agronomy

Review

Shifting from Tillage to Cover Cropping in Warm Climate Viticulture: Seeking the Optimal Balance

Harsh Tiwari, Ginevra Canavera, Francesco Pelusi and Stefano Poni *

Dipartimento di Produzioni Vegetali Sostenibili, Università Cattolica del Sacro Cuore, Via Emilia Parmense 84, 29122 Piacenza, Italy; ginevra.canavera@unicatt.it (G.C.)
* Correspondence: stefano.poni@unicatt.it

Abstract

Vineyard sustainability increasingly focuses on transitioning from traditional soil management practices, such as tillage and herbicides, to environmentally friendly methods like cover cropping and mulching. While this strategy works in cool climates with abundant rainfall, its application in warmer areas is not advisable due to potential disadvantages, such as water and nutrient competition from cover crops, which may outweigh the benefits. We examine the pros and cons of vineyard tillage, including data on evaporation rates from wet and dry tilled soils. We explore methodologies to quantify competition between vine roots and grass roots, focusing on distinguishing native versus spontaneous vegetation, duration and extent of cover cropping, species used in sown mixtures, and cover crop water use rates. Novel soil management practices are discussed as alternatives to traditional green manuring, such as mid-row rolling and sub-row sward mulching. The review updates recent approaches for establishing native or sown under-vine cover crops, which, with irrigation, might control native weeds while colonizing shallow soil, allowing grapevine roots to penetrate deeper, moistened soil layers. Promising grasses include creeping species such as *Glechoma hederacea*, *Trifolium subterraneum*, and *Hieracium pilosella*. Finally, we describe three soil management protocols: two suited to dry farm conditions and one involving blue water availability, which may mitigate cover crop competition for water and nutrients while maintaining benefits such as reduced soil erosion, increased soil organic matter, carbon sequestration, and improved machinery access.

Keywords: soil management; grass mowing; evapo-transpiration; vineyard mechanization; yield; grape composition; mulching

check for updates

Academic Editor: Tie Cai

Received: 12 August 2025
Revised: 8 September 2025
Accepted: 16 September 2025
Published: 23 September 2025

Citation: Tiwari, H.; Canavera, G.; Pelusi, F.; Poni, S. Shifting from Tillage to Cover Cropping in Warm Climate Viticulture: Seeking the Optimal Balance. *Agronomy* **2025**, *15*, 2245. https://doi.org/10.3390/agronomy15102245

1. Introduction

In recent times, the structure and health of vineyard soil have garnered significantly more attention than in the past, when the primary focus was traditionally on canopy management and vine efficiency [1]. The reasons for this shift are evident, with environmental concerns being of paramount importance. To highlight a few: (i) soil erosion poses a real and growing threat to viticulture worldwide [2,3], although its effects have been thoroughly characterized, particularly in Old European wine countries such as Italy, Spain, and France [4]; (ii) soil erosion is exacerbated by the repeated use of mechanical tillage, especially when rotating tools are systematically employed [5,6]; (iii) excessive tillage leads to a rapid reduction in soil organic matter (SOM) due to accelerated mineralization mechanisms [7,8]; (iv) recent studies have shown that soil microbial biodiversity impacts organic matter decomposition [9], nutrient cycling [10], pollutant degradation [11], mycorrhization [12], and resistance induction, while also potentially contributing to pathogenic infections [13]; (v) with its current 7.2 million hectares worldwide (https://www.oiv.int/), viticulture is a true "economic forest" with undeniable value in terms of carbon sequestration, with approximately 30% stored in the plant and 70% in the soil, according to [14].

If vineyard soil becomes a priority, four main techniques are available for its management: weeding, tillage, cover cropping, and mulching (Figure 1). Typically, soil management involves combining at least two of these techniques, with different choices made between the rows and along the row. A classic example is cover-cropping between the rows and cleaning under the row through tilling or weeding. The order in which we listed these four practices is not random; it represents a gradient of increasing appreciation. While cost-effective weeding with herbicides has its merits in challenging viticulture conditions, such as very steep slopes [15], the contamination of many surface and groundwater bodies following herbicide application is well documented [16,17]. With the progressive adoption of organic viticulture, the prohibition of widely used residual herbicides, and increasing consumer concern about chemical residues in food, herbicide application in vineyards is facing growing resistance.

Figure 1. In vineyards, four primary soil management techniques are employed: herbicides, tillage, cover cropping, and mulching. It is rare for a single technique to be applied across the entire vineyard; instead, two practices are typically used in tandem, differentiating between the actions taken for the between-row and in-row spaces. Images courtesy of the authors.

