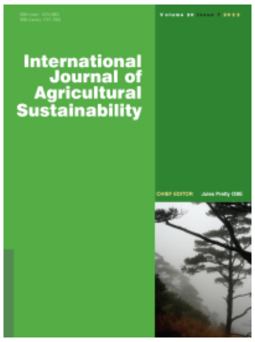

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Assessing the effectiveness of cover crops on ecosystem services: a review of the benefits, challenges, and trade-offs

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ABSTRACT
While it is crucial to consider the ecological trade-offs of cover crop effects to promote sustainable agricultural production, there has been limited analysis of the combined effects of cover crops on various ecosystem services. For this purpose, we synthesized 43 meta-analysis and review studies comparing cover crops to monocropping in order to investigate benefits, challenges, and trade-offs among ecosystem services under cover crop implementation. We summarized the current state of knowledge of cover crops effectiveness across 11 ecosystem services in three categories (regulating, provisioning and supporting). We identified the factors influencing the relative benefits and risks of integrating cover crops into crop production systems. These factors include farm practices, planting and termination season, species of cover and main crop, climatic zone and soil properties, cover crop biomass, and residue management. Our findings highlight that compared to monocropping, in general, cover cropping enhances soil biodiversity and nutrient cycling, prevents runoff and Nitrogen leaching, improves soil physical properties and carbon sequestration over the long term, and suppresses pests and weeds. However, trade-offs comprise inconsistencies in primary crop yields and soil water provision. Overall, our result highlighted that a multifunctional cover crop implementation provides substantially more regulating and supporting than other ecosystem services.

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Green manure; agricultural practices; sustainable agriculture; diversified farming; living mulch; conservation agriculture

1. Introduction

Agricultural expansion in response to increasing demand for food has led to significant habitat degradation and loss of biodiversity (Darvishi et al., 2021; Darvishi et al., 2022; Raven & Wagner, 2021). In addition, nutrient cycles have become imbalanced (Sileshi et al., 2017), and there has been an increase in greenhouse gas emissions (Tubiello et al., 2013) and the release of nitrogen and phosphorus into the environment (Bressler et al., 2021; Tilman, 1999). These environmental issues highlight the need for new approaches to promote sustainable agricultural practices (Darvishi et al., 2024; Yousefi et al., 2020). One of the proposed solutions is the implementation of alternative crop management strategies, such as cover crops. cover crops have been promoted to diversify farming systems (Kremen et al., 2012), support ecological interactions and processes, and sustainable crop production while maintaining other ecosystem processes (Bressler et al., 2021; Groff, 2015; Jacometti et al., 2007; Mario Zuffo et al., 2022). Cover crops have the potential to improve soil health, increase biodiversity, sustain crop production and mitigate the negative impacts of agricultural practices on

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the environment (Blanco-Canqui et al., 2022; Bressler et al., 2021; Groff, 2015; Ma et al., 2021; Muhammad et al., 2019).

Cover crops are plant species introduced into crop rotations to provide beneficial services to the agro-ecosystem (Ma et al., 2021). USDA defines cover crops as '*Crops, including grasses, legumes, and forbs, for seasonal cover and other conservation purposes. The cover crop may be terminated by natural causes such as frost or intentionally terminated through the chemical application, crimping, rolling, tillage, or cutting*'. This definition separates cover cropping as nonharvested crops grown (Scavo et al., 2022) from other crop diversification schemes such as intercropping measures (Wallander et al., 2021). Cover crops can be grouped into categories based on their role on the farm. They can be annuals that act as living mulches, grown either alternately or simultaneously with the crop (Labrada et al., 1994). Cover crops might also be ploughed directly into the soil, allowing their biomass to serve as green manure. Alternatively, cover crops might be harvested and used as fodder for livestock (Rosa-Schleich et al., 2019). Cover crops can also be grouped based on vegetation types, such as grasses, legumes, or non-leguminous dicots. Cover cropping has a long history, extending back to over 2000 years in Europe (Shackelford et al., 2019). The approach was largely lost as a management strategy in the post-war era of modern industrial agriculture, although it has recently attracted renewed interest due to its perceived environmental benefits (Muhammad et al., 2021a; Obour et al., 2021; Sajjad et al., 2019). In the last decade, there has been a remarkable growth of cover cropping practice in every crop-producing region in the world. According to the United States Department of Agriculture (USDA), the area of cover cropping increased from 4,160,489.3 ha in 2012 to 6,228,384.7 ha in 2017 (USDA NASS, 2017 Census of Agriculture).

The use of cover crops is gaining popularity as a sustainable agricultural practice that can provide multiple ecosystem services, such as soil conservation, nutrient cycling, and pest management. However, the impact of cover crops on these services can vary depending on several factors, such as crop species, management practices, and environmental conditions. To date, several studies have investigated the impact of cover crops on ecosystem services, using both field experimental studies and secondary research such as meta-analyses and reviews (Basche & DeLonge, 2017; Blanco-Canqui et al., 2015; Crystal-Ornelas et al., 2021; Morales et al., 2021). The majority of these studies have primarily focused on the influence of cover crops on one aspect of ecosystem services driven by cover crops, such as yield response (Marcillo & Miguez, 2017), soil microbial biomass (Morales et al., 2021) or weed suppression (Osipitan et al., 2019). However, a critical gap persists, as these studies often overlook the potential trade-offs and synergies that may occur when multiple services interact under cover cropping systems. While it is crucial to consider the ecological trade-offs of cover crop effects to promote sustainable agricultural production, there has been limited analysis of the combined effects of cover crops on various ecosystem services. As a result, there is a pressing need for a systematic review that comprehensively elucidates the intricate dynamics and interplay among these ecosystem services within the context of cover cropping and how they affect soil and biodiversity, crop development and production (Koudahe et al., 2022).

