat 87 days after sowing	3.6	beans 87 days after sowing	5.7		yes	
		Wheat 87 days after sowing	3.6	Beans/Wheat 87 days after sowing	2.8		yes	
		Wheat 51 days after sowing	3.2	beans 51 days after sowing	5.6		yes	
		Wheat 51 days after sowing	3.2	Beans/Wheat 51 days after sowing	2.4		yes	
		Wheat 73 days after sowing	3.7	beans 73 days after sowing	4		yes	
		Wheat 73 days after sowing	3.7	Beans/Wheat 73 days after sowing	2.9		yes	
Diacono et al., 2018	Weed biomass	Barley - roller crimper	2.31	Vetch - roller crimper	1.82	Cover crop	yes	SNK; $p \leq 0.05$
		Barley - roller crimper	3.24	Vetch - roller crimper	1.82		yes	
		Barley - roller crimper	2.31	Vetch - green manure	1.62		yes	
		Barley - green manure	3.24	Vetch - green manure	1.62		yes	
		Barley - roller crimper	2.31	Mixture - roller crimper	2.53		no	

		Barley - green manure	3.24	Mixture - roller crimper	2.53		yes	
		Barley - roller crimper	2.31	Mixture - green manure	2.12		no	
		Barley - green manure	3.24	Mixture - green manure	2.12		yes	
		Barley - roller crimper	5.92	Vetch - roller crimper	5.34		yes	
		Barley - green manure	6.2	Vetch - roller crimper	5.34		yes	
		Barley - roller crimper	5.92	Vetch - green manure	6.51		no	
		Barley - green manure	6.2	Vetch - green manure	6.51		no	
		Barley - roller crimper	5.92	Mixture - roller crimper	7.47		yes	
		Barley - green manure	6.2	Mixture - roller crimper	7.47		yes	
		Barley - roller crimper	5.92	Mixture - green manure	7.77		yes	
		Barley - green manure	6.2	Mixture - green manure	7.77		yes	
Masilionyte et al., 2017	Weed density	low humus content_ white mustard	5	low humus content_ narrow-leafed lupine/oil radish	7	Cover crop	no	LSD test, p ≤ 0.05
		low humus content_white mustard/common buckwheat	4	low humus content_ narrow-leafed lupine/oil radish	7		no	
		low humus content_no cover crop	9	low humus content_ narrow-leafed lupine/oil radish	7		no	
		moderate humus content_ white mustard	8	moderate humus content_ narrow-leafed lupine/oil radish	16		no	
		moderate humus content_ white mustard/common buckwheat	2	moderate humus content_ narrow-leafed lupine/oil radish	16		no	
		moderate humus content_ no cover crop	13	moderate humus content_ narrow-leafed lupine/oil radish	16		no	
		low humus content_ white mustard	71	low humus content_ narrow-leafed lupine/oil radish	89		no	
		low humus content_white mustard/common buckwheat	81	low humus content_ narrow-leafed lupine/oil radish	89		no	

low humus content_no cover crop	123	low humus content_ narrow-leafed lupine/oil radish	89		yes
moderate humus content_ white mustard	77	moderate humus content_ narrow-leafed lupine/oil radish	83		no
moderate humus content_ white mustard/common buckwheat	63	moderate humus content_ narrow-leafed lupine/oil radish	83		yes
moderate humus content_ no cover crop	105	moderate humus content_ narrow-leafed lupine/oil radish	83		yes
low humus content_ white mustard	31	low humus content_ narrow-leafed lupine/oil radish	45		no
low humus content_white mustard/common buckwheat	21	low humus content_ narrow-leafed lupine/oil radish	45		yes
low humus content_no cover crop	46	low humus content_ narrow-leafed lupine/oil radish	45		no
moderate humus content_ white mustard	26	moderate humus content_ narrow-leafed lupine/oil radish	53		yes
moderate humus content_ white mustard/common buckwheat	25	moderate humus content_ narrow-leafed lupine/oil radish	53		yes
moderate humus content_ no cover crop	31	moderate humus content_ narrow-leafed lupine/oil radish	53		yes
low humus content_ white mustard	10	low humus content_ narrow-leafed lupine/oil radish	13		no
low humus content_white mustard/common buckwheat	9	low humus content_ narrow-leafed lupine/oil radish	13		no
low humus content_no cover crop	23	low humus content_ narrow-leafed lupine/oil radish	13		no