The next word in the list is "tillage," which has been the most prevalent floor management technique in vineyards from the early 1970s to the present. Operating under the premise that controlling native weeds is the primary objective of any soil management practice, tillage is considered "fast and rewarding," providing an immediate visual indication of a resolved issue. The adoption of tillage in vineyards has been accompanied by significant advancements in tractors and mechanical tools, which now offer great flexibility in adapting to even narrow row spacing and ensure efficient under-row strip cleaning, even with closely spaced vines, thanks to effective sensing devices. However, excessive tillage is now seen as a major contributor to poor soil structure, increased erosion, the formation of a plough pan, and rapid mineralization of SOM. In several field crops, the introduction of minimum or no tillage has sometimes been successful compared to conventional (deep) tillage [18,19]. However, when the terms "no tillage" or "minimum tillage" are applied to the vineyard ecosystem, some doubts arise. [20], in their study comparing the effects of conventional and minimum tillage practices on certain soil properties in a dryland vineyard in South Africa, specify that the "minimum" tillage group consisted of (a) a permanent straw mulch cover, (b) chemical weed control, and (c) a permanent cover of indigenous weeds frequently cut by a bush-cutter. A similar description is also provided in [21]. Thus, the impression is that "minimum" or "no tillage" are, in fact, synonymous with other well-known soil management techniques, applied either individually or in combination.

While [20] were among the pioneers in recognizing the need to reduce tillage in vineyards and simultaneously address concerns about the potential water use of a permanent sod, a significant impetus for transitioning from vineyard tillage to cover cropping has been provided by the approval of the "Eco-schemes" for 15 EU countries [22]. These schemes are poised to play a crucial role in the European Union's Common Agricultural Policy (CAP) post-2022, aiming to deliver environmental and climate benefits and enhance animal welfare. Eco-schemes are conceptually akin to the agri-environmental and climate schemes (AECS) of CAP Pillar 2, with participation being voluntary. A key distinction is that farmers are legally entitled to eco-scheme payments, whereas AECS payments are allocated through a competitive granting procedure. Among the environmental aspects targeted in the eight areas of action, the one most pertinent to our review is "soil protection" [23]. Soil protection is a focus in fourteen countries, with five placing particular emphasis on dedicated soil measures. The eco-scheme measures primarily aim to maintain soil cover through vegetation on arable land, exceeding the respective conditionality rules, and include measures to prevent erosion and non-ploughing requirements. Finland, Hungary, Latvia, the Netherlands, Poland, and Spain have plans for reduced or zero-tillage practices, such as direct seeding or strip tillage. In Italy and Spain, plant cover in interrows is supported to prevent erosion in vineyards, while in Romania and France, this applies to both vineyards and orchards, and in Austria, it extends to hops. In Latvia, Ireland, and Poland, liming on arable land based on soil sampling is an eco-scheme measure aimed at maintaining an agronomically optimal soil pH [22].

Driven by economic incentives, the shift from traditional tillage to vineyard cover cropping is evident in several key wine-producing countries. However, this transition presents inherent contradictions, one of which is particularly noteworthy: while the benefits of adopting a cover crop in vineyards are well-documented, a critical issue requires thorough examination and discussion. Introducing grasses, whether native or intentionally sown, into vineyards leads to increased consumption of water and nutrients. If this competition becomes excessive, it could significantly impair vineyard efficiency, rendering the transition unsustainable. Generally speaking, implementing a cover cropping solution in previously fully tilled vineyards significantly increases the complexity of the vineyard's overall water relations. This is because vineyard water management must also consider the dynamics of cover crop evapotranspiration (ET), which can vary both spatially and temporally. Moreover, while there is a substantial amount of data available on vine and soil water status under different soil management practices, there is considerably less information regarding the water use rates of specific grasses. The forthcoming paragraphs will focus extensively on these crucial points.

The sequence of words defining current soil management practices concludes with "mulching," which, in our view, is the technique that encapsulates the most positive attributes of the others [24,25]. While the primary drawbacks of main tillage include promoting erosion and degrading soil structure and health, mulching operates in precisely the opposite manner. If the main concerns associated with extensive cover cropping involve competition for water and nutrients, mulching once again offers an effective solution. This leads to a perhaps naive question: given the multitude of benefits, why is mulching so infrequently adopted in vineyards worldwide?

The primary aim of this review was to succinctly summarize the advantages and disadvantages of tillage and cover cropping practices within the vineyard ecosystem. It then delves into a comprehensive analysis of the factors and methodologies that, in the context of adapting to hot climate viticulture, could facilitate a transition from tillage to cover cropping. This transition would ideally retain some of the objective benefits of light tillage while fully embracing the well-known advantages of cover cropping.

2. Vineyard Tillage: Pros and Cons

The general advantages and disadvantages of the tillage practice are summarized in Table 1 and discussed in greater detail in [21,26]. Examining the interaction between tillage and vineyard behavior within the context of climate change presents a rather contradictory picture.

