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REVIEW ARTICLE

Ecosystem services and management options of grass-based cover crops in Mediterranean climates: a review

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Abstract

Grasses constitute a key functional group in cover cropping strategies, particularly under the challenging conditions of Mediterranean climates, owing to their drought tolerance, rapid development, high biomass production, and extensive ground cover. Although their role in enhancing ecosystem services and supporting sustainable agroecosystems is increasingly recognized, a comprehensive synthesis specifically addressing Mediterranean climates is still lacking. To evaluate management options for efficient cover cropping strategies and the associated ecosystem services, this systematic review synthesizes evidence from 64 peer-reviewed field studies on grass cover crops, grown as single species or within grass-based mixtures, across three major Mediterranean agroecosystems (vineyards, orchards, and arable cropping systems). The following key points emerged: (1) cool-season grass species, either grain annual cereals or perennial forages, are the most effective at increasing soil organic matter content and nutrient availability, decreasing soil erosion, and suppressing weeds in Mediterranean environments; (2) if not properly managed, grass cover crops can compete with cash crops, immobilize soil N, and decrease crop yield; (3) species selection should be based on specific pedo-climatic characteristics and intended agronomic purposes; (4) despite context-specific differences, recommended management options in Mediterranean climate regions include drill planting, early autumn sowing, an appropriate seeding rate, and timely mechanical termination; and (5) optimizing cover cropping management based on biomass production and C/N ratio can help balance benefits and trade-offs, enabling targeted enhancement of specific ecosystem services. Grasses, when combined with legumes, often deliver even greater ecosystem services than when grown alone, as legumes complement grasses by increasing N availability, improving residue quality, and supporting more balanced biomass production. We conclude that grass cover crops hold considerable promise for promoting sustainable Mediterranean agriculture but require more long-term, multifunctional research to optimize their use.

Keywords Cover cropping · *Poaceae* · Soil health · Soil properties · Weed management · Sustainability

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1 Introduction

In recent decades, modern agriculture has faced multiple challenges, including increasing global food demand, soil degradation, and climate change. To address these issues, many farming systems have intensified their practices; this has often exacerbated existing problems, resulting in declining soil quality, loss of organic matter, accelerated erosion, reduced biodiversity, and heightened environmental pollution.

In Mediterranean climate regions, these challenges are particularly acute. Characterized by hot, dry summers, high solar radiation and high evaporative demand, cool-wet winters and irregular rainfall patterns, Mediterranean climates face significant soil water imbalances and seasonal water scarcity, which complicates soil and crop management. These scenarios, combined with poor soil management, accelerate the decomposition of soil organic matter (SOM), undermining soil health and ecosystem stability by impairing water infiltration and nutrient cycling (Ferreira et al. 2022). Consequently, the management of crops and trees in these regions must be tailored to these climatic constraints to ensure ecological and agronomic benefits.

Among various agroecological practices, cover cropping stands out as an effective and widely adopted technique for improving soil health and mitigating the negative effects of climate change (Silva and Moore (2017). Cover crops (CCs) are non-harvested crops that grow alongside or in addition to cash crops to provide numerous regulating and supporting ecosystem services (Blanco-Canqui et al. 2015; Sharma et al. 2018). To maximize ecosystem services, CCs need proper cover cropping management, which includes the selection of appropriate species/varieties, seeding rates and sowing times, termination stages, and termination methods (Scavo et al. 2022). CCs are typically intercropped with trees in orchards, vineyards and arable crops. They can also be introduced between two annual cash crops or during fallow periods to increase the functionality of agroecosystems without entering the food chain. Cover cropping can be total (full field coverage) or partial (localized between rows), artificial (*ad hoc* sown species) or natural (spontaneous flora), mixed (mixture of complementary species from different functional groups) or monophytic (Scavo et al. 2022). Compared with monoculture, mixed cover cropping is typical of advanced cropping systems, and it is often associated with greater ecological and productive benefits (von Cossel et al. 2025) mainly due to more stable biomass production from year to year (Chapagain et al. 2020; Florence and McGuire 2020). Cover cropping can be managed as living mulch in intercropping with cash crops and can be terminated chemically or mechanically for dead mulching or green manuring. Additionally, CCs are divided into three groups: leguminous broadleaves (commonly used for their biological N-fixation ability), non-leguminous broadleaves such as Brassicaceae members (mainly adopted for pest-suppressive potential and robust tap-root systems), and grasses (mostly used to increase soil C levels, porosity, nutrient cycling, and reduce erosion) (Koudahe et al. 2022).

Among the functional groups adopted as CCs, grasses are particularly relevant. They encompass a large group of plants belonging to the *Poaceae* family, which includes more than 12,000 species with different uses, such as human food, animal fodder, biofuel, fiber, construction materials, and ornamentals (Tzvelev 1989; Scordia and Cosentino 2019). Grasses are distributed across all continents and occur at various latitudes and altitudes. In addition to their climatic adaptability, these species are well known for their rapid development, high biomass productivity, and uniform ground cover (Fig. 1). Owing to these characteristics, grasses are widely used as CCs in both perennial (vineyards, orchards) and annual cropping systems (Celette et al. 2008; Blanco-Canqui and Jasa 2019), especially under water-limited conditions (Blanco-Canqui et al. 2022).

However, their adoption for cover cropping requires appropriate and context-specific management to minimise drawbacks and maximise agronomic benefits (Adetunji et al. 2020). Grass CCs not only may pose challenges under certain conditions (including increased input costs and competition for water and nutrients with cash crops, particularly in arid and semiarid environments) but can also



Fig. 1 Experimental field with a mixture of grass cover crops in the alleys of a vineyard in Sicily (Messina, Italy). Photo credit: Francesca Calderone

build up pathogens and pests, and have detrimental effects on seed germination, consequently resulting in lower crop yields (Muscas et al. 2017; Visconti et al. 2022).

Although numerous studies on grass CCs across different agroecosystems have been published, a comprehensive synthesis specifically addressing Mediterranean climates is still lacking. Existing literature generally addresses CCs across broad climatic regions or focuses on single ecosystem services, which limits their applicability to Mediterranean agroecosystems, characterized by distinct climatic constraints and increasing climate change pressures. Consequently, the functional roles, benefits, and potential trade-offs of grass CCs in Mediterranean systems remain fragmented across the literature. A better understanding and a Mediterranean-focused synthesis of grass CCs are therefore needed to (i) consolidate the available evidence on the functional roles of grass CCs, (ii) identify knowledge gaps and potential drawbacks, and (iii) support the development of context-specific management options. The present article aims to fill this gap by systematically reviewing the current knowledge on the use of grass CCs in Mediterranean agroecosystems, with a focus on their general characteristics, ecosystem services, commonly used species, and management practices in vineyards, orchards, and arable crops.

2 Study selection, screening, and analysis

To assess the role of grass CCs in Mediterranean cropping systems, we conducted a systematic review with quantitative synthesis of peer-reviewed field studies in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (Page et al. 2021). The PRISMA protocol was first applied to perform a literature search on 6 November 2025 in the Web of Science (Clarivate) and Scopus (Elsevier B.V.) databases with the following strings of keywords:

- WoS: (grass OR grasses) AND (intercrop OR cover crop OR mixed farm OR mixed crop OR agroforestry OR mulch OR green mulch OR dead mulch OR minimum till OR no till) AND (multifunctionality OR ecosystem service OR ecosystem functions OR carbon sequestration OR nutrient cycling OR water regulation OR soil biology OR GHG abatement OR erosion resistance OR climate regulation OR biodiversity OR yield OR crop productivity) AND Mediterranean.
- Scopus: ("grass*" OR grasses) AND (intercrop* OR "cover crop*" OR "mixed farm*" OR "mixed crop*" OR agroforestry* OR mulch* OR "green mulch*" OR "dead mulch*" OR "minimum till*" OR "no till*") AND (multifunctionality* OR "ecosystem service*" OR "ecosystem functions*" OR "carbon sequestration*" OR "nutrient cycling*" OR "water regulation*" OR "soil biology*" OR "GHG abatement*" OR "erosion resistance*" OR "climate regulation*" OR biodiversity* OR yield* OR "crop productivity*") AND Mediterranean.

These strings of keywords were selected to capture the highest possible number of studies related to ecosystem services of grass CCs in the Mediterranean. A total of 316 published articles were found, 178 from WoS, 103 from Scopus, and 35 from other sources through citation searching. The database search was further refined for language (English) and subject category (agricultural and biological sciences, environmental science, agronomy and agriculture multidisciplinary), resulting in 127 and 71 records from WoS and Scopus, respectively. Out of 233 articles, 41 duplicates were removed. Thereafter, the records were subjected to a two-level screening process. In the first step, only titles, keywords and abstracts were assessed, and 127 documents were excluded because of a lack of representativeness. Specifically, we defined the following exclusion criteria: (i) field studies not performed in Mediterranean climatic areas, namely Bsk, Csa, Csb and Csc of the Köppen-Geiger climate classification (Peel et al. 2007); (ii) nonoriginal research (reviews, meta-analyses, conference papers and book chapters) or model work; (iii) greenhouse, pot and lab trials; and (iv) documents addressing different issues (e.g., forage or silage production, pastures and landscapes). A full-text assessment was conducted as a secondary screening, implementing further inclusion criteria: (i) articles reporting at least one grass-like species as CCs and at least one ecosystem service; and (ii) articles reporting an experimental design with replicates and a control treatment different from CCs. Sixty-four studies fulfilled the inclusion criteria and were eligible for this systematic review. The eligible articles were divided by agroecosystem type: 23 for vineyards, 12 for orchards, and 29 for arable crops. The complete screening process is reported in the PRISMA flowchart (Fig. 2).

To quantify the effects of grass CCs, ecosystem service data were extracted from eligible articles and used to calculate the percentage difference between CCs and non-CC controls (bare soil or spontaneous vegetation). Based on the eligible articles, in this review the following ecosystem services were considered (MEA 2005): provisioning (cash crop yield), regulating (weed suppression, erosion control, water regulation, and natural enemy promotion), and supporting (nutrient cycling, soil fertility, and microbial activity). Ecosystem service categories were based on the descriptions of Calderone et al. (2025). When the results were presented in figures or plots, numerical data were extracted with the WebPlotDigitizer (Rohatgi 2017). When the climate or the soil conditions were not stated in a

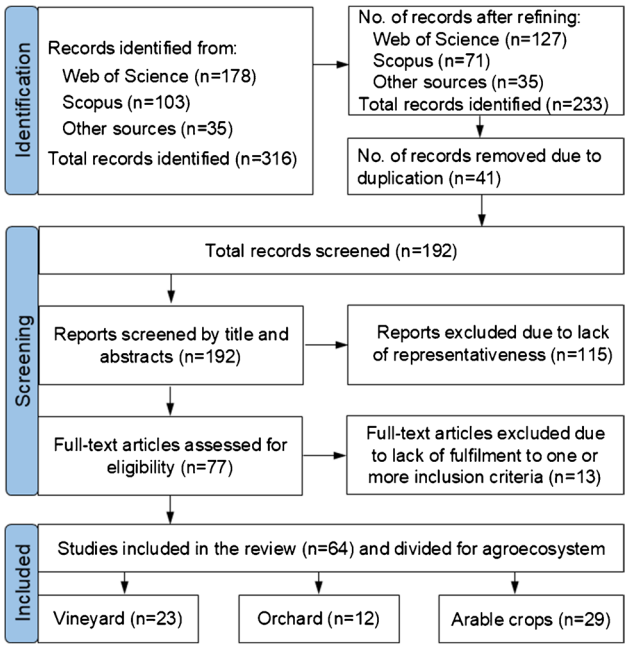

Fig. 2 Flowchart of the literature search and screening according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) methodology

study, the geographic coordinates of the site (or otherwise the nearest location) and the USDA soil texture classification, respectively, were used to include these metrics in our analysis.