By considering the trade-offs and synergies between different ecosystem services, we can lay the foundation for the development of holistic and sustainable agricultural management practices. This can help farmers and policy-makers make informed decisions about the adoption of cover crops and contribute to the development of more resilient and productive agro-ecosystems.

Our study is positioned within this research gap and seeks to systematically synthesize the extensive body of literature related to cover crop practices. Specifically, we aim to investigate the intricate web of trade-offs between ecosystem services to shed light on the complexities of sustainable agricultural systems.

2. Method

In this study, we conducted a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009) which describes the minimum reporting standards of a systematic reviews (O'Dea et al., 2021). To select the key ecosystem services for our study, we first conducted a comprehensive review of the literature to identify the most commonly reported ecosystem services associated with cover crop practices. We then applied a systematic process to identify the most relevant and well-documented ecosystem services, as recommended in the literature on ecosystem services assessment. Our final selection of 11 key ecosystem services was based on several criteria, including their relevance to cover crop practices, their importance in supporting ecosystem functioning, and the availability of sufficient data in the literature. The selected ecosystem services included regulating (runoff prevention, weed suppression, carbon sequestration, climate regulation, and pest biocontrol), provisioning (primary production, habitat provision and water provision), and supporting (soil nutrient cycle, N leaching prevention, soil physical structure) services. By focusing on these key ecosystem services, we were able to conduct a comprehensive assessment of the effectiveness of cover crop practices and identify trade-offs between different ecosystem services, which have important implications for sustainable agriculture and environmental management.

2.1. Search for articles

For the next step, we prepared a search strategy for data acquisition and we conducted a literature search on the Web of Science Core Collection (WoSCC) and Scopus in March 2022. Web of Science and Scopus are updated for their extensive coverage of academic journals and scientific literature across various disciplines (Zhu & Liu, 2020). This breadth allows us to encompass a wide range of research that might not be as available in other databases. The search term for the database was as follows:

'living mulch' OR 'cover crop*' OR 'green manure' OR 'catch crop' AND 'meta analysis' OR 'review'. During an appraisal phase, we evaluated and screened the selected literature to identify relevant papers for the review process based on pre-defined inclusion and exclusion criteria. The search was not restricted based on specific geographical areas.

2.2. Inclusion and exclusion criteria

To ensure a systematic and rigorous review process, we developed specific criteria for the selection of literature. These criteria were consistently applied during the appraisal stages to identify relevant publications for the review.

Inclusion Criteria: Papers were included if they met the following criteria: 1) articles comparing cover crop treatments with control groups (no cover crop) in the agricultural domain were considered. This comparison is essential to evaluate the impact of cover crops on the key variables. 2) papers were considered if they assess the impact of cover crops on the above mentioned ecosystem services.

Exclusion Criteria: Papers were excluded based on the following criteria: 1) to ensure consistent data interpretation and analysis, the search was limited to articles published in the English language. 2) Searches in databases were not limited to year, however, access restricted to specific years by institutional subscriptions.3) Non-peer-reviewed sources such as grey literature, conference abstracts, or theses were excluded to prioritize the quality and reliability of the data.

2.3. Screening process

To minimize the likelihood of bias, a blinded dual-reviewer, with a two-step selection procedure based on pre-established inclusion criteria was implemented. The titles and abstracts of all studies through database searches were independently checked for relevance by two qualified reviewers during the primary screening. Research technicians and qualified research assistants participated as reviewers; were blind to each other's selection for inclusion. Each study was classified as 'include', 'exclude' or 'maybe'. Studies designated as 'maybe' decisions were re-examined through secondary screening. The full texts of articles that had been previously classified as 'exclude' or 'maybe' were independently reviewed by two trained reviewers following pre-established inclusion criteria for the secondary screening. Inconsistencies were resolved by discussion with a third reviewer (main author), who was blinded to which reviewer did not vote 'exclude' to prevent bias. If the full texts of possibly included studies were unavailable, we contacted the stated associated author, twice with a one-week interval between each attempt. If this method was ineffective, the article was excluded from the review.

The search yielded 1360 publications. A total of 148 publications were retained based on the title and the abstract screening. The full texts of these articles were read in detail and a total of 43 articles were included in the synthesis. Paper screening and selection procedure are presented in a PRISMA diagram (Figure 1).