Table 1. Overview of the main benefits and drawbacks of implementing soil tillage or cover cropping in vineyards. For each item, pertinent references are indicated.

Soil Tillage		Cover Cropping	
Pros	**Cons**	**Pros**	**Cons**
➢ Eliminate weeds [27–29] ➢ Break up soil cracks [30] ➢ Alleviate compaction layers [20,31,32] ➢ Incorporate fertilizers [26,33] ➢ Enhance soil water infiltration [34,35] ➢ The frequency of interventions is dictated by weed growth [36] ➢ Disrupt the habitat and life cycle of soil borne pests [37–40] ➢ Effortless and gratifying—rewarding for the worker [21]	• Deteriorated soil structure [32,41,42] • Erosion (considering texture, slope, and length) [5,6,43–47] • Compaction soil layers [31,48–51] • Depletion of organic matter [7,8,52,53] • Vine health issues (such as wounds and trunk diseases) [25,26,54] • Carbon footprint and associated costs [55–58] • Obstacles to machinery access [59]	➢ Prevention of erosion and landslides [6,60–64] ➢ Reduce runoff and nitrate leaching [63,65–68] ➢ Improved soil structure [32,41,69] ➢ Higher SOM and soil biological activity [7,70,71] ➢ More regular water infiltration rates [72,73] ➢ Better fine root development [74–76] ➢ Facilitated machinery access [32,59] ➢ Increased biodiversity [77–80] ➢ Reduced splashing of soil borne spores [81,82] ➢ Improved grape composition [25,83–86] ➢ Conducive to ecosystem services [78,87,88] ➢ Hosting pest predators or antagonists [89–93] ➢ Control vine vigor—reduce rot [93–96] ➢ Control vineyard surface heating [97–99] ➢ Increase soil C sequestration [57,100–102]	• Competition for water [72,84,103–107] • Competition for nutrients [84,108–110] • Decrease vine yield [86,103,111,112] • Hosting pest vectors or alien species [90,113] • Increase susceptibility to spring frost [41,93,114–116] • Temporary winter cover cropping might hinder machine transit in spring [87,93]

On the downside, it must be acknowledged that during unusually wet spring seasons, particularly under organic management where fungal defense relies on copper and sulfur, bare or tilled soil can hinder access to the vineyard alley, leaving canopies unprotected [117,118]. In cases of severe and uncontrolled downy mildew outbreaks, not only might the current season's yield be compromised, but the next season's crop could also be affected due to unaided bud induction and differentiation. It is also well established that from vine bud burst to flowering, most of the primary inoculum of both air- and splash-borne fungi (such as grey mold, downy, and powdery mildew) is transferred from the ground to vine foliage [81,119]. In a specific trial examining the effects of primary inoculum of *Botrytis cinerea* conidia due to rain splashing under different vineyard soil management techniques [81], found that in bare soil plots, 71.5% of the sample area was impacted by raindrops, which was higher than in plots with cover crops of 30 and 60 cm in height (38.2% and 39.2%, respectively), and especially higher than the 90 cm tall cover crops (18.6%). It is also quite well established [120] that soil invertebrates influence many aspects of vineyard management, from pest control to their role as ecosystem engineers, making them ideal indicators of the vineyard agro-system [121]. In their work, Sharley and Thomson provide evidence that cultivating the interrow reduces the abundance of invertebrates: specifically, out of the eight isolated species, three groups (ants, millipedes, and centipedes) were severely curtailed. A somewhat similar conclusion was drawn by [122], who pointed out that vineyard ant communities benefit from inter-row vegetation and/or the absence of soil disturbance, although partial interrow tillage of vineyards may be tolerated and even benefit several species.

Returning to vineyard management, the practice of running tilled interrow around harvest time has become increasingly unsustainable, particularly when mechanical harvesting is anticipated. The shortage of human labor during picking times is exacerbated by the fact that, due to global warming, harvest dates are becoming more compressed, necessitating a significant workload within a relatively narrow time frame [123]. This situation is significantly driving the shift towards mechanical harvesting. Overrow machines typically operate in the interrow soil band, and a tilled, wet surface could render the operation impractical.

On the positive side, examining the impact of vineyard ground management on the presence and activity of entomopathogenic nematodes (EPNs) and related soil organisms, Ref. [38] found higher EPN numbers or activity rates in cover crops compared to bare soils (i.e., conventional tillage). It is also well established that tillage can effectively control vineyard infestations by the grape berry moth (*Paralobesia viteana* C), a major vineyard pest that overwinters as pupae in leaf litter on the vineyard floor. In a sophisticated study by [124], it was demonstrated that the survival rate of pupae collected from the vineyard immediately after tillage and held until emergence was not significantly different from those collected from an untilled control area, suggesting minimal mechanical damage to this pest. However, a single pass of the tillage implement buried three-quarters of the pupae under at least 1 cm of soil.