	moderate humus content_ white mustard	12	moderate humus content_ narrow-leafed lupine/oil radish	14		no
	moderate humus content_ white mustard/common buckwheat	9	moderate humus content_ narrow-leafed lupine/oil radish	14		no
	moderate humus content_ no cover crop	22	moderate humus content_ narrow-leafed lupine/oil radish	14		no
	low humus content_ white mustard	28	low humus content_ narrow-leafed lupine/oil radish	40		no
	low humus content_white mustard/common buckwheat	19	low humus content_ narrow-leafed lupine/oil radish	40		yes
	low humus content_no cover crop	53	low humus content_ narrow-leafed lupine/oil radish	40		no
	moderate humus content_ white mustard	19	moderate humus content_ narrow-leafed lupine/oil radish	38		no
	moderate humus content_ white mustard/common buckwheat	16	moderate humus content_ narrow-leafed lupine/oil radish	38		yes
	moderate humus content_ no cover crop	82	moderate humus content_ narrow-leafed lupine/oil radish	38		yes
	low humus content_ white mustard	29	low humus content_ narrow-leafed lupine/oil radish	35		no
	low humus content_white mustard/common buckwheat	23	low humus content_ narrow-leafed lupine/oil radish	35		no
	low humus content_no cover crop	41	low humus content_ narrow-leafed lupine/oil radish	35		no
	moderate humus content_ white mustard	37	moderate humus content_ narrow-leafed lupine/oil radish	42		no

		moderate humus content_ white mustard/common buckwheat	28	moderate humus content_ narrow-leafed lupine/oil radish	42	no
		moderate humus content_ no cover crop	22	moderate humus content_ narrow-leafed lupine/oil radish	42	yes
		low humus content_ white mustard	8	low humus content_ narrow-leafed lupine/oil radish	11	no
		low humus content_white mustard/common buckwheat	8	low humus content_ narrow-leafed lupine/oil radish	11	no
		low humus content_no cover crop	12	low humus content_ narrow-leafed lupine/oil radish	11	no
		moderate humus content_ white mustard	6	moderate humus content_ narrow-leafed lupine/oil radish	11	no
		moderate humus content_ white mustard/common buckwheat	9	moderate humus content_ narrow-leafed lupine/oil radish	11	no
		moderate humus content_ no cover crop	17	moderate humus content_ narrow-leafed lupine/oil radish	11	no
	Weed biomass	low humus content_ white mustard	0.5	low humus content_ narrow-leafed lupine/oil radish	0.9	no
		low humus content_white mustard/common buckwheat	0.1	low humus content_ narrow-leafed lupine/oil radish	0.9	no
		low humus content_no cover crop	2.3	low humus content_ narrow-leafed lupine/oil radish	0.9	no
		moderate humus content_ white mustard	1.3	moderate humus content_ narrow-leafed lupine/oil radish	0.5	no
		moderate humus content_ white mustard/common buckwheat	0.4	moderate humus content_ narrow-leafed lupine/oil radish	0.5	no

moderate humus content_ no cover crop	2.4	moderate humus content_ narrow-leafed lupine/oil radish	0.5		yes
low humus content_ white mustard	1.8	low humus content_ narrow-leafed lupine/oil radish	2		no
low humus content_white mustard/common buckwheat	0.5	low humus content_ narrow-leafed lupine/oil radish	2		no
low humus content_no cover crop	7.4	low humus content_ narrow-leafed lupine/oil radish	2		yes
moderate humus content_ white mustard	1.5	moderate humus content_ narrow-leafed lupine/oil radish	2.1		no
moderate humus content_ white mustard/common buckwheat	1.5	moderate humus content_ narrow-leafed lupine/oil radish	2.1		no
moderate humus content_ no cover crop	9.5	moderate humus content_ narrow-leafed lupine/oil radish	2.1		yes
low humus content_ white mustard	1.8	low humus content_ narrow-leafed lupine/oil radish	2		no
low humus content_white mustard/common buckwheat	1.6	low humus content_ narrow-leafed lupine/oil radish	2		no
low humus content_no cover crop	4.5	low humus content_ narrow-leafed lupine/oil radish	2		yes
moderate humus content_ white mustard	1.9	moderate humus content_ narrow-leafed lupine/oil radish	3.2		no
moderate humus content_ white mustard/common buckwheat	1.9	moderate humus content_ narrow-leafed lupine/oil radish	3.2		no
moderate humus content_ no cover crop	3.9	moderate humus content_ narrow-leafed lupine/oil radish	3.2		no