2.4. Data extraction

The selected articles were thoroughly reviewed for the study's objectives, including the effect of cover crops on the ecosystem services. The articles were critically analyzed, and the relevant information was extracted and recorded. The recorded information included the title of the study, authors, year of

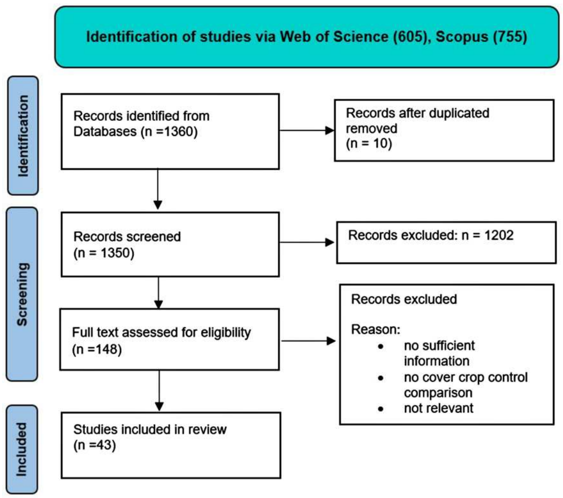

Figure 1. The procedure of paper screening and selection in a PRISMA diagram

publication, the type of cover crop studied and the impact on the ecosystem services.

We used a qualitative and descriptive synthesis approach to summarize and present the findings of the selected articles. This method was chosen to provide an overview of the current state of knowledge on the effect of cover crops on ecosystem services, given the heterogeneous nature of the selected studies.

In our systematic review, we aimed to identify the most commonly reported parameters of each ecosystem service related to cover crop performance. To achieve this, we conducted a thorough analysis of the included studies and extracted relevant data. The extracted data was then compiled and presented in Table 1, which provides a comprehensive overview of the various ecosystem services that were evaluated in the studies.

2.5. Ranking approach

We applied a ranking method based on Rosa-Schleich et al. (2019) to assess the overall performance of cover crops across the identified ecosystem services. For each ecosystem service, we coded the positive output as 1 and the negative output as −1. If both positive and negative effects were reported, or no effects were found, we applied a coding of 0. We then summed the numbers for each outcome, divided them by the number of studies or records found for each outcome, and ranked cover crop performance accordingly. This ranking approach allowed us to compare the performance of cover crops across different ecosystem services and to identify the most beneficial services that cover crops can provide. The results of this ranking method were presented in Table S1, providing a comprehensive overview of the performance of cover crops across the various ecosystem services evaluated in the included studies.

Table 1. Ecosystem service indicators and parameters.

Ecosystem service categories	Ecosystem service	Metric
Regulating services	Runoff prevention	Runoff Sediment production Infiltration rates
	Carbon sequestration	Organic carbon content Soil organic matter
	Climate regulation	N2O emission
	Pest biocontrol	Biocontrol services Abundance of omnivore-predators
	Weed suppression	Weed biomass Weed abundance Weed density
Supporting services	Soil physical structure	Precipitation storage efficiency Total porosity Soil compaction Macropores
	Nitrogen leaching prevention	Nitrogen leaching rate
	Soil nutrient cycle	Soil organic matter Nutrient balance
Provisioning services	Habitat provision	Total bacteria
	(soil biodiversity)	Total fungi Soil microbial abundance and activity and biomass
	Water provision	Water-use efficiency Soil available water Water regulation Soil water content
	Primary production	Crop yield

3. Result and discussion

We identified the factors that influence the relative benefits and risks of integrating cover crops into crop production systems. These included farm practices (Bowles et al., 2017; Ruis et al., 2019; Toler et al., 2019), cover crop biomass (Brennan & Smith, 2005), residue management (Karuku et al., 2014), planting and termination season (Ruis et al., 2019; Schutter et al., 2001), species of cover and main crop (Shekoofa et al., 2020), and climatic zone and soil properties (Kim et al., 2020) (Figure 2).

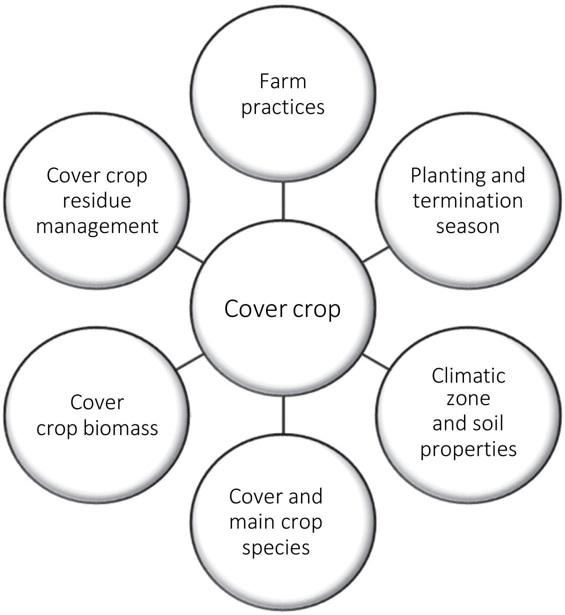

Figure 2. Factors influencing the effectiveness of cover cropping (source: literature review)

Effectiveness that depends on farm practices, such as tillage systems, nitrogen fertilizer applications, and residue management, affect the relative benefits of cover crops since they alter the soil physical, chemical, and biological properties (Peixoto et al., 2020). Farmers can therefore optimize benefits by combining cover crops with other farm practices to reduce soil disturbance. For example, cover cropping combined with no-till, enhances arbuscular mycorrhizal fungi colonization of summer annual main crop roots by 30% (Bowles et al., 2017). Toler et al. (2019) reported that the incorporation of cover crops by tillage resulted in a 42% yield increase in cotton seeds.