Managing the soil cover and row middles in a vineyard can greatly influence vineyard temperatures during a frost event, and effective weed control can significantly impact these temperatures [125]. Traditionally, it has been advised against using cover crops in frost-prone vineyards. The guidelines suggest keeping soil surfaces bare, tilled, and irrigated to darken them, thereby absorbing more heat from the sun during the day and releasing it at night, providing up to 0.6 °C to 1 °C of protection [126]. Given that the minimum temperature damage threshold for green tissues generally ranges between −1 and −2 °C, depending on their developmental stage and hydration level, the protection mentioned above can be crucial in preventing severe damage. This underscores the importance of maintaining a weed-free soil surface during frost events [127].

The role of traditional tillage in modern vineyards is evolving, particularly under the influence of global warming, and its portrayal as a sort of "unwanted evil" likely needs reconsideration. Specifically, the role of tillage should be re-evaluated in terms of its impact on vineyard water and nutrient dynamics. Additionally, an analysis is necessary to determine how tillage might contribute to maintaining vineyard efficiency, which involves achieving maximum yield at the desired quality while minimizing production costs.

3. Tillage, Vineyard Water Relations, and Vine Balance

Dry-land farming, also known as "aridoculture," encompasses all strategies designed to enable cultivation in arid environments, characterized by the absence of irrigation and low rainfall [128,129]. A key aspect of dry farming is repeated tillage, which involves three main processes: (i) eliminating soil water evaporation from native or sown cover crops; (ii) enhancing rainfall absorption into the soil compared to untilled soil [32]; and (iii) reducing deep percolation and surface runoff by breaking up compact plough pans or cracks. The combined effect of these factors generally leads to the conclusion that soil moisture during the vineyard's vegetative period is higher in traditionally tilled parcels than in cover-cropped plots [35].

If global warming is indeed increasing the frequency and severity of meteorological drought events [130], then the "poor thinking" behind abandoning tillage seems unjustified. This is because water and nutrient competition from any grass cover could easily compromise vineyard efficiency. Even in instances where soil moisture was not directly measured, numerous studies confirm a robust outcome: vine vigor, productivity, and leaf function typically improve under a prevalent tillage regime compared to other floor management options [85,95,112,131].

The role of tillage in sustainable vineyard management varies significantly depending on pedoclimate and weather conditions. In cool and wet climates, where excessive vine vigor is a constant concern, maintaining tillage would be an unnatural choice. In such environments, the disadvantages of tillage are exacerbated, while its benefits, such as improved soil water storage and conservation, are unnecessary. In these scenarios, there are extreme cases where a native or sown cover crop is intentionally maintained under the trellis to control excessive vine vigor and enhance grape quality [94,132,133]. Conversely, in Mediterranean areas practicing dry-farmed viticulture, where irrigation is often unavailable or severely restricted by national regulations (e.g., in Italy and Spain), the impact of global warming raises the critical question of whether traditional tillage should regain some importance. There is a concern that a rapid shift in these districts towards cover crops, which are frequently established and managed unprofessionally, might lead to an unsuccessful wine business.

The effects of soil tillage on vineyard performance should be considered separately for the young training phase and the maturity stage. There is a clear consensus that aggressive weeds hinder the development of newly transplanted vine cuttings. Weed control under the row can be achieved through herbicides, mulching, or tillage. An intriguing study conducted during the training phase [134] of a GDC-trained cv Pignoletto vineyard in the Central Po Valley aimed to establish, in the fall following spring planting, five soil management treatments: full tillage (T), full permanent cover crop (CC), mid-permanent cover plus under-the-row tillage (CC-T), herbicides (CC-H), and plastic mulching (CC-M). As illustrated in Figure 2, by the end of the second vegetative season, T exhibited the highest canopy filling (57%), significantly surpassing the other treatments, with CC imposing the greatest limitation, which persisted into the third growing season. Notably, T achieved much faster canopy filling than the CC-T treatment, despite both sharing a tilled under-the-vine soil strip. Given the very young age of the vineyard, it is highly unlikely that the roots of the grapevines and the mid-row grass have already physically interacted, suggesting direct competition. However, it can be reasonably assumed that the water consumed by the alley grass during the spring and summer of the second season somewhat deprived the grapevine roots of a valuable water source, resulting in more restricted cane development. This gap between the two treatments persisted throughout the vineyard's maturity phase, with T achieving a yield of 4.61 kg/m compared to 4.08 kg/m recorded in CC-T (5-year mean). As a compensatory response, CC-T reached higher total soluble solids (TSS) at harvest: 22.1 Brix versus 20.5 in T [134]. In southern Australia, ref. [135] observed that young vines exhibited the same susceptibility to competition, whereas older vines, with their robust and well-established root systems, drew water from beyond the rooting zone of a wallaby grass cover.