3 Agronomic and ecological relevance of grass CCs

3.1 Key traits of grass CCs under increasing drought intensity

Grasses are herbaceous monocotyledonous plants adapted to a wide range of pedo-climatic conditions. They are characterized by a high level of genetic polymorphism in terms of their morphological structure and physiological functions (Bouchenak-Khelladi et al. 2010). Understanding their morphology and physiology is of key importance for effective management and diverse agricultural applications.

Despite the diversity within the *Poaceae* family, grasses share several specific morphological traits that can be summarized as follows: a wide fibrous root system, the presence of specialized stems like rhizomes (underground) or stolons (along the soil surface) that serve as storage tissues for vegetative propagation, a bunchy or creeping growth habitus, crown-producing buds, a marked tillering capacity allowing regrowth, high production of seeds (achenes, dry fruits) per plant, and high biomass production. Grasses also possess a combination of several physiological features, including C3 or C4 photosynthetic pathways for adapting to cool or warm environments, apical dominance, compensatory growth, compensatory photosynthesis, and C allocation (Gibson 2023). These traits not only influence plant survival under drought but also increase the functional role of grasses as CCs, especially in dryland farming systems.

Grass CCs can be either annual cereals (oat, barley, wheat, rye, triticale), which are predominantly used in crop rotations and as winter or summer CCs, or perennial forages (fescue, ryegrass, orchard grass, brome, etc.) for permanent CCs, especially in orchards. The major grasses employed for cover cropping across Mediterranean areas are listed in Table 1. Among the 30 species, 57% are perennial and 43% annual, 50% are hemicryptophytes and 47% therophytes, with the only geophyte *Poa bulbosa* L. While annual grasses are generally more suited to flexible rotation systems and short-term biomass production, perennial grasses are more effective at building long-term soil organic carbon (SOC), reducing erosion, and improving soil stability through their persistent root systems. Except for Bermuda grass [*Cynodon dactylon* (L.) Pers.], cool-season species are the most suitable grass CCs in Mediterranean and temperate summer-dry environments, as they adapt well to the lower soil radiation intensity of the cooler season, whereas C4 species are more sensitive to frost (Pau et al. 2013).

In a scenario of increasing warming and water deficit, which in combination are leading to an additional month of summer in the Mediterranean Basin (Giannakopoulos et al. 2009), drought stress is likely the most significant environmental constraint, as it negatively affects stomatal conductance, photosynthetic pigments, growth, and survival in many plant species (Pirnajmedin et al. 2024). Unsurprisingly, the grass CCs reported in Table 1 are predominantly autumn-winter species. The adaptive strategies of grasses result from a combination of morphological, physiological, and biochemical characteristics that can be summarized as follows: drought escape, avoidance, tolerance, associations with fungal endophytes, and recovery (da Silveira Pontes et al. 2015; Norton et al. 2016; Pirnajmedin et al. 2024).

Drought escape in perennial grasses is a strategy consisting of becoming dormant during growth or completing reproduction and seed set before dry conditions for annual grasses (Kooyers 2015). Summer dormancy (i.e., the cessation or reduction of leaf growth and the complete or partial senescence of biomass while maintaining live meristems for regrowth in autumn) is typical of cool-season perennial grasses from arid and semiarid Mediterranean climates with summer dry periods of four months or more (Pirnajmedin et al. 2024). Grasses can also avoid drought by maintaining high tissue water potential (through leaf modification,

Table 1 List of the major grasses used as cover crops in temperate agroecosystems. Classification into biological groups was based on the Raunkiaer system

Scientific name	Common name	Photosynthetic pathway	Life cycle	Biological group	Ecophysiological group
Avena sativa L.	Oat	C3	Annual	Therophyte	Autumn–winter
Brachypodium distachyon L.	Purple false brome	C3	Perennial	Therophyte	Autumn–winter
Bromus carinatus Hook. & Arn.	California brome	C3	Perennial	Hemicryptophyte	Autumn–winter
Bromus catharticus Vahl	Rescue grass	C3	Annual	Therophyte	Autumn–winter
Bromus erectus Huds	Upright brome	C3	Perennial	Hemicryptophyte	Autumn–winter
Bromus hordeaceus L.	Soft brome	C3	Annual	Therophyte	Autumn–winter
Bromus rubens L.	Red brome	C3	Annual	Therophyte	Autumn–winter
Cynodon dactylon (L.) Pers.	Bermuda grass	C4	Perennial	Hemicryptophyte	Spring–summer
Dactylis glomerata L.	Orchard grass	C3	Perennial	Hemicryptophyte	Autumn–winter
Elymus glaucus Buckley	Blue wildrye	C3	Perennial	Hemicryptophyte	Autumn–winter
Festuca arundinacea Schreb.	Tall fescue	C3	Perennial	Hemicryptophyte	Autumn–winter
Festuca ovina L.	Sheep fescue	C3	Perennial	Hemicryptophyte	Autumn–winter
Festuca rubra L.	Red fescue	C3	Perennial	Hemicryptophyte	Autumn–winter
Hordeum brachyantherum Nevski	Meadow barley	C3	Perennial	Hemicryptophyte	Spring–summer
Hordeum depressum (Scribn. & J.G.Sm.) Rydb	Low barley	C3	Annual	Therophyte	Autumn–winter
Hordeum vulgare L.	Barley	C3	Annual	Therophyte	Autumn–winter
Lolium arundinaceum (Schreb.) Darbysh.	Tall fescue	C3	Perennial	Hemicryptophyte	Autumn–winter
Lolium multiflorum Lam.	Italian ryegrass	C3	Annual	Therophyte	Autumn–winter
Lolium perenne L.	Perennial ryegrass	C3	Perennial	Hemicryptophyte	Autumn–winter
Lolium rigidum Gaudin	Rigid ryegrass	C3	Annual	Therophyte	Autumn–winter
Melica ciliata L.	Hairy melic	C3	Perennial	Hemicryptophyte	Autumn–winter
Nassella cernua (Stebbins & A.Love) Barkworth	Nodding needlegrass	C3	Perennial	Hemicryptophyte	Spring–summer
Poa bulbosa L.	Bulbous bluegrass	C3	Perennial	Geophyte	Autumn–winter
Poa pratensis L.	Kentucky bluegrass	C3	Perennial	Hemicryptophyte	Autumn–winter
Secale cereale L.	Rye	C3	Annual	Therophyte	Autumn–winter
Trisetum flavescens (L.) P.Beauv.	Golden oat grass	C3	Perennial	Hemicryptophyte	Spring–summer
Triticosecale Wittm. ex A.Camus	Triticale	C3	Annual	Therophyte	Autumn–winter
Triticum aestivum L.	Bread wheat	C3	Annual	Therophyte	Autumn–winter
Triticum turgidum subsp. *durum* (Desf.) Husn.	Durum wheat	C3	Annual	Therophyte	Autumn–winter
Vulpia microstachys var. *pauciflora* (Scribn. ex Beal) Lonard & Gould	Pacific fescue	C3	Annual	Therophyte	Autumn–winter

stomatal conductance, or osmotic adjustment) during periods of moisture deficit or by increasing soil water uptake through rooting system improvement (Norton et al. 2016). Drought tolerance is the ability of several grasses to maintain the integrity of their cell membranes for prolonged dry periods via metabolic processes and the accumulation of compatible osmolytes, including late embryogenesis-enriched proteins, sugars, and reactive oxygen species. Moreover, certain cool-season perennial grasses from northern zones of the Mediterranean basin, such as tall fescue, establish symbiotic associations with the endophytes of the genus *Epichloë* spp. as a drought tolerance mechanism to improve their adaptation to hotter regions of the Mediterranean. Recovery is a typical trait of perennial grasses to regenerate new tissues from the crown, stolons or rhizomes, or to compensate for the growth of surviving tissue (He et al. 2017).

3.2 Ecosystem services provided by grasses

The abovementioned morphological and physiological characteristics of grass CCs underpin their capacity to deliver a wide range of regulating and supporting ecosystem services (reduction in runoff, soil erosion and compaction, C sequestration, nutrient cycling, and weed control), as summarized in Fig. 3. These ecosystem services are closely interconnected, often resulting in cascading effects. Such

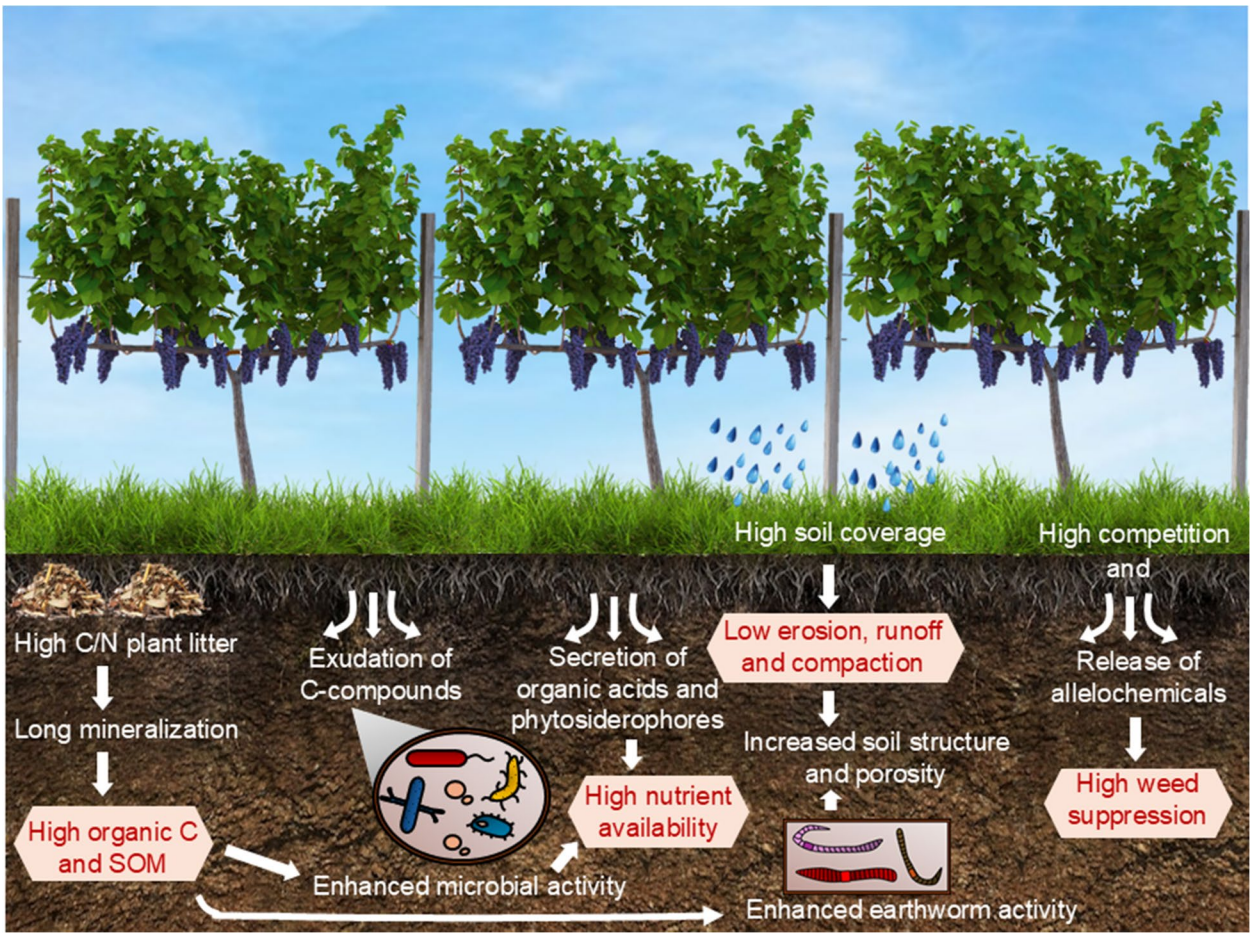

Fig. 3 Example of schematic representation showing the main regulating and supporting ecosystem services provided by grass cover crops in a vineyard: increase of organic carbon (C) and soil organic matter (SOM) levels, increase of nutrient availability, decrease of soil erosion, runoff and compaction, and suppression of weeds

characteristics make grass CCs particularly suitable for vineyards, orchards, and arable systems, especially in water-limited regions prone to soil erosion and degradation (Fageria et al. 2005; Koudahe et al. 2022).