Brennan and Smith (2005) suggested that the amount of biomass generated by a cover crop is the most important predictor of weed control, while diversity does not play a role. Cover crop biomass was larger in humid than semi- arid regions, but could be substantially increased in the latter using irrigation at the establishment (Ruis et al., 2019). Extending the cover cropping growing season through early planting or late termination can also increase cover crop biomass (Ruis et al., 2019).

If cover crops terminate and the biomass returns to the soil, the residues from both aerial and root biomass can be involved in the process of soil carbon supply. On the other hand, cover crop residues left on the soil surface provide topsoil protection, which reduces water evaporation and enhances soil water content due to the mulching effect and enhanced infiltration (Karuku et al., 2014).

The timing and duration of cover crops influence outcomes. Cover crops can be grown in the autumn through the winter or in the early spring through to the summer, providing seasonal protection from soil erosion and weed suppression (Reed-Jones et al., 2016). Early termination of spring cover crops can occur because of environmental circumstances such as temperature and precipitation, which reduces the ecosystem services benefits (Inveninato Carmona et al., 2021).

Selection of the appropriate cover crop species is crucial for maximizing benefits while reducing risks, especially in managing potential allelopathic impacts (Shekoofa et al., 2020). Cover crop type affects nutrient concentration, runoff (Miller et al., 1994), trade-offs between N retention and N supply to the main crops (Kaye et al., 2019), mycorrhizae-mediated nutrient uptake, pest management (Murrell et al., 2020), weed emergence (Cornelius & Bradley, 2017), and grain yield productivity (Campiglia et al., 2014; Wagger, 1989). The effectiveness of cover crop types can be explained by the characteristics of crop species and performance, such as the potential of biomass production and C:N ratio (Cook et al., 2010), biomass decomposition rate (Bavougian et al., 2019), transpiration rate (Salmerón et al., 2011), root system architecture (Burr-Hersey et al., 2017), synchronization with the main crop in terms of nitrogen uptake (Salmerón et al., 2011), etc.

3.1. Cover crop effects on regulating ecosystem services

3.1.1. Runoff prevention services

Our analysis of the literature revealed seven records that demonstrated a combined value of 1 for the Runoff prevention ecosystem service provided by cover crops. Runoff declined significantly under cover crops, due to enhanced soil infiltration (especially in long-term cover crop implementation) (Basche & DeLonge, 2019). This reduces runoff volume and sediment loss (Blanco-Canqui, 2018), lowers soil bulk density and increases soil macropores under cover crops facilitating water infiltration (Basche & DeLonge, 2019; Blanco-Canqui et al., 2015; Haruna et al., 2020). Cover croping has a particularly strong effect on improving the infiltration rate in coarse soil textures (Basche & DeLonge, 2019). Blanco-Canqui (2018) reported thatas a result of better infiltration, cover crops increased the time to the start of runoff by 10 to 40 min, reduced runoff volume by 10 to 98% and sediment loss by 22 to 100%. However, enhanced water infiltration may increase the leaching of nitrogen and other nutrients from the root zone (Lu et al., 2000).

3.1.2. Carbon sequestration

We found 12 records with a combined value of 0.91 that show the use of cover crops increased Soil Organic Carbon (SOC) content compared to fallow controls (Jian et al., 2020; Ma et al., 2021), although this was not consistent across all studies. Crystal-Ornelas et al. (2021) found no overall effect of cover cropping on SOC concentrations. However, they recorded a temporal trend that cover cropping significantly increased SOC concentrations after five years of its adoption. Soil carbon change was also affected by annual temperature, the number of years after cover cropping cultivation, geographical latitude, initial SOC concentrations in the soil, microbial community condition, biomass of cover crops production, and soil texture (Alvarez et al., 2017; Jian et al., 2020; McClelland et al., 2021; Norris & Congreves, 2018; Six et al., 2006). Annual cover crop biomass production positively affected total soil Carbonstocks (Jian et al., 2020; McClelland et al., 2021), while cover crop C:N ratio was negatively correlated with SOC changes (Jian et al., 2020). Regarding soil texture, SOC was higher in coarser than fine-textured soils under cover crops (Alvarez et al., 2017). Comparing winter and summer growing windows to cover crops planted as continuous cover or autumn sown and terminated led to a 20–30% increase in overall soil Carbon (McClelland et al., 2021). Cover crop mixtures resulted in greater SOC increases than mono-species cover crops (Ma et al., 2021), though there was no significant difference between legume and non- legume treatments. Utilizing legumes did, however, increase SOC more than a grass cover treatment (Jian et al., 2020).