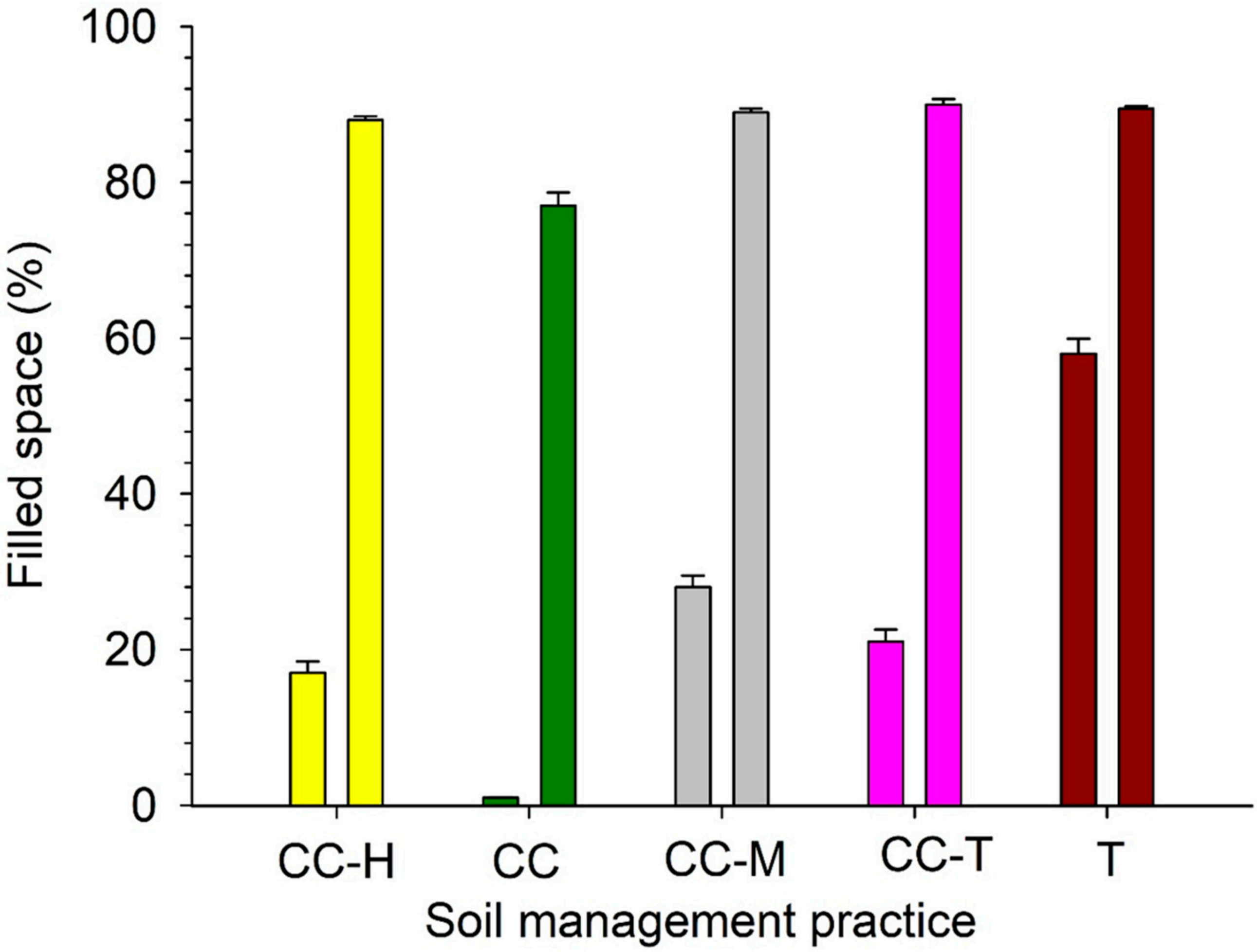


Figure 2. A vertical bar graph depicts the effects of five distinct soil management practices, defined as follows: CC-H (cover crop between rows and herbicides under row), CC = full cover crop, CC-M (cover crop between rows and plastic mulching under row), CC-T (cover crop between rows and tillage under row), and T = full tillage. These practices influence the fraction of filled space available on the supporting wires during the training phase of GDC training systems grown in northern Italy. For each treatment, the vertical bars on the left show the canopy filling recorded at the end of the second year after planting, while the bars on the right represent the filling fraction at the end of the third year of growth. Data are adapted from [134].