3.2.1 Regulating ecosystem services

The most pronounced benefits of grass CCs primarily affect soil physical properties, though the magnitude of such benefits depends on climate, soil texture, CC species, and management (Blanco-Canqui and Ruis 2020; Haruna et al. 2020). Grass CCs tend to produce more biomass than legumes. In a 4-year wheat-fallow system with CCs planted after winter wheat in Kansas (USA, Bsk Mediterranean climate), for example, Blanco-Canqui et al. (2013) found that the CC biomass yield was 4.12 for winter triticale, 2.09 for spring triticale, 1.60 for spring pea, 0.43 for spring lentil, and 0.30 Mg ha^{-1} for winter lentil. In general, due to their high soil coverage and substantial fibrous root systems, grass CCs reduce soil bulk density, decrease runoff, and compaction caused by raindrop impact and agricultural machinery, and prevent water and wind erosion (Kaspar et al. 2001). These effects, combined with rhizodeposition (i.e., the loss of C-containing compounds into the rhizosphere via root exudation) and microbial activity, contribute to the role of grass CCs in improving soil structure, porosity and hydraulic properties such as water infiltration, water holding capacity, and hydraulic conductivity (Koudahe et al. 2022). Improvements in soil available water have been reported by several authors in the USA using rye CC on loamy and silty-loamy soils (Basche et al. 2016; Villamil et al. 2006).

Compared with legume residues, grass residues are commonly characterized by higher C/N ratios, dry matter, and lignin contents, resulting in slow decomposition due to long mineralization processes (Adetunji et al. 2020). The prolonged permanence of a canopy or surface residue contributes to intercepting and reflecting solar radiation, shading the surface and reducing evaporation, mainly in dry and hot environments. Hence, in addition to reducing extreme fluctuations in soil temperature, soils under grass

CCs are generally cooler during the day and warmer at night, especially at greater soil depths (Evans et al. 2016). In drought-prone environments, slow soil warming in spring decreases seed germination, enhances root growth and biological activity, reduces evaporation, and improves soil water storage (Blanco-Canqui et al. 2022).

In arid and semiarid Mediterranean agroecosystems, weeds pose a significant constraint for crop production, and weed control is carried out mainly chemically. In such a context, grasses are well known to suppress weeds more than broadleaf CCs due to tillering, greater biomass production, and soil coverage (Osipitan et al. 2019). In a meta-analysis on 53 studies published from 1990 to 2018 about the impact of CCs on weed suppression, Osipitan et al. (2019) indicated that cereal rye, oat, triticale, wheat, and ryegrass had a significantly higher weed-suppressive ability than *Fabaceae* and *Brassicaceae* species. The weed-suppressive ability of grass CCs has a dual explanation: on the one hand, grass CCs represent a continuous physical barrier at the soil surface, and hamper seed germination and seedling growth by competing for space, water, light, and nutrients (Teasdale et al. 2007); on the other hand, grasses can control weeds chemically by releasing allelochemicals into the environment through root exudation, leaching from aboveground plant parts, and residue decomposition (Scavo and Mauromicale 2021). Allelopathy is widespread in the *Poaceae* family, and their major allelochemicals are hydroxycinnamic acids and benzoxazinoids, such as 2,4-dihydroxy-(2*H*)−1,4-benzoxazin-3(4*H*)-one (DIBOA), and 2,4-dihydroxy-7-methoxy-(2*H*)−1,4-benzoxazin-3(4*H*)-one (DIMBOA), among others (Macías et al. 2006).

However, grass CCs, particularly when grown as monocultures, are less effective at providing certain regulating services, such as pollination, pest control, and the support of natural enemies, compared with more diverse plant mixtures that include species from other botanical families (Calderone et al. 2025).

3.2.2 Supporting ecosystem services

The high biomass production coupled with the long persistence of grass residues on the soil surface significantly contributes to the accumulation of SOC and increases C sequestration. For instance, after 5 years of grass cover cropping in the alleys of a Californian vineyard, with the CCs mowed and left as mulch on the soil surface, Steenwerth and Belina (2008) found that triticale CC had 1.1-fold greater total soil C than rye CC, and both grass CCs were 1.4-fold greater than a cultivation control consisting of a tandem disc every two months. A similar result was reported by Mazzoncini et al. (2011) with durum wheat on loamy soil in central Italy. Furthermore, grass CCs exude a relevant number of C-compounds into the rhizosphere, which are estimated to constitute 5–21% of all photosynthetically fixed carbon (Marschner 1995). Soil C accumulation is rarely detectable in the first few years after establishment but tends to become significant in the long term (Scavo et al. 2022). This accumulation effect is particularly pronounced in clay and eroded soils (Blanco-Canqui et al. 2015).

In addition to the creation of suitable habitat conditions by soil moisture and temperature regulation, grass CCs support soil food webs and ecological successions through their interactions with beneficial microorganisms and earthworm populations (Clapperton et al. 2007). In the first instance, earthworms take advantage of the habitat and energy provided either directly or indirectly by grass CCs, as indicated by Schreck et al. (2012) for *Aporrectodea nocturna* after 3 years of a mixture of grasses (50% tall fescue, 30% perennial ryegrass, and 20% red fescue) in the alleys of a vineyard located in southwestern France. Earthworms, in turn, promote SOM formation, regulate the macroporosity/microporosity ratio, and consequently increase water infiltration and aggregate stability (Scavo et al. 2022). An increase in SOC stocks is positively correlated with an increase in microbial biomass, microbial community structure and activity (Blanco-Canqui et al. 2015). For example, when evaluating the effects of different agricultural systems in a rainfed orchard located in Valencia Province (southeast Spain), García-Orenes et al. (2010) showed that, compared with bare soil treated with herbicides (oxyfluorfen), an oat CC plowed 4 times per year increased SOC (+37%), microbial biomass (+12%), and soil respiration (+32%) three times per year. The authors reported greater positive effects when oat was included in a mixture with vetch, increasing SOC by 53%, microbial biomass by 73%, and soil respiration by 62%. The influence on soil microbial communities is closely related to the quality of CC residues, meaning that grass CC residues with high C/N ratios stimulate better fungal growth, whereas bacteria and actinomycetes are favored by N-rich legume matrices (Muhammad et al. 2021). In this regard, several reports have explored the positive relationship between grass CCs and arbuscular mycorrhizal fungal (AMF) associations (Morimoto et al. 2018). AMF, in turn, can promote plant diversity by stimulating the growth of mycorrhizal-dependent subordinate species through P availability and interplant C transport (van der Heijden 2002).

Another important supporting ecosystem service provided by grass CCs is the improvement of nutrient availability. This can be attributed to the following: (i) the reduction in nutrient leaching and runoff; (ii) the enrichment of microbial activity and SOM; (iii) the stimulation of AMF networks that reduce nutrient losses (van der Heijden 2010) and allow greater soil exploration, mainly concerning P absorption; (iv) the secretion of organic acids (carbonic, malic, citric, etc.) to lower rhizospheric pH levels and

increase P solubilization (Scavo et al. 2019); and (v) the exudation of phytosiderophores, which are metal-chelating amino acids that form organic complexes with microelements to increase their solubility (Ueno et al. 2007). Phytosiderophore release is typical of several grasses, including *Poa pratensis* L., *Festuca rubra* L., *Lolium perenne* L., wheat, sorghum, oat, and barley (Cesco et al. 2006; Ueno et al. 2007; Scavo et al. 2019). In summary, grass CCs offer strong potential to improve nutrient availability and reduce external inputs in Mediterranean agroecosystems, especially for N retention (mainly during rainy periods), P mobilization (mainly in calcareous soils), and micronutrient uptake (in alkaline soils). Potential trade-offs related to nutrient availability in the Mediterranean lie between nutrient retention and crop competition, as grass CCs may compete for available nutrients in early spring, and between nutrient immobilization and nutrient supply due to a short-term reduced availability, especially for nitrates. In this context, practical solutions can be (i) aligning nutrient release (mineralization) from CCs biomass with crop demand under water-limited conditions through seeding time, (ii) terminating early CCs to control immobilization and competition, (iii) adjusting the spatial arrangement (e.g., strip cover cropping in orchards), and (iv) combining grasses with broadleaf CCs.

3.3 The role of management in grass CC performance

In arid and semiarid environments, which are typical of Mediterranean areas, water availability is the most limiting factor. In this context, CC growth is often limited by water stress; however, the interannual variability in biomass production can still be substantial in the same region (Blanco-Canqui et al. 2017). It is common that grass CCs tend to reduce available water and crop yield in severe dry years, whereas they can have low competitiveness with crops during years with regular rainfall (Nielsen et al. 2016). This section discusses the principal management practices that determine the successful implementation of grass CCs in the Mediterranean region.

3.3.1 Establishment and management

Under sub-optimal pedo-climatic conditions, the most important limits for CCs are poor establishment and, consequently, low biomass production. This might be related to three main drawbacks: (1) poor intrinsic characteristics of seeds (e.g., low germination rates), (2) seedbed components (physical, chemical, and biological soil properties), and (3) nonoptimal management (inappropriate seedbed preparation and seeding machinery, sowing dates and density, mainly for CC mixtures because of differences in seed size and thousand-seed weight) (Lamichhane and Alletto 2022). Overall, poor CC establishment will result in insufficient biomass production. Allowing the maximum CC biomass production without depleting soil moisture and competing with the cash crop is therefore the key target.

On the one hand, CC biomass production—including grasses—often correlates positively with CC performance in terms of improved soil health, erosion control, weed suppression, and nutrient cycling (Garba et al. 2022). The greater biomass production, together with its taller growth and more durable residues, explains the greater effectiveness of grass CCs than legumes and other broadleaf CCs in suppressing weeds, reducing nutrient leaching, or improving the SOM content. In this regard, a key aspect is achieving a minimum biomass yield threshold, i.e., the amount of biomass needed to provide a specific ecosystem service, which depends on CC species, management, and the pursued goal (McGuire 2025). Meta-analyses and research articles have revealed specific biomass thresholds of grass CCs required by grass cover crops (CCs) to deliver ecosystem services (Table 2). This information is critical for designing effective CC strategies, especially in Mediterranean agroecosystems where biomass accumulation is often constrained by limited water and shorter growing seasons. Weed suppression generally requires biomass levels above 3–5 t ha^{-1}, whereas soil erosion control can be achieved with much lower biomass if sufficient soil cover ($\geq$ 30%) is maintained (Prabhakara et al. 2015; Nichols et al. 2020). However, for building SOM, studies suggest that a biomass $\geq$ 4–5 t ha^{-1}, which is sustained over multiple seasons, is needed, especially in warm, dry climates with high decomposition rates (Moukanni et al. 2022). N leaching reduction can occur at $\geq$ 1 t ha^{-1} in temperate systems but other studies report that 3–4 t ha^{-1} may be required to retain 30–60% of nitrates (Hively et al. 2009). Overall, the table emphasizes that biomass thresholds are ecosystem service-specific and often relatively high in Mediterranean systems, highlighting the need for site-adapted species, early sowing, and optimized management to ensure sufficient CC growth.