	low humus content_ white mustard	1	low humus content_ narrow-leafed lupine/oil radish	1.6		no
	low humus content_white mustard/common buckwheat	1	low humus content_ narrow-leafed lupine/oil radish	1.6		no
	low humus content_no cover crop	1.8	low humus content_ narrow-leafed lupine/oil radish	1.6		no
	moderate humus content_ white mustard	1.4	moderate humus content_ narrow-leafed lupine/oil radish	1.9		no
	moderate humus content_ white mustard/common buckwheat	1.3	moderate humus content_ narrow-leafed lupine/oil radish	1.9		no
	moderate humus content_ no cover crop	1.8	moderate humus content_ narrow-leafed lupine/oil radish	1.9		no
	low humus content_ white mustard	1.5	low humus content_ narrow-leafed lupine/oil radish	1.7		no
	low humus content_white mustard/common buckwheat	1.2	low humus content_ narrow-leafed lupine/oil radish	1.7		no
	low humus content_no cover crop	3.4	low humus content_ narrow-leafed lupine/oil radish	1.7		no
	moderate humus content_ white mustard	1	moderate humus content_ narrow-leafed lupine/oil radish	1.3		no
	moderate humus content_ white mustard/common buckwheat	1	moderate humus content_ narrow-leafed lupine/oil radish	1.3		no
	moderate humus content_ no cover crop	4.4	moderate humus content_ narrow-leafed lupine/oil radish	1.3		yes
	low humus content_ white mustard	0.6	low humus content_ narrow-leafed lupine/oil radish	0.7		no

		low humus content_white mustard/common buckwheat	0.4	low humus content_ narrow-leafed lupine/oil radish	0.7		no	
		low humus content_no cover crop	1	low humus content_ narrow-leafed lupine/oil radish	0.7		no	
		moderate humus content_ white mustard	0.8	moderate humus content_ narrow-leafed lupine/oil radish	1.2		no	
		moderate humus content_ white mustard/common buckwheat	0.6	moderate humus content_ narrow-leafed lupine/oil radish	1.2		no	
		moderate humus content_ no cover crop	1.7	moderate humus content_ narrow-leafed lupine/oil radish	1.2		no	
		low humus content_ white mustard	2.7	low humus content_ narrow-leafed lupine/oil radish	4.4		no	
		low humus content_white mustard/common buckwheat	1.4	low humus content_ narrow-leafed lupine/oil radish	4.4		yes	
		low humus content_no cover crop	4.7	low humus content_ narrow-leafed lupine/oil radish	4.4		no	
		moderate humus content_ white mustard	0.4	moderate humus content_ narrow-leafed lupine/oil radish	2.8		yes	
		moderate humus content_ white mustard/common buckwheat	0.8	moderate humus content_ narrow-leafed lupine/oil radish	2.8		yes	
		moderate humus content_ no cover crop	3.5	moderate humus content_ narrow-leafed lupine/oil radish	2.8		no	
Costanzo and Bàrberi, 2016	Weed biomass	Wheat sole crop_first node detectable	39.9	Subclover living mulch_first node detectable	31	Cover crop	no	LSD test, $p \leq 0.05$
		Wheat sole crop_Fully ripe	114.2	Subclover living mulch_Fully ripe	115.7		no	
		Wheat sole crop_first node detectable	52.7	Subclover living mulch_first node detectable	65.6		no	

	Wheat sole crop_mid-flowering	150.5	Subclover living mulch_mid-flowering	184.7		no
	Wheat sole crop_first node detectable	26.6	Subclover living mulch_first node detectable	25.6		no
	Wheat sole crop_mid-flowering	157.8	Subclover living mulch_mid-flowering	117.1		yes
	Wheat sole crop_first node detectable	59.8	Subclover living mulch_first node detectable	48.8		no
	Wheat sole crop_mid-flowering	272.8	Subclover living mulch_mid-flowering	196.9		yes