3.1.3. Climate regulation

The potential of cover crops to reduce N2O emissions through the nitrate assimilation in biological processes largely depends on whether the cover crop is established before the winter, residue incorporated into the soil and soil texture, cover crop type, N fertilizer application rate, and climate (Abdalla et al., 2019; Muhammad et al., 2019). Therefore, the outcomes across different studies are mixed, subject to the local contexts. Cover crops increase direct N2O emissions when residues are incorporated into the soil as compared to when residue is placed on the soil surface or removed from the soil (Abalos et al., 2022; Abdalla et al., 2019; Webb et al., 2000). The type of cover crop is essential. Abdalla et al. (2019) reported that legume cover crops significantly increased direct N_2O emissions, but non-legume and legume mixture (legume–non-legume) had no effects on N_2O emissions compared to no cover crops treatments. Ekwunife et al. (2021) showed that under the cover crop intervention, N2O emissions increased in humid climates but decreased in drier climates. Higher soil moisture in winter and during the spring thaw facilitates denitrification as the main process contributing to freeze–thaw N2O emissions (Negassa et al., 2015). One study found no significant effect of cover crops on direct N2O emissions, though there did appear to be a tendency towards reduced emissions (Ekwunife et al., 2021). However, Muhammad et al. (2019) reported that cover crop biomass explained 55% percent of the variation in decreased N2O emissions. Reduced N2O emissions with increased cover crop biomass is due to an increase in N uptake that decreases the accumulation of soil mineral N available for N2O emission.

3.1.4. Weed suppression

We examined seven records on the effect of cover cropping on weed suppression that estimated a value of 0.85. Effectiveness depends on management decisions such as tillage system, cover crop species, growing season and termination date (fall or spring), delay in main crop sowing date after cover crop termination, and involving other weed control inputs in cover cropping (Mennan et al., 2020; Osipitan et al., 2019). Regarding conservation tillage, cover crops provide enhanced weed suppression in reduced tillage systems than no-tillage (Osipitan et al., 2019). By creating a physical barrier and releasing allelopathic compounds into the soil, cover crop residues can suppress weeds during the early growth stages of the main crop (Fikre & Mulatu, 2014; Gerhards & Schappert, 2020; Kanatas, 2020). Nichols et al. (2020) reported that to decrease weed biomass by 75%, at least 5 Mg ha $^{-1}$ of cover crops biomass is required. Producing this amount of cover crop biomass, however, needs early planting and late spring termination. Osipitan et al. (2019) showed that grass cover crops such as cereal rye, oat, and triticale, or ryegrass, offer more weed control than dicot cover crops. Compared to legume-based mixtures, non- legume mixtures enhanced weed suppression in the farm system (Lavergne et al., 2021). Regarding conservation tillage, Cover crops provide enhanced weed suppression in reduced tillage systems than no-tillage (Osipitan et al., 2019).

3.1.5. Pest biocontrol

Cover crops provide habitat and resources to arthropods before and after termination, though different species and mixtures vary in their ability to do so (Inveninato Carmona et al., 2021). The interaction between cover crops and arthropods is poorly known, largely due to several potentially interacting issues including species, termination method, biomass, and environmental circumstances (Inveninato Carmona et al., 2021). We found two studies that gave a total value of 1 for such ecosystem service. Cover crops increase the activity and/or density of several useful natural pest-control arthropod species (Davis et al., 2009; Dunbar et al., 2017), which decreases pest populations (Couëdel et al., 2019; Koch et al., 2015). Inveninato Carmona et al. (2021) reported that the abundance of natural enemies such as Carabidae and spiders increased with the addition of cover crops into corn and soybean fields in the United States.

3.1.6. The trade-offs among regulating ecosystem services

In evaluating the trade-offs among the five key regulating ecosystem services provided by cover crops, a clear pattern emerged (Figure 3). Runoff prevention

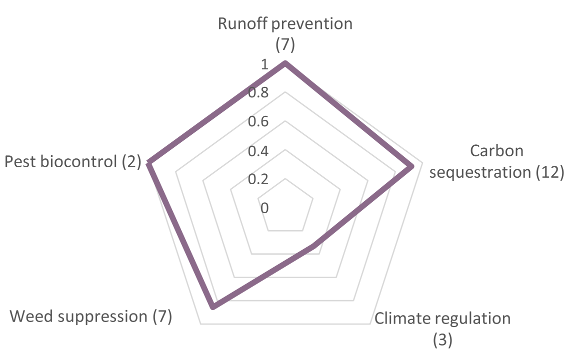

Figure 3. The trade-off between regulating services under cover crops. The number in the parentheses reflects the number of studies or observations for each metric. The values were calculated based on the ranking method (see methodology section).

services demonstrate a high positive impact on soil structure as a result of cover crop practice, however, this improvement raises concerns about nutrient leaching. Carbon sequestration is generally high, with increased SOC, though subject to variability influenced by diverse factors. Weed suppression and pest biocontrol improved under cover cropping, but necessitate careful management decisions. However, climate regulation, specifically in reducing N_2O emissions, presents mixed outcomes, influenced by cover crop types and local contexts. While all services are generally valuable, climate regulation introduces complexities, marking a comparatively lower impact. Achieving an optimal balance requires context-specific strategies to sustainably manage these multiple ecosystem services in agricultural system.