On the other hand, while achieving a biomass threshold is crucial for ecosystem service delivery, exceeding this threshold may risk competition with the cash crop, especially in dry years. In fact, potential negative effects can occur once a maximum biomass threshold is exceeded, including nutrient immobilisation, competition and/or allelopathy with the cash crop, increased pest presence, and management challenges (Yousefi et al. 2024). The factors affecting the biomass production and effectiveness of grass CCs are numerous and include soil texture, climatic conditions (rainfall patterns and temperatures), farming practices (tillage and irrigation), and cover cropping management options (species/varietal selection, sowing method, seeding rate and time, termination method and termination stage) (Ruis et al. 2019;

Table 2 Average biomass thresholds for grass cover crops (CCs) by ecosystem service

Ecosystem service	CC biomass threshold	CC species	Description	Reference
Weed suppression		Grasses *vs*. non-grasses	Meta-analysis performed in maize–soybean rotations in the Midwest (USA).	Nichols et al. (2020)
General suppression	> 3 t ha^{-1}			
75% of biomass reduction	5 t/ha			
Soil erosion control		Barley, rye, ryegrass, triticale and wheat	Research performed in Maryland (USA) on six winter CC fields over the 2012–2013 growing season.	Prabhakara et al. (2015)
–50%	30% soil coverage ~ 0.2 t ha^{-1}			
–80%	60% soil coverage ~ 0.8 t ha^{-1}			
–100%	100% soil coverage ~ 1.6 t ha^{-1}			
Soil organic matter (SOM)		Not specified grasses	Mediterranean agroecosystems, characterized by accelerated decomposition rates, require more biomass to build SOM and at least 3 years of cover cropping.	Moukanni et al. (2022)
Stable or modest increase	≥ 4 t ha^{-1}			
Noticeable increase	≥ 5 t ha^{-1}			
Nitrogen leaching reduction				
Effective nitrate retention	≥ 1 t ha^{-1}	Rye, barley and wheat	Research performed on 136 fields in Maryland (USA). In the Mediterranean, 3-4 t ha^{-1} of CC biomass are needed to retain 30-60% of nitrates.	Hively et al. (2009)

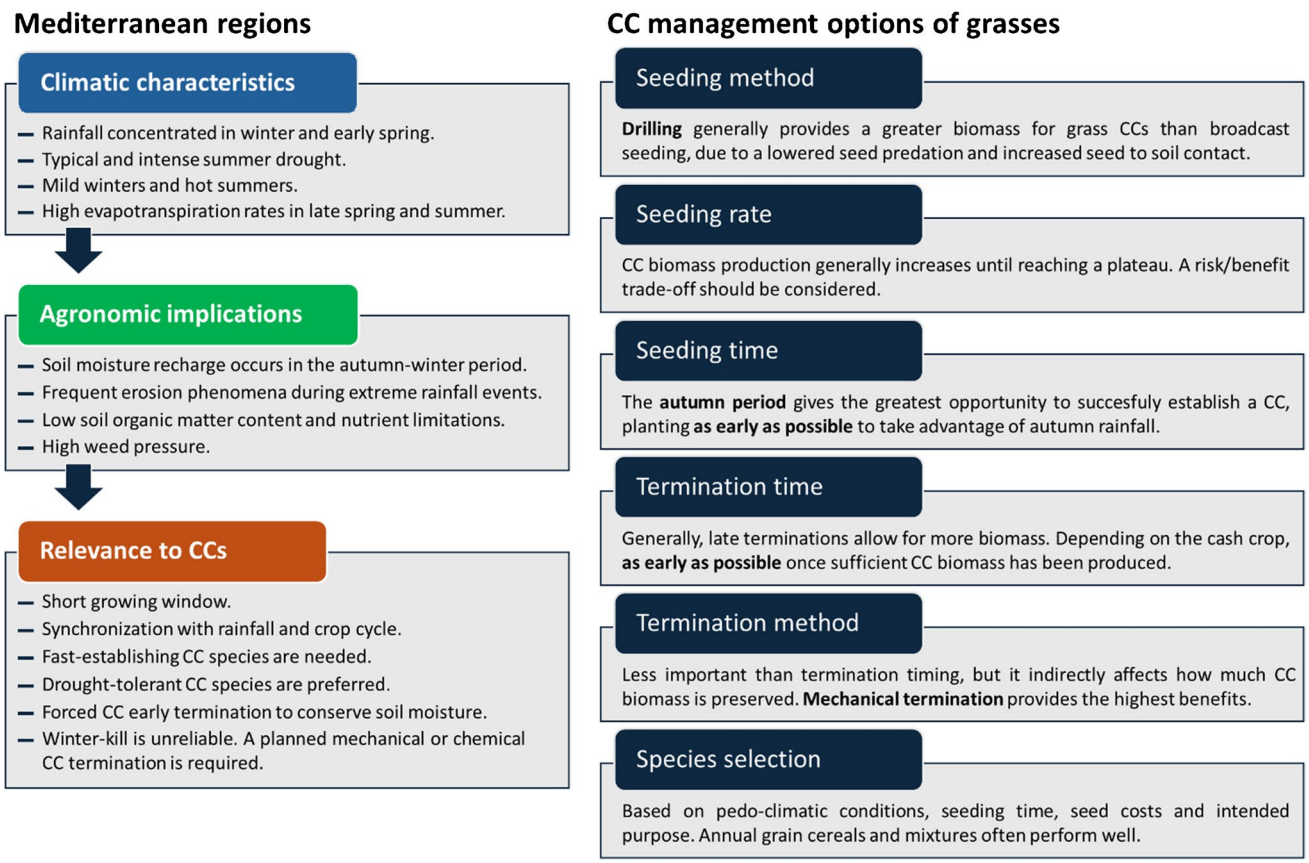

Fig. 4 Agronomic implications of Mediterranean characteristics and relevance to grass cover crops (CCs). Key aspects of cover cropping management for grass CCs in Mediterranean regions

Blanco-Canqui et al. 2022) (Fig. 4). The competition for water is recognized as the primary reason for the limited adoption of CCs in dryland agriculture. Surveying 321 farmers in the Netherlands, Germany, and Spain about the adoption of cover cropping, Vidal Morant et al. (2026) showed that, keeping the example of Spain, most research on cover cropping in Mediterranean climates focuses on perennial or irrigated systems, denoting the difficulty of upscaling the practice in rainfed arable land mainly due to water scarcity. The authors concluded that the main constraints for cover cropping adoption are related to CC establishment, while the primary drivers are increased SOM and reduced nitrate leaching.

According to the review by Blanco-Canqui et al. (2022) focused on water-limited areas (<500 mm annual precipitation), CCs can provide several ecosystem services even under these climatic conditions due to moderate biomass production (2.37 ± 2.30 t ha^{-1} on average), which is nevertheless lower than the value indicated by Ruis et al. (2019) for temperate regions (3.37 ± 2.69 t ha^{-1}). The authors, reviewing several reports from different regions, found that neither soil texture nor rainfall appears to have a large effect on CC effectiveness, although further long-term experiments are needed. Grasses are the most recommended CC species in Mediterranean climates due to their ability to develop significant aboveground biomass under drought conditions, high weed-suppressive ability, and enrichment of soil organic C stocks (Blanco-Canqui and Jasa 2019). The choice of CC species is context- and goal-specific but annual grain cereals (rye, oat, wheat, sorghum) are often recommended as the most suitable grasses in environments with scarce rainfall (Ruis et al. 2019). Koudahe et al. (2022) suggested that the ideal characteristics of grass CCs are: quick growth and ground cover, a short growing window, drought tolerance, and the capacity to be easily terminated. In a multicriteria decision analysis among 5 species and 20 varieties for targeted CC selection in a field trial conducted in Central Spain during two seasons, Ramírez-García et al. (2015) suggested that grasses were the most suitable cover crops, catch crop and fodder, while the vetches were the best for green manuring. Varietal differences were also found, since Hispanic was the most suitable barley cultivar as a cover and catch crop, Albacete as fodder and the triticale Titania attained the highest rank as cover, catch crop and fodder. In temperate climates, mixtures seem to enhance multiple ecosystem services because different species generally offer different benefits, but there is no clear trend of better performance than single species in Mediterranean climates (Blanco-Canqui et al. 2022). Additional research is needed to further evaluate the role of mixtures *vs*. single grass CCs (or varietal grass mixtures) in water-limited areas.

Concerning cover cropping management, the growing window (i.e., combination of sowing and termination dates) is the most important factor affecting the biomass production of grass CCs. Studies have shown that CC biomass generally increases with drill sowing (i.e., placing the seeds below the soil surface) and increased seeding rate and growing window (Ruis et al. 2019). Higher seeding rates generally enhance the biomass production of CCs, as reported, for example, by Boyd et al. (2009) for rye in vegetable systems. However, it should be stated that exceeding optimal seeding rates may reduce cost efficiency, crop yield, and soil moisture (Kankanen and Eriksson 2007). Hence, a risk/benefit trade-off should be considered on the basis of the specific characteristics of the context, for example, suboptimal seedbed preparation. With respect to the CC growing window, its maximization is achievable by early planting (in early autumn to take advantage of rainfall, although early spring-seeded grasses are gaining in popularity owing to the available soil moisture from winter rainfall) combined with late termination. At the same time, a grass CC terminated in late spring or early summer may be too competitive and often causes reduced yields of the companion or subsequent cash crop (Blanco-Canqui et al. 2022).

Evidence from the literature suggests that CC management in Mediterranean agroecosystems is fundamentally aimed at optimizing, rather than maximizing, ecosystem service provision. The key trade-off lies between increased biomass production and the associated rise in water consumption, which can lead to yield penalties in the main crop. Therefore, maximizing CC biomass at all costs should be avoided, as water competition remains the primary limiting factor in these environments. The practical implications of CC establishment and management practices in Mediterranean climates are (1) adopting a suitable growing window, with early autumn sowing at the onset of reliable rains, and termination before late spring drought; (2) preferring drill sowing, although broadcasting may still be appropriate in low-input or marginal areas; (3) using moderate seeding rates to balance biomass production with the risk of excessive water use; and (4) implementing flexible and rainfall-dependent management, aligning sowing with autumn rains for appropriate establishment or, where appropriate, opting for early spring sowing when sufficient soil moisture is available from winter rainfall. These implications should be explicitly grounded in knowledge of CC-specific morphological and physiological traits that determine functional performance under Mediterranean conditions. Key morphological traits include root system architecture and spatial distribution, rapid early growth coupled with timely senescence, a prostrate growth habit, and high tillering capacity. Complementary physiological attributes, such as efficient stomatal regulation, low specific leaf area, reduced transpiration rates, and high water-use efficiency, are equally critical in shaping resource-use dynamics and the overall delivery of ecosystem services.

3.3.2 Termination

Termination refers to the process of killing or suppressing CCs before the establishment of the main cash crop (e.g., annual systems) or before the growth resumption of the main crop (e.g., perennial systems). Cover crops may terminate naturally (e.g., through frost- or heat-induced mortality) or be artificially terminated using chemical or mechanical methods. A timely CC termination stage should be related to the quality of CC residues, especially the C/N ratio. Fig. 5 shows the trend of the C/N ratio in Mediterranean grass CCs (averages of annual and perennial grasses) across their phenological stages, provided that the C/N ratio does not vary significantly across grass species. At the early vegetative stage, grass CCs have a low C/N ratio (10−20), and then it grows proportionally with plant development due to increased structural components such as lignin, reaching the maximum value at maturity/senescence (50−70 or more). The decomposition rate and N availability of grass residues show opposite trends to those of the C/N ratio: therefore, early termination of grass CCs results in a lower C/N ratio, leading to faster decomposition and more immediate N release; in contrast, late termination results in a higher C/N ratio, favoring slower decomposition and more C input but also potential N immobilization. Other ecosystem services provided by grass CCs, like regulating, can be optimized by selecting an appropriate termination that targets not only CC biomass production but also the quality of CC residues (Opoku et al. 2024). C input and erosion control increase with more mature biomass, while weed control peaks in early stages and declines as CC biomass becomes denser and lignified. Therefore, the choice of grass species and termination time should also consider the quality of residues and the target ecosystem service, as summarized in Table 3. Overall, the choice of grass CC management options is of key importance and depends on the context, available resources, and main intended goal. A recent meta-analysis by Calderone et al. (2025) indicated that regulating ecosystem services are primarily associated with mowing or green manuring, whereas supporting services are linked to roller-crimping termination. Moreover, Garcia et al. (2024) reported that the termination method was more influential than the termination period to limit water competition with grapevine, indicating that tillage termination is the most effective in stopping service crop transpiration, increasing soil water stocks, and improving grapevine water status. However, these findings apply to cover crops in general rather than to grass CCs specifically. Crucially, the authors highlighted a marked lack of experimental evidence assessing regulating ecosystem services under roller-crimper CC termination, revealing a key knowledge gap in the current literature.