Recent studies have assessed changes in vine vigor and productivity under various soil management treatments, which involve different proportions of tilled soil relative to the total area. Data collected in France on Syrah [103] clearly demonstrate that an increasing proportion of tilled soil (specifically 0, 40, 70, and 100%) corresponds to a linear increase in both vigor and production. A similar outcome was observed in a trial conducted in a dryland vineyard in the Colli Piacentini, where increasing the proportion of tilled soil from 25% to 100% resulted in a linear increase in vine vigor. However, in this particular case, the effect on grape yield was somewhat less pronounced [136].

If the positive relationship between soil tillage and grapevine vigor is well documented, then the role that traditional tillage might still play in the context of global warming becomes even more pertinent. In fact, excessive vine weakening in warm to hot grape-growing areas is increasingly common, exacerbated by more frequent and severe summer droughts. It is recognized that one reason for such poor vine development is low organic matter content, which is further diminished by repeated tillage [7,53,70]. Additionally, it should be noted that untilled fine-textured soil, which in summer does not benefit from any root grass function—due to the cover crop being dry or absent—develops soil cracks, and soil compactness reaches a level where infiltration is compromised and surface runoff is exacerbated. In such circumstances, soil loosening with relatively shallow tillage seems more than appropriate. Moreover, suggesting a universally negative relationship between SOM and traditional tillage seems overly restrictive. In their review paper, Ref. [26] state that "boosting of SOM mineralization and nutrient release in plant-available forms" is a primary goal of soil tillage. To explore this, Ref. [137] tested over a six-year period the hypothesis that soil C and N mineralization kinetic parameters are higher in reduced tillage (RT) than in conventional tillage (CT) systems due to differences in soil disturbance and mixing. Their hypothesis was rejected, as RT systems exhibited lower soil cumulative C mineralization (20%), potential mineralizable C (17%), and rate constants for labile C (10%) compared to CT systems. Cumulative N mineralization was also lower (23%) in RT (20.7–34.3 $mg \cdot kg^{-1}$) than in CT (28.1–42.2 $mg \cdot kg^{-1}$). Therefore, particularly in organically managed vineyards where the use of promptly releasing inorganic N forms is prohibited, supplying organic matter or soil amendments followed by some tilling to promote mixing and/or burying for more rapid mineralization might be an effective strategy to support vine growth and yield potential. Additionally, the practice of green manure, which has medium-term positive effects on vine nutrition and health, anticipates a type of termination where tilling plays a crucial role [138,139].

Another aspect that has not been thoroughly explored is the dynamics of water evaporation from wet or dry soil. Conducting such measurements in a vineyard is challenging due to the lack of affordable commercial equipment capable of providing reliable short-term readings and the high diurnal variability. For instance, a specific soil area can quickly alternate between shade and sun, influenced by the interaction of sun position, training system, and canopy geometry. It is incorrect to assume that bare soil, simply because it lacks transpiring grass, does not significantly contribute to water evaporation within the vineyard ecosystem. More broadly, there is substantial evidence that water loss from the surface of wet soil is much higher than the evaporation rate from a pure water surface [140]. Figure 3 presents the diurnal time series of potential evaporation (PE) from lysimeter columns filled with saturated fine sand (s) and water (w), along with the average diurnal cycles. The time series of PEs and PEw differed in both absolute values and temporal dynamics. For PEs, approximately 78% of daily evaporation occurred between sunrise and sunset (~5:30–19:30), with the remaining 22% evaporating after sunset. Conversely, for the water lysimeter, nighttime evaporation exceeded daytime evaporation by about 5%. During the analyzed period, differences of up to 21% between the two average PE rates were observed. In summer, the diurnal cycle of PEw lagged almost 4–5 h behind that of PEs. The saturated bare soil and water columns differ in the following physical properties: (1) surface albedo, and (2) thermal properties, including variations in heat capacity, thermal conductance, and the depth of energy adsorption.