Table 5: Soil health

Reference	Soil Health / Soil Quality Parameter (unit)		Without Legumes	With Legumes	Positive	Negative	Differences Significant?	Test
Lavergne et al., 2025	**Physical indicators**	Soil water content (%)	Field Margins	Maize-soybean-small grain	-	-	Yes	Tukey's HSD post-hoc test
		Bulk density ($g\ cm^{-3}$)			12 % higher in the cropped field than in the field margins		Yes	
		Water-stable aggregates (WSA, %)				Twice as high in the field margins compared to the field	Yes	
		Available water capacity (AWC, %)			-	-	No	
		Surface hardness (kPa)			-	-	Yes	
		Subsurface hardness (kPa)					Yes	
	Biological Indicators	Permanganate-oxidizable carbon (POXC, $mg\ kg^{-1}$)				1.8 > Higher in the field Margins	Yes	
		Autoclaved-citrate-extractable protein (ACE protein, $\mu g\ mL^{-1}$)			-	-	Yes	
		Soil respiration ($mg\ CO_2\ g^{-1}$)			-	-	Yes	
		Soil organic carbon (SOC, $g\ C\ kg^{-1}$)				1.6 times higher in the field margins than within fields	Yes	

		Total nitrogen (TN, g N kg^{-1})				1.6 times higher in the field margins than within fields	Yes	
		Carbon-to-nitrogen ratio (C:N)			-	-	No	
		Particulate organic matter carbon (POM-C, % of SOC)				1.6 times higher in the field margins than within fields	Yes	
		Particulate organic matter nitrogen (POM-N, % of TN)				1.6 times higher in the field margins than within fields	Yes	
	Chemical Indicators	Residual nitrate ($N–NO_3$, kg ha^{-1})			-	-	No	
		Residual ammonium ($N–NH_4$, kg ha^{-1})					Yes	
		pH			-	-	No	
Nascimento et al.	**Biological**	Microbial Biomass Carbon (MBC) (mg kg^{-1})	Triticale-wheat	Pea-wheat	By the end of the one-year decomposition period, preceding pea had mitigated the MBC decline by ~86% relative to triticale.		Yes	Tukey's HSD test
		β-Glycosidase (nmol g^{-1} h^{-1})			[*It showed a tendency towards higher activity when wheat was preceded by pea* ($p = 0.080$)]		No	
		Protease (nmol g^{-1} h^{-1})			-	-	No	
		Phenol oxidase (nmol g^{-1} h^{-1})			Preceding wheat with triticale led to a significantly greater increase in PO levels compared to preceding it with pea ($p < 0.001$)		Yes	
	Chemical	Soil Organic Carbon (SOC) (g kg^{-1})			The SOC concentration exhibited greater stability upon incorporating wheat residues following pea instead of triticale (p =		Yes	

					0.003). By the end of the experiment, the pea–wheat sequence had mitigated the SOC decline by ~78% relative to the triticale–wheat sequence. This indicates a strong positive effect of the legume rotation on short-term SOC preservation.			
		Particulate Organic Carbon (POC) (mg kg^{-1})			[Trend of higher stability under Pea]		No	
		Mineral-Associated Organic Carbon (MAOC) (mg kg^{-1})			-	-	No	
		Soil Mineral Nitrogen (SMN) (kg N ha^{-1})			-	-	No	
		Soil C:N ratio			Preceding pea reduced the C:N ratio of wheat residue by 38% compared to preceding triticale		Yes	
	Physical	Soil water content (%)			-	-	No	
Lavergeb et al., 2025	**Earthworm community**	Total abundance (ind. m^{-2})	Field Margins	Maize-soybean-small grain	-	-	No	
		Juvenile abundance (ind. m^{-2})			-	-	No	
		Anecic abundance (ind. m^{-2})			-	-	No	
		Endogeic abundance (ind. m^{-2})			-	-	No	Tukey's HSD post-hoc test

		Epigeic abundance (ind. m^{-2})			-	-	No	
		Total biomass (g m^{-2})			The total biomass in cropped fields is about 80% higher than in field margins under the crop rotation scheme.		Yes	
		Juvenile biomass (g m^{-2})			-	-	No	
		Anecic biomass (g m^{-2})			-	-	No	
		Endogeic biomass (g m^{-2})			-	-	No	
		Epigeic biomass (g m^{-2})			-	-	No	
		Richness			-	-	No	
		Simpson's diversity index			-	-	No	
	Soil Properties	Soil temperature 10 cm (°C)			At 10 cm soil depth, the mean soil temperature in the crop rotation scheme was 17.2% higher compared to the field margins		Yes	
		Soil temperature 20 cm (°C)			At 20 cm soil depth, the mean soil temperature in the crop rotation scheme was 16.8% higher compared to the field margins		Yes	
		Bulk density (g cm^{-3})			Bulk density was 8.87% higher in the fields compared to the field margins	-	Yes	
		Soil water content (%)			-	-	No	