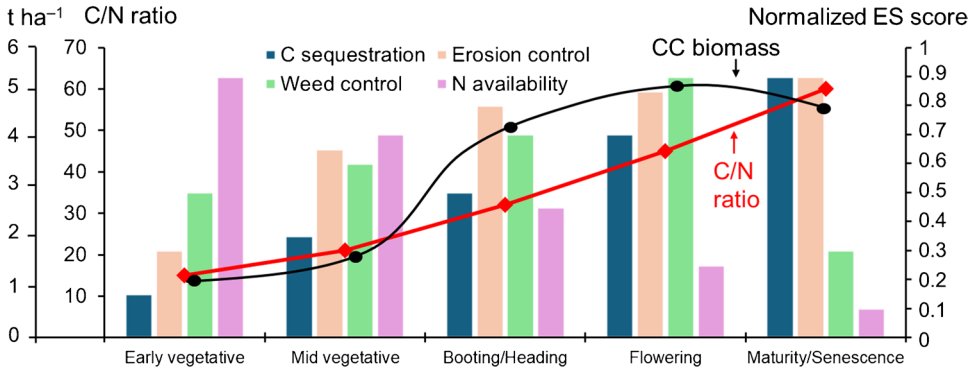

Fig. 5 Variation of cover crop (CC) biomass (black-dotted line) and C/N ratio (red line) across phenological stages of grass CCs and influence on major ecosystem services (ES). ES are expressed as normalised scores, adjusted values in a 0−1 scale resulting from the ratio between the average-observed value for each ES and the maximum or reference value

Table 3 Recommendations of grass cover crop management for target ecosystem services.

Objective	Target C/N	Ideal termination time	Species selection
C sequestration	> 50	Heading – Flowering	Pure grass stand (e.g., annual grain cereals)
Erosion control	25 – 45	Tillering – Heading	Rapid and dense canopy-forming grasses
Weed suppression	40 – 60	Heading – Flowering	High biomass and allelopathic grass species (e.g., rye)
N availability	< 25	Early vegetative – Tillering	Grass – legume mixture

4 Use of grass CCs in Mediterranean agroecosystems

4.1 Vineyards

Although Mediterranean viticulture plays major environmental and socioeconomic roles worldwide, it is increasingly threatened by adverse climatic and environmental factors, especially rising temperatures and summer drought (Droulia and Charalampopoulos 2021), the loss of SOM and soil nutrients, as well as erosion and compaction phenomena (Panagos et al. 2020). Soil degradation is further exacerbated by the intensive tillage practices adopted by conventional viticulture for weed control and for improving soil aeration and water conservation. However, the negative impact of tillage on soil health is well documented (Marques et al. 2010; Gómez et al. 2011; Novara et al. 2011, 2019), making it essential to preserve the ecological ability of Mediterranean vineyards through agroecological approaches (Raffa et al. 2021). In this context, both permanent and temporary grass CCs are potential solutions to current challenges in viticulture, as they can mitigate the impact of climate change, reduce chemical inputs, and improve soil health.

Twenty-three eligible articles on vineyard agroecosystems were selected on the basis of the inclusion criteria of this review, and the most relevant documents are listed in Table 4. These studies showed that grass CCs in Mediterranean vineyards improve soil physical properties (lower erosion and greater structural stability) and reduce weed pressure (up to −62% weed biomass), although negative effects, which are related mainly to water competition with vines, may cause yield reductions.

Peregrina et al. (2010) and Peregrina (2016) indicated that, compared with conventional tillage, rescue grass sown in a vineyard located in La Rioja (Spain) with a mean annual rainfall of 477 mm increased soil water aggregate stability, SOC (+145%), microbial biomass C (+241%), and β-glucosidase activity (+1097%) at the soil surface (0–2.5 cm). In agreement with these findings, both perennial and temporary grass CCs combined with no tillage for two consecutive growing seasons served as a vineyard C sink for short-term implementation across two sites located in California (USA), although the net ecosystem C balance was influenced by soil texture and tillage (Zumkeller et al. 2022). From the same study, emerged also that cover cropping had negligible beneficial effects on grapevine physiology, mineral nutrition or productivity, with no detrimental effects on vineyard water footprint (Zumkeller et al. 2023).

Vinatier et al. (2024) assessed how bermudagrass CC management influenced water infiltration rates (f_{cp}) over time in a Montpellier vineyard (France), comparing the results with those of bare soil under different management solutions (burning, mowing, and chemical weeding). The authors reported a lower f_{cp} in the bare soil than in the grass-covered soil, especially in summer, whereas CC management strategies did not have significant effects. Moreover, through rainfall simulation experiments, the runoff and soil moisture patterns under a purple false brome CC in a rainfed vineyard located in Campo Real (Spain) with annual rainfall < 400 mm were studied. Marques et al. (2010, 2020) found that, compared with conventional tillage, grass CCs reduced runoff in autumn (in turn increasing soil moisture) by improving water infiltration, with greater effects observed at the soil surface (0−10 cm). In a rainfed vineyard located on a hill with an average 15% slope and clay soil in northwestern Italy, Capello and co-authors (2019) also found higher penetration resistance, lower runoff (−76%), and soil loss (−83%) in naturally grass-covered alleys compared to tillage, thus allowing the possibility to limit the tractor traffic.

The positive effects of grass CCs in vineyards are often expressed also in terms of weed-suppressive ability. For instance, Valencia-Gredilla et al. (2020) showed that the noxious weed Bermuda grass (*C. dactylon*) was effectively managed by an alley tilled soil combined with a seeded barley CC in an irrigated vineyard in Lleida (Spain). The ability of grass CCs to control weeds in Mediterranean vineyards is often higher for grass-based mixtures with legumes. Torun (2024), investigating a three-year triticale-common vetch mixture in an irrigated vineyard with a restricted water supply in southern Turkey, reported higher weed-suppression rates compared with the spontaneous vegetation.

However, a potentially limiting factor in the adoption of grass CCs in Mediterranean vineyards is the competition for water and nutrients with associated vines (Cunial et al. 2025). The studies performed by Celette et al. (2008) and (2009) in a vineyard near Montpellier (France) with a mean annual water deficit of 150–200 mm, indicated that the adoption of permanent tall fescue CC caused both water and N stress in grapevines compared with bare soil. However, the intensity of this competition was shown to depend on soil characteristics—particularly depth and water-holding capacity—as well as root distribution patterns. In deep soils, grapevines adapt by extending their root systems to lower horizons, thereby minimizing overlap with the CC root zone (Celette et al. 2008). While this allowed access to additional water reserves, it also led to reduced N uptake due to partial avoidance of the surface mineralization zone, which contains the highest concentrations of inorganic N. These findings suggest that the intensity of competition can be moderated through strategic choices, such as selecting

Table 4 Examples of grass cover cropping applications in vineyards. % to control refers to the percentage difference between cover crops and non-cover crop controls

Climate	Soil texture	Irrigation	Control type	Ecosystem service	CC species	% to control	Reference
Csa	Clay-loam	Rainfed	Bare soil by herbicides	SOM	Tall fescue	–2.3	Celette et al. (2009)*
					Barley	–2.7	
				Organic C	Tall fescue	–1.6	
					Barley	–2.3	
				Total N	Tall fescue	+4.7	
					Barley	–3.4	
				C/N	Tall fescue	–6.7	
					Barley	+1.2	
Csa	Sandy-loam (location I)	Irrigated	Spontaneous vegetation	NECB	Barley + no tillage	–1	Zumkeller et al. (2022)*
					Bulbous bluegrass + no tillage	–0.8	
					Barley + conventional tillage	+9.2	
					Bulbous bluegrass + conventional tillage	+2.6	
				CO_2 emissions	Barley + no tillage	–15.9	
					Bulbous bluegrass + no tillage	–0.5	
					Barley + conventional tillage	+19.9	
					Bulbous bluegrass + conventional tillage	+9.8	
Csa	Loam (location II)	Irrigated	Spontaneous vegetation	NECB	Barley + no tillage	–2.7	Zumkeller et al. (2022)*
					Bulbous bluegrass + no tillage	–12.1	
					Barley + conventional tillage	–4.0	
					Bulbous bluegrass + conventional tillage	–11.6	
				CO_2 emissions	Barley + no tillage	+12.3	
					Bulbous bluegrass + no tillage	+19.1	
					Barley + conventional tillage	+28.6	
					Bulbous bluegrass + conventional tillage	+21.8	
Csa	Sandy-clay-loam	Irrigated	Tillage 3-4 times per year	SES	Red fescue-perennial ryegrass-sub clover mixture	–66.2	Novara et al. (2011)*
					Red fescue-sheep fescue-sub clover mixture	–76.3	
					Durum wheat	–56.0	
					Durum wheat-vetch mixture	–69.8	
				Water runoff	Red fescue-perennial ryegrass-sub clover mixture	–16.9	
					Red fescue-sheep fescue-sub clover mixture	–21.9	
					Durum wheat	–15.4	
					Durum wheat-vetch mixture	–17.8	
Csa	NA	Irrigated	Spontaneous vegetation	Weed coverage	Vetch-triticale mixture	–77.7	Torun (2024)*
				Weed density	Vetch-triticale mixture	–68.8	
				Weed biomass	Vetch-triticale mixture	–61.8	

Table 4 (continued)

Climate	Soil texture	Irrigation	Control type	Ecosystem service	CC species	% to control	Reference
Bsk	Sandy-loam	Rainfed	Tillage	SES	Purple false brome	–93.4	Marques et al. (2010)*
					Rye	–94.1	
				Water runoff	Purple false brome	–20.0	
					Rye	+50.0	
				SST	Purple false brome	+2.4	
					Rye	+4.6	
Cfb	Loam	Rainfed	Tillage more than 4 times per year	Organic C	Rescue grass	+145.1	Peregrina (2016)
					Spontaneous grasses	+258.8	
				MBC	Rescue grass	+241.4	
					Spontaneous grasses	+408.6	
				GLU	Rescue grass	+1096.6	
					Spontaneous grasses	+1454.4	
Csa	Loam (location I) Clay-loam (location II)	Rainfed	Tillage 3 times per year	SOM	Barley-squarrosum clover mulching	+31.3	Raffa et al. (2021)‡
					Barley-squarrosum clover green manure	+15.6	
				Total *N*	Barley-squarrosum clover mulching	+14.0	
					Barley-squarrosum clover green manure	+20.6	
				SPR	Barley-squarrosum clover mulching	+30.7	
					Barley-squarrosum clover green manure	+27.7	
				SST	Barley-squarrosum clover mulching	+9.1	
					Barley-squarrosum clover green manure	+6.2	

* Average of growing seasons; ‡ average of growing seasons and locations; *SOM* soil organic matter; *NECB* net ecosystem carbon balance; R_s respiration; *SES*soil erosion sediments; *MBC* microbial biomass C; *GLU* β-glucosidase activity; *SPR* soil penetration resistance; *SST* soil structure stability

CC species with shallow root systems, adjusting termination timing to limit peak water use overlap, or implementing supplemental irrigation when feasible. In this regard, Volaire and Lelièvre (2010), studying three perennial forage grasses with a range of summer dormancy in a rainfed vineyard in southern France, indicated *Dactylis glomerata* L. subsp. *hispanica* cv. Kasbah as the best intercrop because of its low biomass production and complete summer dormancy, and *Lolium arundinaceum* (Schreb.) Darbysh. cv. Centurion as the most competitive due to its deep root system and incomplete summer dormancy.