3.2. Cover crop effects on supporting ecosystem services

3.2.1. Soil physical structure

Soil physical structure determines the water and nutrient holding capacity of the soil and influences water, nutrient movement, and soil organism activity (Basche & DeLonge, 2017; Hopmans, 2019). We identified six studies that reported a value of 0.5 for soil physical structure benefits of cover cropping. It shows that the physical properties of soil (including precipitation storage efficiency, total porosity, soil compaction, and macropores) can be improved during cover cropping, but not in all circumstances. Soil texture, tillage system, and cover crop duration influenced the effect of covercrop. Blanco-Canqui and Ruis (2020) based on 98 studies, demonstrated that cover crops reduced bulk density by about 31%, but had no effect in 69% of cases. Other soil physical indicators were, however, improved by cover cropping (Blanco-Canqui & Ruis, 2020). Soil bulk density as an indicator of soil compaction is essential for the growth of plant roots, the movement of water and other substances, and soil aeration (Helliwell et al., 2019). Cover crops have differing effects on penetration resistance and bulk density (Blanco-Canqui & Ruis, 2020). Increasing soil organic matter and bioturbation by cover crops roots can reduce soil compaction (Ma et al., 2021). In a meta-analysis conducted by Basche and DeLonge (2017), continuous cover crops significantly increased total porosity. Cover cropping also generally reduces soil penetration resistance, which is considered an indicator of soil compaction (Benevenute et al., 2020; Blanco-Canqui & Ruis, 2020).

3.2.2. Soil nutrient cycle

Our findings with four records confirmed that cover crops provide important benefits for soil nutrient dynamics and balance in farming systems by fixing atmospheric N2, reducing N leaching, and reducing nutrient erosion and accumulation (Blanco-Canqui et al., 2015). Incorporating cover crops residues into the soil accelerates nitrogen mineralization (Kuo & Sainju, 1998), while legume cover crops fix nitrogen which is especially beneficial in low-fertility soils (Becker, 2001; Blanco-Canqui et al., 2015; Fageria et al., 2005). In northern China, cover crops increased the content of hydrolyzable nitrogen by 29% in the 0–20 cm soil layer, which improved crop growth (Ma et al., 2021). Nonetheless, a meta-analysis in the Argentine Pampas region showed the opposite results, with lower nitrate under both non-legume and legume cover crops (Alvarez et al., 2017). Differences in the results between China and Argentina might be attributable to differences in climate and soil. Indeed, soil nutrient cycling status under cover crops is affected by differences in climate conditions and soil texture within a region (Alvarez et al., 2017).

P and K are critical soil elements for plant growth and were significantly boosted by cover cropping in the > 20 cm soil layer at sites in northern China (Ma et al., 2021). Cover crops have the potential to enhance P uptake of main crops in a wide range of agro-ecosystems and under different management strategies (Hallama et al., 2019). Soil phosphorus availability is greatly increased due to the rhizosphere influence of cover crops (Ma et al., 2021). Additionally, legume cover crops can increase crop nutrient concentration in the topsoil layers by absorbing low accessible nutrients from the soil profile (Blanco-Canqui et al., 2011; Fageria et al., 2005; Hallama et al., 2019).

3.2.3. Nitrogen (N) leaching prevention

Our examination of the published literature revealed 10 studies for the N leaching prevention ecosystem service that demonstrated cover crops generally reduce N leaching (considering all forms of nitrogen, a combined value of 1). However, the strength of this effect depends on the timing of the release of N from cover crops and its uptake by the main crop (Bawa et al., 2021). Non-leguminous cover crops can substantially reduce N leaching into freshwater systems (Quemada et al., 2013; Thapa et al., 2018). In a global meta-analysis, non-leguminous cover crops reduced N leaching by 67% to 71% compared to no cover crop treatments, especially in dry years (Thapa et al., 2018). However, a regional meta-analysis from the Argentine Pampas reported lower N under both non-legume and legume cover crops (Alvarez et al., 2017). Thapa et al. (2018) reported that the efficacy of non-leguminous cover crops in reducing N leaching was correlated positively with shoot biomass. The discrepancy between the studies might be due to differences in climate conditions and soil textures among the farming regions where this effect was assessed.

3.2.4. The trade-offs among supporting ecosystem services

In comparing the trade-offs among the three highlighted supporting ecosystem services (soil physical structure, soil nutrient cycle, and N leaching prevention) a nuanced picture emerges (Figure 4). Soil physical structure, influenced by factors such as soil texture and cover crop duration, can be improved by cover cropping, although effects vary across circumstances. The reduction in bulk density is notable in some cases, contributing to better water movement and nutrient holding capacity. On the other hand, the soil nutrient cycle, essential for maintaining a balanced nutrient dynamic, is positively impacted by cover crops. However, regional variations suggest that climate conditions and soil texture influence these effects. Moreover, the N leaching prevention service provided by cover crops generally holds, with a notable reduction in N leaching reported in various studies. The decrease in N leaching improves water and soil quality (McDowell et al., 2021).

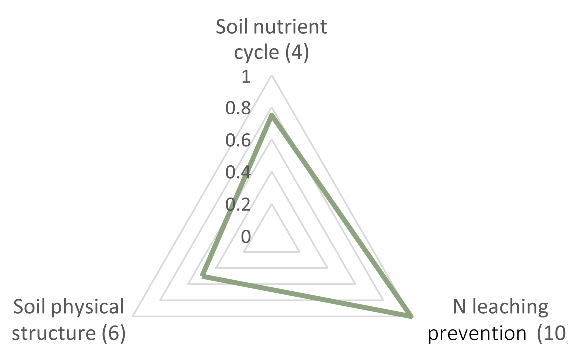

Figure 4. The trade-off between supporting services under cover crops. The number in the parentheses reflects the number of studies or observations for each metric. The values were calculated based on the ranking method (see methodology section).