Carrascosa-Robles et al.,2024	**Chemical and physico-chemical properties**	pH	Purslane (*Portulaca oleracea* L.) monocrop grown in the summer (Control)	CR1 (Crop rotation 1) Purslane – Pea (*Pisum sativum* L.) crop rotation, CR2 (Crop rotation 2) mixed system of Purslane – Pea – Cowpea intercropping and crop rotation	-	-	No	post hoc Tukey's HSD test
		Electrical conductivity (µS cm^{-1})			-	-	No	
		Total organic carbon (TOC) (g Kg^{-1})			-	-	No	
		Total nitrogen (TN) (g Kg^{-1})			-	-	No	
		C/N ratio			-	-	No	
		Total phosphorus (TP) (g Kg^{-1})			-	-	No	
		Available phosphorus (AP) (g Kg^{-1})			-	-	No	
	Biochemical and biological indicators of soil quality	β-Glucosidase (GLC) (µmol PNF * g-1 h-1)			Increased by 24.6% under rotation (CR 1) and 35.2% under intercropping + rotation (CR2) compared to the control.		Yes	
		Alkaline phosphomonoesterase (PHO) (µmol PNF * g-1 h-1)			Rose by 39.7% in CR1 and 35.0% in CR2, enhancing phosphorus mineralization.		Yes	
		Urease (URE) (µmol N–NH$_4$ * g-1 h-1)			Increased by 28.3% in CR1 and 31.9% in CR2 compared to the control.		Yes	
		Dehydrogenase (DHA) (µmol TPF * g-1 h-1)			Was 21.9% higher in CR1 and 29.1% higher in CR2, compared to the control.		Yes	
	Microbial community	Shannon or Chao1			-	-	No	
Stagnari et al.,2018	**Chemical and physical measurements**	SOC (%)	Wheat monocropping	Wheat-Faba bean			No	Fisher's LSD test
		N (%)					No	

		FCO_2 (μmol m^{-2} s^{-1})			In these measurements the effects of Year x Factor 1 (Soil Tillage) x Factor 2 (Crop sequence) were not statistical different.		No	
		T_{soil} (°C)					No	
	Visual Soil Assessment (VSA) indicators	Soil structure and consistence			In these measurements the effects of Year x Factor 1 (Soil Tillage) x Factor 2 (Crop sequence) were not statistical different.		No	
		Soil Color					No	
		Soil mottles (%)					No	
		Earthworm counts					No	
	community-Level Physiological Profiles (CLPP)	Average well-color development (AWCD)			Although there were no statistically significant differences in the Year × Factor 1 × Factor 2 interaction, there were significant differences in the factor related to crop sequence; specifically, the AWCD was higher in the Wheat–Faba bean crop rotation by 29% compared to Wheat monoculture.		No	
		Shannon–Weaver index (*H*)			-	-	No	
		Richness (*R*)			-	-	No	
Agomoh et al., 2020	**Soil Health Indicators**	soil respiration (mg C kg^{-1} h^{-1})	Winter wheat	soybean (*Glycine max* L.)–winter wheat (S–WW) (**CR1**), corn (*Zea mays* L.)–soybean–winter wheat (C–S–WW) (**CR2**), and winter wheat–soybean–soybean (WW–S–S) (**CR3**)	-	-	No	Turkey multiple comparison test
		potentially mineralizable nitrogen (PMN) (mg kg^{-1} soil)			-	-	No	
		permanganate oxidizable carbon (POXC) (mg kg^{-1} soil)			-	-	No	
		inorganic nitrogen (IN) (mg kg^{-1} soil)			-	-	No	
		water extractable organic carbon (WEOC) (mg kg^{-1} soil)			-	-	No	
		water extractable organic nitrogen (WEON) (mg kg^{-1} soil)			-	-	No	
		total carbon (TC) (g kg^{-1} soil)				Monoculture winter wheat had the highest total carbon (27 g kg^{-1} soil). When red clover was	Yes	