The negative effects of CCs on grapevine growth and yield have also been reported by Muscas et al. (2017) and Pou et al. (2011) in three-year field trials conducted in an irrigated vineyard in northwestern Sardinia (Italy) and in an organic vineyard in central Majorca (Spain), respectively. Both studies reported slight improvements in fruit quality compared with bare tilled soils, and recommended grass CC mixtures as interesting agronomic tools to limit excessive vine vigour. In addition, Sulas et al. (2017) showed that, compared with tilled soil, an orchard grass CC in a rainfed Sardinian vineyard (Italy) reduced the dry matter and N content of grapevine annual organs. In contrast, Mercenaro et al. (2014), at the same site as Muscas et al. (2017), reported that both grass-legume mixtures and perennial grass CCs reduce excessive vegetative growth but do not affect grapevine yield. Similar findings were also reported by Monteiro and Lopes (2007) in Central Portugal on sandy-clay-loam soil using a 60/40 permanent grass-legume mixture.

These contrasting outcomes underscore the complexity of grass CC–vine interactions and highlight the importance of context-specific variables such as management timing, CC duration, species selection, and pedo-climatic variability (Calderone et al. 2025). In particular, differences in soil depth, irrigation strategy, and rainfall distribution likely mediate whether CCs compete with vines or instead help regulate vegetative vigor without yield penalties. Grass mixtures are often selected as the best choice to modulate vine vigor and/or productivity levels while correcting nutritional imbalances (Cunial et al. 2025). Although vine-CC competition for soil resources can be strong in Mediterranean vineyards and, therefore, CC application may be constrained, the scientific community is investigating alternative and sustainable CC management solutions to tillage (Raffa et al. 2021; Garcia et al. 2024; Cunial et al. 2025). For example, a barley−squarrosum clover mixture for three consecutive growing seasons, either mown in late spring or left as dead mulch on the soil surface, was found to increase SOM and mineral N compared with conventional tillage in two different areas of central Tuscany (Italy) (Raffa et al. 2021). Additionally, Cunial et al. (2025) suggested the use of novel grass-legume CC termination methods (i.e., inter-row rolling and sub-row mulching) in two vineyards located in northern Italy for weed suppression and soil water conservation, whereas the effects from the same study on grape performance and physiology varied significantly according to the termination type (inter-row rolling crimper or sub-row mulching) and the floristic composition of the sown grass mixture (Pelusi et al. 2025). The adoption of CC mixtures, however, does not always guarantee considerable positive results on soil fertility and grape productivity, as reported for instance by Steenwerth et al (2013) in an irrigated vineyard in California's Central Valley by comparing the combined effects of cover crop type (oats alone or oats grown with legumes) and tillage. These findings suggest that a broad-ranging solution for grass CC mixture design in Mediterranean vineyards is challenging and it should be connected to the termination method and service goal.

4.2 Orchards

Twelve eligible articles were selected for this review on the use of grass CCs in Mediterranean orchards, including studies from arid and semiarid regions (e.g., Bsk) that share key agroecological features with Mediterranean systems. These harsh environments typically experience what is forecasted in the Mediterranean climate under future climate change scenarios (Giannakopoulos et al. 2009). This inclusion is justified because many orchard systems in these regions, especially olives, citrus, and almonds, present similar seasonal rainfall patterns, temperature regimes, and resource constraints. Cover cropping strategies in these contexts often respond to the same ecological pressures: winter growth windows, water scarcity, and soil degradation risks. The inclusion of these studies allows for a broader and more representative assessment of grass CC performance and management under Mediterranean-like conditions. Table 5 summarizes major articles on the application of grass CCs in Mediterranean orchards, including olive, citrus, almond, walnut, apple, peach, clementine, and chestnut systems. Across most studies, grass CCs, either alone or in mixtures with legumes, improved soil health indicators like SOM (from +35 to +124%), total N (from +40 to +72%), and available nutrients (P from +6 to +89%, and K from +28 to +96%), particularly in olive orchards. However, the results varied by species, site, and CC management. Spontaneous grasses and sown species such as fescue, brome, and oat were generally effective at improving soil properties. Weed suppression was particularly strong in apple, peach (from −76 to −81% weed biomass), and walnut (−53%) orchards adopting red fescue, tall fescue, perennial ryegrass and soft brome, the last in mixture with clover. Trade-offs, such as reduced yields or nutrient availability in almond and clementine systems, were observed in some cases, highlighting

the importance of context-specific management, including CC species selection and termination time.

Grass CCs in Mediterranean orchards, particularly olives and, to a lesser extent, citrus and nuts, clearly demonstrate the potential to enhance the soil structure, SOM, and weed control, especially under rainfed conditions. These benefits are largely due to the short growth cycle of grasses, which aligns well with autumn–winter rainfall, allowing them to establish quickly and be terminated before competition with trees for flowering and fruiting.

Managing olive grove soils with the cultivation of grass CCs is an ancient practice that is regaining popularity as the leading an agroecological practice in Mediterranean areas (Kavvadias and Koubouris 2019), even when annual grain grasses are intercropped with olives and harvested for grain production (i.e., "agroforestry system"). For example, Panozzo et al. (2020) investigated a four-year agroforestry system based on the intercropping of durum wheat rotated with faba bean in an organic and no-tilled olive grove located in southern France, hence going beyond the optimal termination windows for cover cropping. The authors observed that the associated durum wheat had a reduced grain yield but gradually stimulated olive production and was an additional source of income. In this sense, the meta-analysis of Scordia et al. (2023) demonstrated that the yield of field crops in association with trees was highly dependent on tree type, tree density, crop species, and variety used in Mediterranean agroforestry; however, grasses (like barley and winter wheat) were found to be more adapted to double systems than legumes and forage, pasture or spontaneous vegetation. Elhaddad et al. (2024) compared six CCs for two years to bare-tilled soil on a Tunisian olive grove with a mean annual rainfall of 380 mm and reported that all the studied grass CCs improved soil health after residue incorporation into the soil, and the best results were obtained when oat was included in a mixture with vetch. Similar findings were also reported by Bogunovic et al. (2020) at a site in Dalmatia (Croatia) with an average annual rainfall of 838 mm by using spontaneous grasses in the alleys, which were mowed and left on the surface as mulch. In another experiment performed in southern Spain over 3 years under semiarid conditions (439 mm annual rainfall), maintaining naturally self-seeded grasses (*Bromus* spp.) in the alleys of two commercial olive orchards (10 ×10 m planting layout) was found to improve weed richness, weed diversity, and soil fertility compared with the region's traditional management practices (vibro-cultivator 3–5 times per year plus incorporation of pruning wood residues), while olive yield was unaffected (Pedraza and Gonzalez-Andujar 2025). The adoption of grass CCs has also been proposed for intensive olive cropping systems. Repullo-Ruibérriz de Torres and co-authors (2021) indicated that the use of the perennial grass *Brachypodium distachyon* L. for four years as a living mulch in an intensive olive grove sited in Andalusia (Spain) highly enhanced SOM (+124%) and exchangeable K (+96%) in the whole profile (0–40 cm) compared with spontaneous vegetation, with greater effects observed at the surface (0–5 cm). This is not surprising as, according to Gómez (2017), the positive effects of CCs on soil properties in orchards and vineyards are often limited to the first 0–20 cm profile and to the spatial extension of the CCs. Moreover, Repullo-Ruibérriz de Torres and co-authors (2021) recommend the use of grass CCs for C and soil nutrient storage to prevent leaching and erosion in olive groves.

In addition to olive groves, the beneficial effects of grass CCs have been reported in several orchard types. Borges et al. (2018) evaluated the effects of no-tillage combined with grass CCs on C fractions and SOM dynamics in a Mediterranean chestnut orchard (12 ×12 m planting layout) located in northeast Portugal, with a mean annual rainfall of 758 mm. Compared with conventional tillage, the authors reported that a spontaneous grass cover (mainly composed of *Vulpia bromoides* (L.) Gray and *Agrostis castellana* Boiss. et Reut.) terminated by sheep grazing and mechanically cut twice per year (in spring and prior to fruit harvest), increased SOC stocks in the 0–10 (+3.4%) and 10–20 (+11.5%) cm soil layers, as well as the labile soil organic fractions, including particulate organic C, active organic C, and hot-water extractable C. The benefits of grass CCs are often higher in grass–based mixtures with broadleaf CC species, similar to vineyard agroecosystems. For instance, a 50/50 grass–clover mixture composed of soft brome and subterranean clover varieties for two consecutive growing seasons and mowed mechanically every year was found to highly suppress weeds (−81% of biomass) and improve soil mineral N (+40%) in a California walnut orchard with 340 mm of mean annual rainfall (Curtright et al. 2025). Effective weed control with three grass CCs (red fescue, tall fescue, and perennial ryegrass) was also reported by Tworkoski and Glenn (2012) for peach and apple, and by Sánchez et al. (2007) for apple with an alfalfa-fescue mixture.

In contrast, the effects of grass CCs appear to be less pronounced in citrus orchards. For example, Visconti et al. (2022) found that a fescue CC sown in the alleys of a clementine orchard on the Valencian coastal plain (Eastern Spain) and cut three times per year with the residues left on the soil surface, enhanced soil biological fertility but had limited effects on its physicochemical properties, compared with those of the spontaneous vegetation. This outcome likely reflects the scarce soil N content at the site and may suggest that grass CCs alone are not sufficient in nutrient-depleted soils and should be integrated with complementary nutrient management strategies. Similarly, Rubio-Asensio et al. (2022) suggested the establishment of

a grass-legume CC mixture combined with deficit irrigation in Mediterranean young almond orchards to reduce water and nutrient leaching, but special attention should be given to management options to avoid competitive issues with trees.

In summary, grass CCs in Mediterranean orchards, especially olives, offer considerable potential to improve soil health, reduce weed pressure, and enhance nutrient retention, particularly when tailored to the orchard type, rainfall regime, and termination strategy. However, site-specific management remains essential to avoid negative interactions with tree crops, especially under nutrient-poor or water-limited conditions. Despite their benefits, the success of grass CCs in orchards largely depends on careful species selection and site-specific management. The limited number of studies addressing species other than olive reveals a substantial knowledge gap for many tree crops and orchard systems typical of the Mediterranean region, highlighting the need for further research on grass CCs in these systems and their potential to deliver multiple ecosystem services.