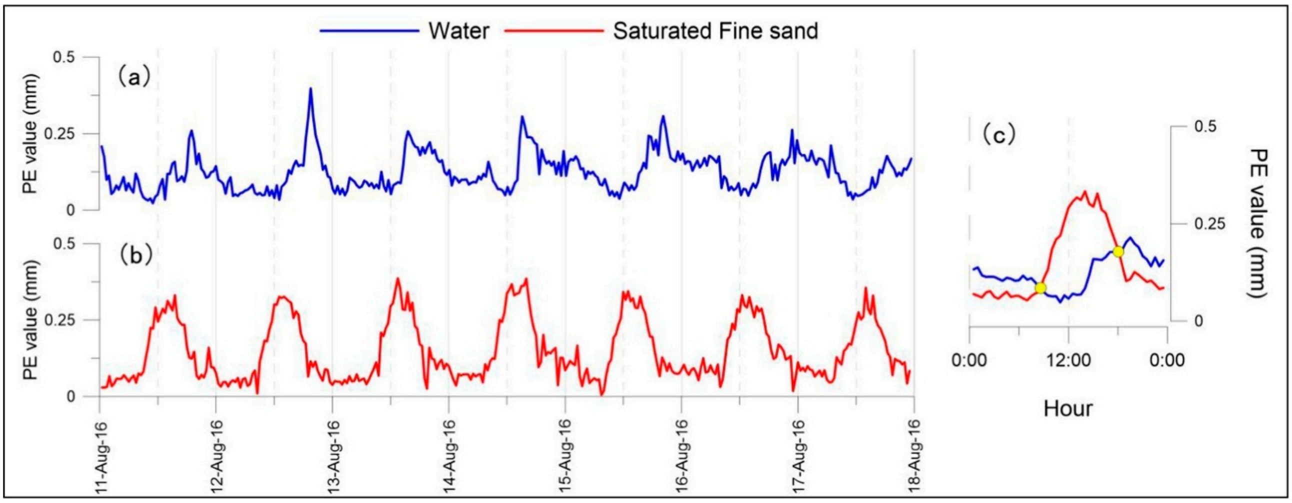


Figure 3. Diurnal time series (on the basis of half hourly data) of potential evaporation (PE) from lysimeter columns filled with saturated fine sand (s) and water (w), (**a**) PEw; (**b**) PEs; (**c**) the average diurnal cycles of PEw and PEs. Data taken from [140].

Despite the limited data on the amount and temporal dynamics of water evaporation from a bare (tilled) soil surface, it is reasonable to assume that both factors depend on (i) variations in resistance to evaporation due to differences in soil texture; (ii) the amount of energy available to drive the evaporative process (e.g., soil light interception depending on the time of day and interaction with the grapevine canopy); and (iii) the amount of water available for evaporation [141]. In bare, wet clay loam soil types, daily evaporation rates have been assessed to reach as high as 7.5 to 9 mm·d^{-1}, remaining around 4.5 to 7.5 mm·d^{-1} for the first six days of the experiment. Overall, the water loss trend from wet soil exhibits a typical exponential dynamic, indicating that 8–10 days after a wetting event, the water loss becomes negligible [141]. More recent data, shown in Figure 4, report diurnal trends of hourly water loss from tilled wet soil (WS) and tilled dry soil (DS), as well as for two grass covers, *Lotus corniculatus* and *Festuca arundinacea* [142]. Daily averaged ET values for WS were 5.43 mm·d^{-1}, while 9 days after the last irrigation event, it recorded a water loss of 1.2 mm·d^{-1}, representing a 78% reduction. Additionally, the loss from DS remained relatively constant throughout the day and did not correspond with air VPD, which peaked at 16:00, a time when ET was lower than the rate measured at 11:00 (Figure 4). Field measurements of evaporation rates on tilled bare soil using an open chamber system after two rain events (a condition similar to the WS treatment) were approximately 3.3 mm·d^{-1} [106], closely aligning with the daily average of 0.54 mm·h^{-1} observed in this study.