						present, TC in the 2-year and 3-year rotations dropped to about 22–23 g kg^{-1}, showing a significant reduction compared with the monoculture. Without red clover, those lower TC values were significant only for the WW–S and WW–S–S rotations.		
		total nitrogen (TN) (g kg^{-1} soil)				total N was significantly greater for WW (2.7 g kg^{-1} soil) than WW-S (2.2 g kg^{-1} soil), C-S-WW (2.2 g kg^{-1} soil), and C-S-WW (2.2 g kg^{-1} soil) with red clover, whereas these differences were not significant without red clover.	Yes	
		soil organic carbon of the particulate organic matter (POMC) (g kg^{-1} soil)			-	-	No	
		soil pH (pH)			-	-	No	
		available soil test phosphorus (STP) (mg kg^{-1} soil)					No	
		extractable potassium (K)			-	-	No	
		calcium (Ca)			-	-	No	
		magnesium (Mg)			-	-	No	
		sulfur (S)			-	-	No	
		zinc (Zn)			-	-	No	
		manganese (Mn)			-	-	No	

		boron (B)			-	-	No	
		copper (Cu)			-	-	No	
Landi et al., (2018)	**Soil physical and chemical properties**	available P (mg kg^{-1})	integrated rice farming system (**INT**), conventional rice farming system (**CONV**)	**ORG**: rice (4-years) and green manure with soybean	-	-	No	Student-Newman-Keuls test
		Total Org C (g kg^{-1})			-	-	No	
		Tot N (g kg^{-1})			-	-	No	
		C/N			-	-	No	
	Soil nematode community structure changes (number of nematodes 100 ml^{-1} soil)	Rabditidae			*Rabditidae* abundance in the ORG was about 655% higher than in CONV and 430% higher than in INT.		Yes	
		Panagroilamidae			-	-	No	
		Cephalobidae			-	-	No	
		Aphelenchidae			*Aphelenchidae* abundance in the ORG was approximately 658% higher than in the INT		Yes	
		Diphtherophoridae			-	-	No	
		Dorylaimidae			-	-	No	
		Mononchidae			-	-	No	
		Tylenchidae			In 2014, *Tylenchidae* abundance in ORG was about +1,570% vs CONV and +840% vs INT.		Yes	
		Pratylenchidae			-	-	No	
		Anguinidae			-	-	No	
		Longidoridae			-	-	No	
		Abundance			-	-	No	
		Taxa richness			Taxa richness in ORG was 26% higher than CONV and 61% higher than INT.		Yes	
	soil nematode indices	Maturity index (MI)				The ORG had a markedly lower MI than the CONV (–40	Yes	

						%) and slightly lower than the INT (–33 %), indicating a community dominated by opportunistic nematodes.		
		plant parasitic index (PLI)			ORG had a 33 % lower PPI than the CONV (a positive effect indicating fewer plant-parasitic nematodes and improved soil health) but a 61 % higher PPI than the INT. showing only a partial improvement in plant-related soil quality.		Yes	
		Basal index (BI)			BI was higher with the introduction of the soybean, suggesting that soybean cropping benefitted the development of the nematode community structure		Yes	
		enrichment index (EI)			-	-	No	
		structure index (SI)				SI in the organic system was 12 % lower than in the CONV and 9 % lower than in the INT system, indicating a more disturbed soil environment.	Yes	
		channel index (CI)			The organic system showed a significantly higher CI (+159 % vs CONV; +157 % vs INT), aN effect associated with enhanced fungal-		Yes	

					driven decomposition and nutrient cycling.			
	Diversity-weighted abundance (θ)	Bacterivores fungivores			all functional classes were higher in the organic (soybean–rice) system, with bacterivores and fungivores significantly greater (+365 % vs CONV; +257 % vs INT). This indicates enhanced microbial activity and nutrient mineralisation due to the legume phase		Yes	
		Predators			-	-	No	
		Plant parasitic nematodes				Higher plant-parasitic nematodes in the organic system showed insufficient regulation by predation, highlighting short-term negative effects	Yes	

Table 6: Associated biodiversity

Paper	Pesticides	Biodiversity Parameter	Control		Treatment		Differences	
			Without legume		With legume			
Reference	Chemical crop protection	Arable flora indicator	Rotation	Biodiversity outcome	Rotation	Biodiversity outcome	Differences significant?	Significance test