3.3. Cover crop effects on provisioning ecosystem services

3.3.1. Primary production

Our analysis of the literature revealed nine records that demonstrated a combined value of −0.1 for the ecosystem services provided by cover crops. Both positive and negative effects were reported in their studies. The studies showed that generally four factors substantially influenced direct crop yield, including both the crop and the cover crop type, farm practices and management, the duration of applying cover crop, and cover crop season (Abdalla et al., 2019; Alvarez et al., 2017; Bhaskar et al., 2021; Fan et al., 2021; Marcillo & Miguez, 2017; Valkama et al., 2015). Cover crops significantly reduced the yield of primary grain crops compared to the control treatments under conventional tillage, but this negative effect was not apparent under conservation tillage (Abdalla et al., 2019). Regarding the cover crop type, Tonitto et al. (2006) showed that non-legume cover crops did not significantly increase yields compared to bare fallow systems. However, non-legume cover crops reduced grain yield, while legumes and mixed catch crops increased both grain yield and grain N content (Ma et al., 2021; Valkama et al., 2015). Alvarez et al. (2017) also reported that corn yield in pampas tended to decrease when the cover crop was a non-legume, but increased after a legume cover crop. Similarly, Ma et al. (2021) reported that wheat yield decreased by 7.2% under non-legume cover crops, and increased by 5.1% under legume cover crops in China. The same study found that for maize, both legume and non-legume cover crops increased crop yield by 12% and 9.4% respectively. A meta-analysis of the effects of cover crops on subsequent corn yields in the United States and Canada was conducted by Marcillo and Miguez (2017), involving 268 observations from 65 studies. At comparatively low nitrogen fertilizer (less than 200 kg N ha^{-1}) and with a no-tillage system, legume winter cover crops increased corn yields by around 30%, especially when cover crop termination was late (Marcillo & Miguez, 2017). Non-legume cover crops, including winter grass, had no significant effect on corn yields (Marcillo & Miguez, 2017). In terms of long-term effects, there is a tendency for cover crops to increase grain yields over time (Doltra & Olesen, 2013). Valkama et al. (2015) reported that the effect of the cover crops on grain yield changed across a decadal time scale from a negative effect in the first year to a positive effect in the last year. The tendency for improved yields over time can be explained by long-term improvements in soil fertility and increasing soil organic matter in cover crop treatments (Doltra & Olesen, 2013; Schjønning et al., 2012).

3.3.2. Habitat provision for soil biodiversity

Soil microbial biomass is considered one of the most responsive soil parameters to cover crops in arid and semi-arid regions (Blanco-Canqui et al., 2022). Through our research, we identified 13 records that reported a cumulative value of 1 for the habitat provision for the soil biodiversity under cover cropping. Cover crops have an overall positive effect on soil biodiversity indicators, including total bacteria and fungi, soil microbial abundance, and activity and biomass. However, the effect of cover crops on microbial biomass depends on residue management practices, soil texture and cover crops species (Muhammad et al., 2021a; Muhammad et al., 2021b). Cover crops might boost the soil microbial community by enhancing mycorrhizal abundance, microbial biomass P, and phosphatase activity (Hallama et al., 2019). A meta-analysis of 81 available studies showed cover crops enhanced microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) by 40–51 percent compared to non-cover crops (Muhammad et al., 2021b). Muhammad et al. (2021b) highlighted the role of non-legume cover crops compared to mixed cover crops and loam soil texture in MBC improvement due to increased biomass. Microbial activity may have increased as a result of an overall enhancement in microbial abundance, though this is less obvious under conditions of continental climates, chemical cover crop termination, and conservational tillage, showed a meta- analysis conducted by 60 relevant studies (Kim et al., 2020). However, the negative effects of conventional tillage on the soil microbial properties appear to be minimized by cover cropping (Kim et al., 2020).

3.3.3. Water provision

Based on our review of the literature, six records indicated a total value of −0.5 for the water provision services offered by cover crops. Soil water content tended to decrease under cover cropping in most studies, though this varied according to climate conditions, season and soil depth (Alvarez et al., 2017; Blanco-Canqui et al., 2015; Ma et al., 2021).

A meta-analysis based on 117 studies across the world showed water use efficiency of succeeding crops could be increased by up to 5% under cover cropping by reducing evapotranspiration (Wang et al., 2021). However, in non-arid regions, cover cropping appears to increase soil water content (Blanco-Canqui et al., 2015). The effect of cover crops on soil water is of most concern in drier climates, as cover crops can decrease yields in dry regions by reducing the availability of water for the main crops (Blanco-Canqui et al., 2022). In arid areas of North America, for every 125 kg ha^{-1} of cover or forage biomass, plant available soil water declined by 1 mm, which resulted in a 5.5 kg ha^{-1} decrease in wheat production (Holman et al., 2018). Yet in Argentina, soil available water was not affected by cover crops in the upper metre of the soil profile, but only at depths of about two metres where cumulative water content dropped by around 20% (Alvarez et al., 2017). Even in winter, soil water is dependent on meteorological conditions and other cover crop management (Selzer & Schubert, 2023).