4.3 Arable crops

In annual cropping systems of Mediterranean climates, grasses can serve as temporary inter-row CCs that are interseeded during the early vegetative stages of arable crops (i.e., relay intercropping or interseeding), with the primary objectives of rapid soil covering, weed suppression, and organic matter input during fallow periods or between cash crop cycles. Table 6 illustrates the highly variable effects of grass CCs in Mediterranean arable systems, depending on crop type, CC species, and management strategy. For example, Alonso-Ayuso et al. (2020) comparing the performance of Italian ryegrass with eight different legumes as interseeded CCs into irrigated maize over two consecutive growing seasons in central Spain, reported that Italian ryegrass provided optimal soil coverage and biomass accumulation, showing exceptional performance without negatively affecting maize productivity or grain quality. Similarly, when compared with traditional winter fallow in irrigated Mediterranean crop rotations, a barley CC can mitigate soil degradation, enhance soil functionality, reduce nitrate leaching, and promote N recycling within the cropping system (Gabriel and Quemada 2011; Gabriel et al. 2012; García-González et al. 2018). This highlights the potential of grass CCs in intensively managed Mediterranean cropping systems when water availability is adequate and timing is well planned. Moreover, in a two-year field experiment performed in northern Greece over two growing seasons, Vasilakoglou et al. (2006) found that two barley cultivars, six triticale cultivars, and three rye populations used as CC mulches and combined with inter-row cultivation reduced the emergence of grass weeds (up to −70%), and enhanced the yield of cotton lint. The authors suggested that although the post-emergence application of herbicides may be necessary to achieve the greatest cotton yield, planting winter cereal CCs in fields infested by grass weed populations may reduce herbicide usage. Conversely, Salmerón et al. (2011), studying the effect of winter CCs on yield and N availability of irrigated maize in Zaragoza (Spain), indicated that barley generated the greatest biomass production but at the same time reduced maize yield (−16%), likely due to an N deficiency caused by insufficient N mineralization from barley CC with a high C/N ratio and/or a lack of synchronization with maize N uptake. This underscores the importance of aligning CC termination time and residue quality with the nutrient demands of the subsequent cash crop. The influence of kill date on a barley-vetch mixture aimed at maximizing CC benefits was also studied by Alonso-Ayuso et al. (2014) in central Spain (~350 mm annual rainfall) on a silty clay loam soil with high N availability. Under these conditions, the authors reported that early kill date (barley at the end of the booting growth stage) reduced the risk of pre-emptive competition for water and N, whereas delayed termination (barley at the emerging inflorescence growth stage) increased CC biomass production, N release through mineralization and labile organic pools. Additionally, Picard et al. (2010) assessed the effects of undersowing two bread wheat varieties (Isengrain and Scipion) with red fescue in a two-year experimental trial performed at Grignon (France) and found that red fescue CC decreased the wheat yield of both varieties (−12% and−7%, respectively). In contrast, Dhima et al. (2006) and Kobayashi et al. (2004) reported increases in maize and soybean yields, respectively, due to the weed-suppressive ability of rye, barley, and triticale CCs.

In Mediterranean systems, due to the short planting window caused by unfavorable climatic conditions, grass CCs are mostly used for double cropping with legumes (Scordia et al. 2024). For instance, lentil–spring cereal intercropping reduced weed pressure by 97%, and bruchid grain loss by 16% in a two-year field trial in central Italy, with the lentil–triticale mixture that had a higher resource use efficiency than lentil–barley (Tosti et al. 2023). However, the highly competitive effect of the cereal reduced lentil yield in intercrops by 59%, suggesting that postponing the sowing date of the cereal together with the canopy architecture (mainly plant height and tillering capacity) as key traits for decreasing the competitiveness of barley, triticale, and other small-grain crops. In some cases, the negative effects of grass CCs associated with N deficiency might be mitigated by adopting cereal–legume mixtures to increase the N content and reduce the C/N ratio of residues. This was demonstrated by Sainju et al. (2005) in central Georgia (USA), where a rye–hairy vetch CC mixture terminated in spring enhanced the performance of subsequent cotton and sorghum crops.

Table 5 Examples of grass cover cropping applications in fruit orchards. % to control refers to the percentage difference between cover crops and non-cover crop controls

Cash crop	Climate	Soil texture	Control type	Ecosystem service	CC species	% to control	Reference
Olive	Csa	Clay	Tillage 3 times per year	SOM	Spring wheat	+55.8	Elhaddad et al. (2024)*
					Oat	+59.9	
					Vetch–oat	+60.3	
				Total N	Spring wheat	+62.8	
					Oat	+42.6	
					Vetch–oat	+72.9	
				Available P	Spring wheat	+88.7	
					Oat	+48.9	
					Vetch–oat	+52.5	
				Available K	Spring wheat	+28.0	
					Oat	+37.0	
					Vetch–oat	+54.0	
				Geometric mean of the soil enzyme activity	Spring wheat	+50.3	
					Oat	+44.9	
					Vetch–oat	+10.8	
Olive	Csa	Clay	Tillage 3-4 times per year	Bulk density	Spontaneous grasses	–7.0	Bogunovic et al. (2020)
				WHC		+6.5	
				SOM		+34.6	
				Total N		+40	
				Available P		+84.4	
Olive	Csa	Silty-loam, clay	Tillage 3-5 times per year + pruning wood residues	Weed richness	Spontaneous grasses (*Bromus* sp.)	+155.8	Pedraza and Gonzalez-Andujar (2025)*
				Weed diversity		+179.8	
				Organic N		+37.5	
				SOM		+60.0	
				Available K		+11.7	
				Available P		–7.0	
				Yield		+11.4	
Olive	Csa	Silty-clay	Spontaneous vegetation	SOM	Purple false brome	+124.0	Repullo-Ruibérriz de Torres et al. (2021)‡
				Total N		–5.0	
				Available P		+6	
				Exchangeable K		+96.0	
Clementine	Csa	Clay-loam	Bare soil by herbicides	Ks	Fescue	–2.6	Visconti et al. (2022)*
				Bulk density		+1.7	
				Organic C		0	
				Total N		–0.5	
				Exchangeable K		–16.7	
				CO_2 emissions		+2.7	
				DHA		+13.2	
Almond	Bsk	Sandy-loam	Bare soil by herbicides and tillage	Yield	Grass-legume mixture	–19.4	Rubio-Asensio et al. (2022)‡
				WUE		–19.2	
				$N\text{-}NO_3$ (0-20 cm)		–60.2	
Walnut	Csb	Coarse-loam	Spontaneous vegetation	Weed biomass	Soft brome-clover mixture	–52.7	Curtright et al. (2025)*
				Mineral N		+39.6	
Chestnut	Csb	Sandy-loam	Tillage twice a year	SOC	Spontaneous grasses	+3.4	Borges et al. (2018)*
				AC		+36.0	
				POC		+41.9	
				HWC		+32.0	
Peach and apple	Csa	Silty-loam	Spontaneous vegetation	Weed biomass	Red fescue	–80.9	Tworkoski and Glenn (2012)*
					Tall fescue	–76.2	
					Perennial ryegrass	–79.0	

Table 5 (continued)

Cash crop	Climate	Soil texture	Control type	Ecosystem service	CC species	% to control	Reference
Apple	Bsk	Sandy-loam	Spontaneous vegetation	SOM	Alfalfa-fescue mixture	+50.0	Sánchez et al. (2007)
				Total N		+52.0	
				Available P		+18.6	
				Exchangeable K		+7.2	
				Exchangeable Fe		+37.3	
				Exchangeable Cu		+42.9	
				Exchangeable Zn		+13.6	
				Yield†		+24.7	

* Average of growing seasons; ‡ average of growing seasons and independent variables; *SOM* soil organic matter; *WHC* water holding capacity; *Ks* soil saturated hydraulic conductivity; *DHA* dehydrogenase activity; *WUE* water use efficiency; *SOC* soil organic carbon; *AC* active carbon; *POC* particulate organic carbon; *HWC* hot-water extractable carbon

In addition to the CC kill date and species selection, designing appropriate mixtures is another key aspect for increasing the ecosystem services provided by grass CCs in Mediterranean arable systems. In this regard, Ranaldo and co-authors (2020) evaluated the weed-suppressive ability of eight cover crop species (field pea, common vetch, crimson clover, squarrosum clover, barley, oat, radish, and black mustard) designed into nine CC mixtures to create a gradient of diversity in terms of number of species and number of functional groups. The authors found that increasing both species diversity and functional diversity can lead to higher biomass production and weed suppression in mixtures compared with monospecific stands, suggesting that exploiting the complementarity of species functional traits in CC mixtures can be used as a strategy to ensure high biomass production and good weed suppression in Mediterranean environments. CC mixtures between grasses and legumes can be a valid option also for mitigating NO_3 leaching risk (Tosti et al. 2014) or for improving N yields and CC biomass, as indicated by Saia et al. (2016) for seven forage legumes grown in monoculture or in mixture with ryegrass in Sicily (southern Italy), although pure legume stands fixed a higher amount of N_2 than mixtures.

Furthermore, the terminal drought and short winter of the Mediterranean climate often preclude the intercropping of grass CCs with annual cash crops; on the contrary, CCs often replace a cash crop with rotation schemes. In such cases, the use of CCs represents a deliberate sacrifice of a cash crop year to rebuild soil health, restore fertility, or break persistent weed cycles, aiming for longer-term system sustainability. In central-northern Spain, the use of *Sorghum sudanense* or *S. bicolor* as CCs in succeeding barley crop effectively controlled weeds during the fallow year and increased barley yield (Urbano et al. 2006). Research conducted across two locations in southwestern Australia under exceptionally dry Mediterranean climate conditions revealed that the inclusion of high-biomass oat CCs in cereal-dominated cropping systems was effective at controlling weeds but did not significantly affect soil N mineralization compared with wheat and barley, indicating that cash crops grown after oat CC would require similar N levels to those grown after cereal harvest (Flower et al. 2012). A similar experiment was conducted by Egbedi et al. (2024) in Louisiana (USA) over three growing seasons under rainfed conditions to evaluate the effects of double cropping and grass−legume CC mixtures on bread wheat, cotton, and soybean under conventional and no tillage systems. The authors found that both double cropping and cover cropping similarly influenced crop yield in the short term, with better results in terms of crop production and soil health than crops preceded by fallow, except for bread wheat. Replacing bare fallow with CCs may, in some cases, lead to adverse effects. Sanz-Cobena et al. (2014), for example, indicated increased greenhouse gas emissions (N_2O, CO_2 or CH_4) associated with a barley CC compared with the control during the autumn–winter intercrop period, with N_2O fluxes further increasing after the incorporation of barley residues. In contrast, Mancinelli et al. (2013) observed no significant differences in CO_2 emissions between a ryegrass CC and fallow soil in a Mediterranean environment with a mean annual rainfall of 730 mm.

The integration of grass CCs into crop rotation schemes is commonly practiced in horticultural systems such as eggplant (Radicetti et al. 2017), pepper (Radicetti et al. 2013), and tomato (Campiglia et al. 2011). Analyzing the effects of different CCs and their residue managements on the following pepper productivity in central Italy on a sandy-loam soil, Radicetti et al. (2013) and Campiglia et al. (2014) showed that oat CC exerted a stronger weed suppression than hairy vetch CC and bare soil, especially with the residues left in strips on soil surface in no-tillage, while hairy vetch determined the highest marketable pepper yield probably due to an abundant availability of soil NO_3 throughout the pepper growing season. Under the same conditions, Campiglia et al. (2012) studied the effects of CCs on pepper and reported that oat CC had the highest weed-suppressive ability among a hairy vetch/oat mixture and hairy vetch CCs, both inside the mulch layer and between the pepper paired

rows, but decreased pepper yield. Similar results are reported in fallowing eggplant, where placing oat CC residues on the soil surface mitigated the shortage of soil inorganic N for the following vegetable and increased soil CO_2 fluxes (Radicetti et al. 2017, 2020). In central Italy, direct transplanting into ryegrass mulches of no-tillage tomato was negative considering a decrease of tomato yield and soil N, likely due to the high C/N ratio of ryegrass residues that caused N immobilization and competition with the succeeding tomato for the available soil N (Campiglia et al. 2011). In northern Iran, a zone characterized by semi-arid climate with ~190 mm of cumulative rainfall from April to August, a barley CC substantially reduced weed pressure, particularly when the residues were retained on the soil surface rather than incorporated, thereby allowing a reduction in herbicide application rates (Langeroodi et al. 2019). However, the legume CC (annual medic) resulted in higher tomato marketable yields. Overall, these findings indicate that legume CCs are more suitable for horticultural crop rotations in Mediterranean climates, whereas grass CCs exhibit a high capacity for weed suppression.

One of the harmful effects linked to unfavorable Mediterranean climatic conditions is soil biological degradation. Cover cropping is known to restore native inoculum and increase the number of AMF species in the subsequent cash crop (García-González et al. 2016). However, the effects of CCs on AMF communities depend on CC species. In a maize cropping system conducted in Madrid (Spain) under semiarid climatic conditions and subjected to different CC treatments after 10 years of rotations, Hontoria et al. (2019) reported that, compared with the fallow treatment, the barley CC treatment significantly increased AMF colonization in maize roots (+143%) and AMF hyphal length to a greater extent than did the vetch CC treatment. This suggests that species selection in cover cropping programs should consider not only biomass and weed suppression but also effects on the soil microbiota. Given their role in plant nutrient uptake and drought tolerance, enhancing AMF through targeted CC species selection can strengthen resilience in dryland systems.