Woźniak (2020) [1]	fungicides, herbicides	species richness	winter wheat-winter barley	8	pea-winter barley	10	no	Tukey's HSD test
				11		16	yes	
				4		7	yes	
				13		10	no	
				22		16	yes	
				15		8	yes	
Wanic et al. (2018) [1]	herbicides	species richness	winter oilseed rape-common wheat	11	pea-common wheat	12	no	Tukey's HSD test
		Simpsons dominance index		0.226		0.256	no	
		Shannon Index		1.823		1.77	no	
		Pielou's evennes index		0.76		0.851	yes	
		species richness		11		10	no	
		Simpsons dominance index		0.268		0.196	no	
		Shannon Index		1.553		1.479	no	
		Pielou's evennes index		0.648		0.617	no	
		species richness	winter wheat-common wheat	12	pea-common wheat	12	no	Tukey's HSD test
		Simpsons dominance index		0.276		0.256	no	
		Shannon Index		1.474		1.77	yes	
		Pielou's evennes index		0.575		0.851	yes	
		species richness		14		10	no	
		Simpsons dominance index		0.193		0.196	no	
		Shannon Index		1.617		1.479	yes	
		Pielou's evennes index		0.63		0.617	no	
		species richness	winter oilseed rape-spelt	15	pea-spelt	18	no	Tukey's HSD test
		Simpsons dominance index		0.241		0.277	no	
		Shannon Index		1.891		1.867	no	
		Pielou's evennes index		0.698		0.646	no	
		species richness		12		12	no	
		Simpsons dominance index		0.282		0.273	no	
		Shannon Index		1.613		1.637	no	
		Pielou's evennes index		0.649		0.659	no	
		species richness	spelt-spelt	17	pea-spelt	18	no	Tukey's HSD test
		Simpsons dominance index		0.273		0.277	no	
		Shannon Index		1.704		1.867	yes	
		Pielou's evennes index		0.602		0.646	no	
		species richness		10		12	no	
		Simpsons dominance index		0.338		0.273	no	
		Shannon Index		1.277		1.637	yes	
		Pielou's evennes index		0.555		0.659	yes	
	no herbicides	species richness	winter oats-maize	13	common vetch-maize	7	yes	

Simić et al. (2020) [1]			fodder kale-maize	8		7	no	least significant difference test
			organic mulch-maize	8		7	no	
			without cover crop-maize	10		7	yes	
Woźniak & Soroka (2018) [1]	fungicide, herbicide	species richness	spring barley- spring wheat-durum wheat	13	pea -spring wheat-durum wheat	19	NA	none
				21		24	NA	
				11		16	NA	
Gawęda et al. (2018) [1]	fungicide, herbicide, insecticide	species richness	rapeseed-winter wheat	18	soybean-winter wheat	14	NA	none
				20		16	NA	
Simić et al. (2016) [2]	herbicide	species richness	maize-winter wheat	4	maize-soybean-winter wheat	7	NA	none
	herbicide			7		8	NA	
	no herbicide			14		16	NA	
	herbicide			2		6	NA	
	herbicide			9		9	NA	
	no herbicide			17		15	NA	
Dorado et al. (1999) [1,3]	glyphosate	species richness	barley-sunflower	22	barley-vetch	26	yes	least significant difference test
			barley-barley	21		26	yes	

Comments:

[1] = based on the rotational design of the comparators, these studies allow to deduce the explicit pre-crop effect of legumes

[2] = based on the rotational design of the comparators, these studies only allow to deduce the general effect of legume integration into the rotation, but no pre-crop effect

3 = soil seedbank analysis was conducted

Table 7: Climate resilience

Paper	Climate Resilience	Cropping Systerm	Effect		Legume use	Differences	
Reference	Parameter	Without legume Cropping systems	Legume effect Positive	Negative		Significant differences?	Significance test
Fiorini et al., 2025	GHG emission	Soybean-rye+hairy vetch - sunflower- rye+hairy vetch - maize	Optimize nutrient availability while minimizing greenhouse gas emissions	-	Cover crop	yes	Tukey's test, p ≤ 0.05.
		Soybean- ray+tillage radish - sunflower- ray+tillage radish - maize	No legumes	-		yes	
		Soybean-hairy vetch+tillage radish -sunflower-hairy vetch+tillage radish -maize	-	-		no	