3.3.4. The trade-offs among provisioning ecosystem services

In evaluating the trade-offs among the three focal provisioning ecosystem services, complex dynamics are observed (Figure 5). Primary production, encompassing the yield of main crops influenced by cover crops, displays a mixed impact. The impact varies across factors such as cover crop type, farm practices, management duration, and seasonal considerations, emphasizing the intricate trade-offs associated with cover crop management. In contrast, habitat provision for soil biodiversity consistently stands out

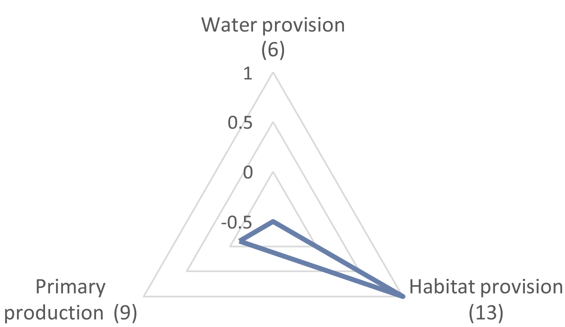

Figure 5. The trade-off between provisioning services under cover crops. The number in the parentheses reflects the number of studies or observations for each metric. The values were calculated based on the ranking method (see methodology section).

positively, with cover crops demonstrating an overall enhancement of soil microbial abundance, activity, and diversity. However, the effectiveness depends on factors such as residue management practices and soil texture. Lastly, water provision, revealing a more nuanced scenario, indicates a potential decrease in soil water content under cover cropping, particularly in drier climates. The impact on water availability for main crops varies with regional and meteorological conditions, showcasing the intricate trade-offs involved in managing these ecosystem services concurrently.

4. Adaptation strategies

Cover crops provide multiple services to the agro-ecosystem, such as regulating and cultural services. However, due to biophysical, economic, and social constraints and demands, there are likely trade-offs among services provision. Some of these trade-offs could be resolved by identifying and implementing appropriate management practices. If trade-offs cannot be avoided through farm management practices, decision-makers and farmers might prioritize certain ecosystem functions over others. Adaptation strategies for cover crops involve identifying and implementing appropriate management practices to address various constraints and demands while maintaining the benefits provided by cover crops. Cover crop selection and management could play an essential role in this respect, especially given local farm contexts. One of the major drawbacks of growing cover crops in dry agro-ecosystems is the potential reduction of main crop yields as a result of water depletion. Maintaining cover crop biomass at 5 Mg ha^{-1} could mitigate such negative impacts, and enhance the water-related sustainability of cover cropping management (Wang et al., 2021). Yet relatively high cover crop biomass is needed for significant benefits to erosion control, weed suppression, and soil biological activities (Blanco-Canqui et al., 2022). Another approach to improve water use efficiency in cover cropping is to choose cover crops that need less water to grow. Leaving cover crop residues on the ground can also increase soil water storage by reducing evaporation (Wang et al., 2021). Terminating cover crops in spring (late enough to avoid nitrate leaching after spring rains but not too early to compete with the main crop) could also enhance water recharge (Blanco-Canqui et al., 2022).

5. Conclusion

This review provides a comprehensive understanding of the combined effects of cover crops on various ecosystem services, addressing a significant gap in the existing literature. Our findings underscore the potential of well-designed cover crop implementations in substantially enhancing ecosystem services, and promoting sustainable agriculture. Cover crops have the potential to increase beneficial pest-control species, thereby reducing the need for chemical pest and weed control. Legume cover crops increase nitrogen fixation, decreasing the need for chemical fertilizers. Non-legume cover crops recycle Nitrogen and reduce soil Nitrogen losses. Cover crops increase SOC and improve soil porosity and aeration. Rain infiltration into the soil and drainage are also enhanced by cover crops, resulting in reduced runoff and erosion. The two major drawbacks of growing cover crops in dry agro-ecosystems are soil water content inconsistencies and the potential reduction of main crop yields mostly as a result of water depletion. This is particularly relevant to dry agro–ecosystems, underlining the importance of smart irrigation and management. Adaptation strategies for cover crops involve a combination of selecting appropriate cover crops, optimizing management practices, and integrating cover crops into cropping systems to achieve multiple benefits while minimizing trade-offs. Automated irrigation control systems can help address the issue of water depletion in dry agro-ecosystems, which is a major challenge for growing cover crops. By using Internet of Things (IoT) technology, sensors can collect real-time data on soil moisture, temperature, and other environmental factors to optimize irrigation schedules and amounts. This can help reduce water use and ensure that cover crops receive the appropriate amount of water without negatively impacting main crop yields. Establishing multifunctional cover crop benefits will also require a toolkit of policy instruments to facilitate and to incentivize uptake by rewarding beneficial ecological outcomes. Overall, the success of cover crops as a sustainable agricultural practice will depend on a combination of technological innovation, effective farm management practices, and supportive policy frameworks that promote ecological outcomes. Future research is needed to include more statistics exploring economic trade-offs associated with cover crop adoption while assessing the effectiveness of policy incentives. Such holistic studies will help overcome the conspicuous barriers limiting cover crop integration in diverse production systems and environmental conditions.

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Availability of data and materials

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