5 Limitations of the study and future perspectives

This review focused exclusively on peer-reviewed original research based on replicated field trials, ensuring methodological robustness and minimising the risk of bias or low-quality data. However, we acknowledge that this approach may have excluded valuable insights from non-experimental studies, technical reports, or grey literature, which could further enrich our understanding of cover cropping practices in Mediterranean countries (Scordia et al. 2023).

Despite these constraints, we qualitatively synthesized the literature across the three most important Mediterranean agroecosystems (orchards, vineyards, and arable systems), highlighting the potential of grass CCs to support provisioning, regulating, and supporting ecosystem services. The main ecosystem services, risks and recommended practices for each Mediterranean agroecosystem are shown in Table 7. Overall, the selected articles in this review highlighted that grass CCs are effective at controlling weeds and improving soil physical properties in all agroecosystems, although specific trade-offs can be found. Water competition with cash crops is the most relevant risk in Mediterranean vineyards, thus suggesting early autumn sowing and mechanical termination with CC residues left on the soil surface as mulch to limit soil evaporative losses. N immobilization and low soil coverage are common in high-density and shaded orchards, especially in citrus groves; low CC seeding rates and the adoption of grass–legume mixtures are suggested to prevent N immobilization, especially in olive and almond orchards, whereas high CC seeding rates and permanent grasses are preferred for intensive groves. In the case of arable crops, the main trade-off is related to timing conflicts between the growing window of cash and cover crops, either when they are sown in intercropping with the cash crop or during fallow periods. Drill sowing to allow better CC establishment and early spring termination appears to be the most favorable management option in this situation.

Overall, these findings emphasize that the benefits of grass CCs are system-dependent and that careful species selection, residue management, and synchronization with nutrient demands are critical for maximizing both ecological and agronomic outcomes. From a practical standpoint, a key challenge for farmers is identifying grass CC species (or species mixtures or varietal mixtures) and agronomic practices that increase sustainability, particularly by reducing reliance on external inputs while maintaining productivity. Although no one-size-fits-all solution exists, the adoption of context-specific, locally adapted cover cropping strategies appears central to optimizing both ecological performance and farm-level outcomes.

Nevertheless, current evidence lacks long-term monitoring and consistency in measured outcomes, which are essential for assessing the multifunctionality and resilience benefits of grass cover cropping in these climate-sensitive regions.

6 Conclusion

This review aimed at consolidating the knowledge about the functional roles of grass CCs in the Mediterranean, identifying both knowledge gaps and potential drawbacks, in order to support the development of context-specific management options. The available literature on the topic highlights the role of grass CCs in delivering key ecosystem services across Mediterranean vineyards, orchards and arable crops, especially in improving SOC and SOM levels, enhancing soil structure and porosity, reducing soil compaction, runoff

Table 6 Examples of grass cover cropping applications in arable crops. % to control refers to the percentage difference between cover crops and non-cover crop controls

Cash crop	Climate	Soil texture	Control type	Ecosystem service	CC species	% to control	Reference
Maize	Bsk	Loam	Bare soil	Yield	Italian ryegrass	+44.9	Alonso-Ayuso et al. (2020)*
				Soil inorganic N		–64.6	
Cotton	Csa	Loam	Bare soil by herbicides	Weed biomass	Barley		Vasilakoglou et al. (2006)*
					Athinaida	–70.0	
					Thessaloniki	–46.2	
					Triticale		
					Niovi	–41.3	
					Thisvi	+35.0	
					Vronti	+91.3	
					Vrito	+80.1	
					Artemis	+38.8	
					Catria	–65.0	
					Rye		
					Albania	–55.0	
					Greece	–36.2	
					Germany	+76.3	
Bread wheat	Cfa	Silty-loam	Wheat following fallow	Yield	Sunn hemp-sorghum sudangrass mixture	–5.2	Egbedi et al. (2024)*
				Bulk density		–0.8	
				SOM		+29.0	
				Total C		+9.7	
				Total N		+12.6	
Cotton	Cfa	Silty-loam	Fallow following cotton	Yield	Winter pea-bread wheat mixture	+8.9	Egbedi et al. (2024)*
				Bulk density		–0.8	
				SOM		+3.4	
				Total C		–0.1	
				Total N		–9.4	
Soybean	Cfa	Silty-loam	Fallow following soybean	Yield	Winter pea-bread wheat mixture	+14.2	Egbedi et al. (2024)*
				Bulk density		–3.7	
				SOM		+11.4	
				Total C		+17.9	
				Total N		0.0	
Maize	Csa	Clay-loam	Bare soil	Yield	Barley	–15.9	Salmerón et al. (2011)*
				Soil inorganic N		–59.6	
Fallow following sunflower	Csa	Clay-loam	Bare soil	NO_3 leaching	Barley-hairy vetch mixture	–60.8	Tosti et al. (2014)*
Forage legumes	Csa	Clay	Legume monoculture	N_2 fixation	Ryegrass-fenugreek mixture	–19.3	Saia et al. (2016)*
					Ryegrass-hairy vetch mixture	–33.6	
					Ryegrass-Persian clover mixture	–65.7	
					Ryegrass-snail medick mixture	–35.0	
					Ryegrass-sulla mixture	–38.2	
					Ryegrass-squarrosum clover mixture	–35.4	

Table 6 (continued)

Cash crop	Climate	Soil texture	Control type	Ecosystem service	CC species	% to control	Reference
Bread wheat	Bsk	Not provided	Wheat monoculture	Yield	Red fescue + wheat cv. Isengrain	–12.0	Picard et al. (2010)*
				Yield	Red fescue + wheat cv. Scipion	–7.0	
Fallow following pepper	Csa	Sandy-loam	Bare soil by hand weeding	Yield	Oat + no tillage	+142.1	Radicetti et al. (2013)*
					Oat + minimum tillage	–25.9	
					Oat + conventional tillage	+2.9	
				Weed biomass	Oat + no tillage	–56.8	
					Oat + minimum tillage	–74.6	
					Oat + conventional tillage	–61.1	
Fallow following eggplant	Csa	Sandy-loam	Bare soil by hand weeding	$N\text{-}NO_3$	Oat	–19.9	Radicetti et al. (2017)*
				$N\text{-}NH_4$	Oat	+8.3	
				CO_2 emissions	Oat	+26.8	
Fallow following tomato	Csa	Sandy-loam	Bare soil by rotary harrow and glyphosate	Yield	Ryegrass + no tillage	–5.4	Campiglia et al. (2011)*
				$N\text{-}NO_3$	Ryegrass + no tillage	–5.6	
Maize	Bsk	Clay-loam	Bare soil	Mycorrhizal colonization	Barley	+53.6	Hontoria et al. (2019)
				Mycorrizal hyphae length		+143.4	

*Average of growing seasons; *SOM* soil organic matter

and nutrient leaching, and decreasing weed pressure. The magnitude of these effects is closely related to the amount of biomass produced, which, even in the water-limited regions of the Mediterranean, can reach significant average values, and to the quality of CC residues, mainly the C/N ratios.

These benefits are in line with many Sustainable Development Goals (UN 2015) of the United Nations, notably SDG 2 (target 2.4), SDG 12 (target 12.2), SDG 13, and SDG 15 (target 15.3). At the European level, the effects of grass CCs in the Mediterranean are in line with several *Green Deal* objectives (EC 2019), such as the *Farm2Fork* and *Biodiversity* strategies, as well as with the Common Agricultural Policy (CAP).

A clear message emerging from the literature is that species selection and management must be tailored to local pedo-climatic conditions and the target ecosystem services. For instance, annual species such as barley or spontaneous

Table 7 Recommended practices for grass cover crop use in Mediterranean vineyards, orchards, and arable systems

Agroecosystem	Recommended grass CC species	Key ecosystem services	Main risks/Trade-offs	Recommended practices
Vineyard	Fescue, spontaneous grasses	Erosion control, soil structure stability, weed suppression	Water competition	Early autumn sowing, mechanical termination
Orchard	Perennial grasses	Nutrient cycling, soil compaction reduction, weed suppression	N immobilization, low soil coverage in high-density and shaded orchards (e.g., citrus)	Low seeding rate in low-density orchards (e.g., olives), grass–legume mixtures
Arable	Oat, barley, and other annual grain cereals	Weed suppression, organic matter build-up, yield improvement	Timing conflicts	Drill sowing, early termination

grasses in minimum or no-tillage systems perform strongly in terms of weed suppression and erosion control in sloping vineyards. Perennial grasses are more suited to orchard systems with frequent machinery traffic and a need for permanent soil cover, while annual grain cereals in intercropping or relay-cropping with cash crops are commonly adopted for arable cropping systems. In many cases, mixing grasses with legumes (or other botanical families) often provides more ecosystem services across all Mediterranean agroecosystems due to their complementary effects. Nonetheless, a high level of technical knowledge is required regarding CC spatial arrangement, species combinations, and plant density ratios, as these factors critically determine the degree of species dominance within the cover cropping mixture.

Furthermore, if not well-managed, grass CCs may not adequately establish or may have detrimental effects on soil properties and crop yield, with differentiated effects based on the specific agroecosystem. For example, the ability of grasses to immobilize N can result in nutrient competition with the cash crop, especially in low-input orchard systems. In rainfed vineyards, the high transpiration rates and rapid development of grass CCs may intensify competition for water, potentially reducing cash crop yields if not properly managed. Competitive or allelopathic effects can also occur for arable crops due to timing conflicts between grass CCs and cash crops. These risks highlight the importance of site-specific temporal optimization (e.g., early autumn sowing, timely termination) to minimize interference with the main crop while maximizing service delivery.

Moreover, some consistent management patterns emerged. Practices such as drill planting and low or high CC seeding rates respectively for olive and citrus orchards, early sowing and mechanical termination for vineyards, species mixtures and early termination for arable crops, are frequently associated with enhanced outcomes across systems. However, threshold effects, such as the biomass level at which erosion control or weed suppression becomes effective, are rarely quantified, making it difficult to translate findings into operational guidelines. Consequently, more on-farm, multifunctional long-term (>5 years) studies are needed, performed across several soil types and rainfall regimes, which comprehensively assess multiple and standardized ecosystem services under a holistic approach. Such efforts are critical for informing evidence-based policies and management recommendations for farmers and stakeholders in water-limited and climate-vulnerable agricultural landscapes. Possible standardized indicators for ecosystem services provided by grass CCs include: (1) soil erosion rate, ground cover, aggregate stability, and runoff coefficient to assess erosion control; (2) macro- and micronutrient contents to evaluate nutrient cycling; (3) SOC and changes in SOC stocks to quantify C sequestration; (4) soil water content, infiltration rate, and water use efficiency to characterize water regulation; (5) greenhouse gas fluxes to assess climate regulation; (6) weed biomass, density, and suppression efficiency for weed control; and (7) CC biomass and cash crop yield for system productivity. Beyond these direct measurements, cash crops may also benefit indirectly, not only in terms of productivity but also in provisioning services. In particular, improvements in soil health and nutrient cycling may enhance the mineral and vitamin content, as well as the concentration of bioactive compounds in harvested products. These effects could also be associated with reduced reliance on synthetic inputs and increased recycling of nutrients derived from SOM mineralization, although such outcomes would need to be assessed over the long term.

In conclusion, this review highlights the potential of grass CCs as a tool for agroecological transition in Mediterranean agriculture. Realizing their full potential will require not only technical adjustments but also a deep understanding of CC traits that shape species interactions, along with participatory experimentation and integration with broader landscape and climate strategies.

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