		Soybean- rye+hairy vetch+tillage radish - sunflower- rye+hairy vetch+tillage radish -maize	--	--		no	
		Soybean-rye+ hairy vetch+common vetch +radish+black oat +common oat+crimson clover+squarrose clover-sunflower- rye+ hairy vetch+common vetch +radish+black oat +common oat+crimson clover+squarrose clover -maize	-	-		no	
Skovgaard Andersen et al., 2025	N_2O emission	Spring barley-Fallow	No legumes	-	Cover crop	-	Tukey's test p ≤0.05
		Spring barley-hairy vetch	-	Slight increase in N_2O emission		no	
		Spring barley-crimson clover	-	Slight increase in N_2O emission l		no	
		Spring barley-oilseed radish	No legumes	-			
		Spring barley-winter rye	No legumes	-			
Valujeva et al., 2023	GHG emission	Sunflower-spring pea-mustard cover crop–durum wheat-mustard cover crop	-	-	Main crop	yes	Non-parametric, p ≤ 0.05
		winter rapeseed-spring barley-field beans-winter wheat-spring rapeseed - reduced and conventional tillage	The lowest CO_2 emission	-		no	
		field beans-winter wheat-winter rapeseed-spring barley-field beans - reduced and conventional tillage	-	Higher CO_2 emission		no	
		Spring barley-field beans-winter wheat-winter rapeseed-spring barley - reduced and conventional tillage	The lowest average N2O emission; lower CH4 assimilation	-		yes	
Reckling et al., 2022	Yield stability and	(SE) Oilseed crop-Winter wheat-Spring oat-Spring barley + undersown ley-Red	Higher environmental adaptability	-	Grass-clover	yes	Coefficient of variation and Tinlay-

	environmental adaptability	clover/grass ley -Red clover/grass ley			ley/main crop		Wilkinson regression coefficient
		(SE) Oilseed crop -Winter wheat-Spring oat-Spring barley + undersown ley-Grass ley-Grass ley	No legumes	--		--	
		(SE) Oilseed crop-Winter wheat-Spring oat-Spring barley-Spring wheat-Black fallow	No legumes	-		-	
		(UK) Clover/grass ley-Clover/grass ley-Clover/grass ley-Oat-Swede-Undersown oat	Higher environmental adaptability			yes	
		(UK) Clover/grass ley-Clover/grass ley-Clover/grass ley-Clover/grass ley-Oat-Undersown oat	Higher environmental adaptability	--		yes	
		(FR) Durum wheat-Sorghum-Sunflower	No legumes	-		-	
		(FR) Durum wheat-Sunflower-Winter pea/Winter faba bean	Increased yields of durum wheat in lower-yielding years	Reduced yields of cereals in high yielding environments; lower environmental adaptability		yes	
Plaza-Bonilla et al.2018	GHG emission	Sorghum-sunflower–durum wheat	No legumes	-	Main crop and cover crop	yes	ANOVA.
		Sunflower-winter pea–durum wheat	Reduction in external and on-site emissions related to N fertilizers	Introduction into low input crop rotations led to SOC losses		yes	
		Sunflower-spring pea–durum wheat	Reduction in external and on-site emissions related to N fertilizers	Introduction into low input crop rotations led to SOC losses		yes	

		Sorghum-vetch cover crop-sunflower-rye+vetch cover crop—durum wheat	Annual soil C sequestration was higher	-		no	
		Sunflower-mustard cover crop-winter pea-mustard cover crop–durum wheat	-	-		no	
		Sunflower-spring pea-mustard cover crop–durum wheat-mustard cover crop	-	-		yes	
Vaziritabar et al., 2025	Yield in different climatic conditions	Maize-winter wheat-winter ray-spring barley	No legumes		Pre-crop	-	ANOVA
		Summer oat-winter wheat-winter ray-spring barley	No legumes			-	
		Field bean- winter wheat-winter ray-spring barley r	No effect	No effect		no	
		Crimson clover- winter wheat-winter ray-spring barley	Higher winter wheat and spring barley yields in dry years	No effect		yes	
		Hairy vetch- winter wheat-winter ray-spring barley	Higher winter wheat and spring barley yields in dry years	No effect		yes	

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