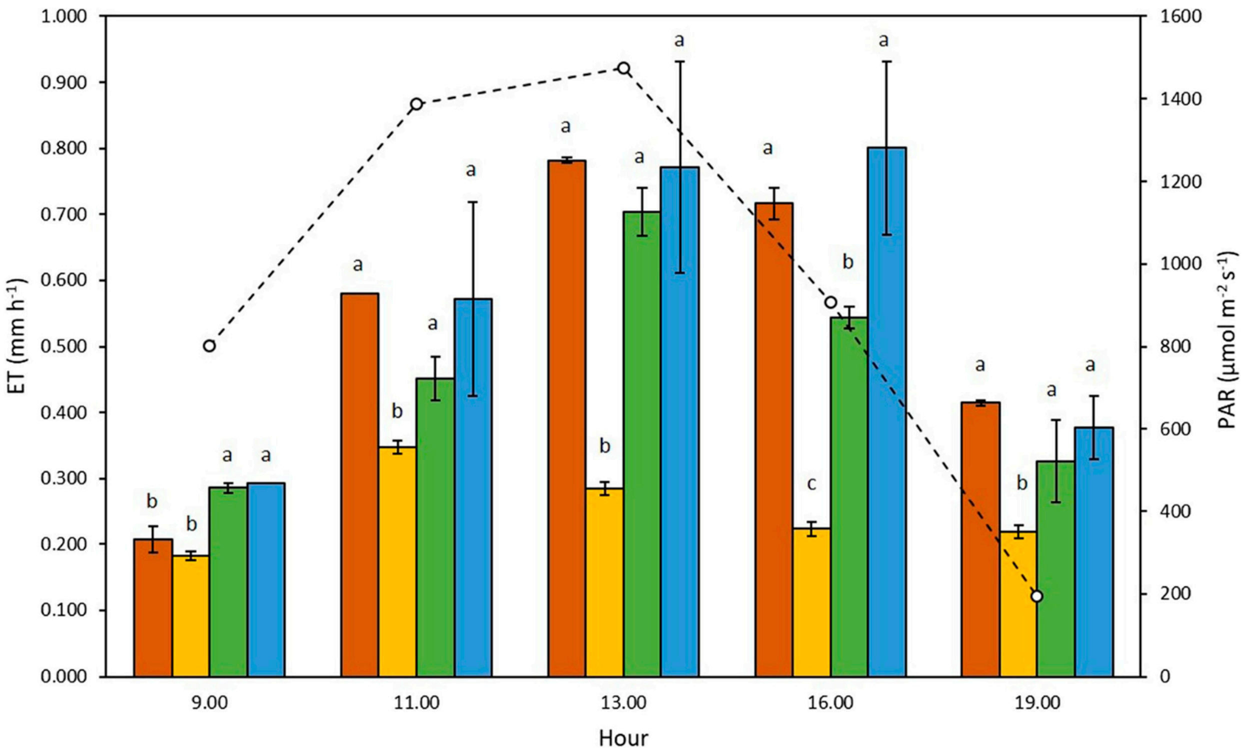


Figure 4. Diurnal trends of evapotranspiration (ET, mm h^{-1}) from wet bare soil (brown), dry bare soil (orange), *Festuca arundinacea* cover (green), and *Lotus corniculatus* cover (blue). Open circles indicate hourly PAR (µmol m^{-2} s^{-1}). Data were collected on 23 July. ET are means ± SE (n = 3). For a given hour, different letters indicate significant differences among treatments (SNK test, $p < 0.05$). Data refer to pot conditions and are extrapolated from [142].

4. Vineyards Cover Cropping: The Central Issue of Grass vs. Vine Competition

The primary advantages and disadvantages of using cover crops in vineyards have been thoroughly examined in several review papers [25,29,41,76,77]. Consequently, we will limit our discussion to the summary shown in Table 1. When implementing a cover crop in a vineyard, the optimal approach is to maximize benefits while minimizing or eliminating any drawbacks. Achieving this largely depends on the type of cover cropping, which can vary based on several factors: origin and floristic composition (i.e., native or intentionally sown by farmers), spatial extent (i.e., entire vineyard or a portion), and temporal duration (i.e., permanent or temporary/seasonal).

When deciding between native (spontaneous) vegetation and a sown cover crop, it initially seems like a non-issue: the predominant practice in vineyards today is to maintain spontaneous vegetation in the interrow spaces through periodic mowing [86]. This method is undeniably accessible and cost-effective. However, native grass can also compete intensely with the vines for water and nutrients [143], and if it remains permanent, it can absorb most of the occasional summer rains in Mediterranean countries, thereby reducing water uptake by vine roots. Although direct assessments of water use by different grass species are scarce in the literature, ref. [144] provided data from Geisenheim (Germany), showing that the water use of the native aggressive *Malva neglecta* can reach 4.45 mm·day^{-1} compared to 0.7 mm·day^{-1} for a *Festuca rubra* cover, a species with a relatively shallow root system. In a recent study conducted in the Colli Piacentini area (northern-central Italy), Ref. [136] found that a permanent native grass can consist of up to 34 different species, with the most abundant belonging to the Asteraceae, Convolvulaceae, Poaceae, and Polygonaceae families, many of which exhibit traits of high competitiveness. A comprehensive paper [145] addresses the assessment of soil threats in various vineyard sites located in the Colli Piacentini and Oltrepò Pavese wine districts. These threats include erosion, low organic matter, soil compaction, hard pan, contamination, summer drought, low biodiversity, and waterlogging. The study evaluates the impact of soil mitigation (SM) solutions, which involve a sown cover crop in mid-rows with the slashed sward either left on site or piled beneath the row or in temporary winter grassing followed by green manuring. In all instances, this transition improved vine performance compared to tillage and native grassing. A SWOT analysis revealed that while these SM solutions are well-received by growers, they remain hesitant to incur additional costs for implementation. The total ecosystem service benefit was estimated at 1454 EUR·ha^{-1}, with soil erosion containment contributing 700 EUR·ha^{-1}.

If converting native vegetation to a sown, less competitive grass does not appeal to farmers—despite the challenge of finding official statistics, it is known that in Italy, approximately 98% of vineyard grassing relies on native vegetation due to its simplicity, readiness, and cost-effectiveness—then mitigating competition with the associated vines depends on two factors: (i) periodic mowing, which is expected to limit grass water use over a certain time period, and (ii) reducing the fraction or duration of soil covered by grass to increase the weedless area. While the first factor will be discussed in the next chapter, the latter involves the challenging decision of maintaining a partial or temporary cover crop that offers acceptable competition with the vine.

Moreover, the decline in grapevine growth and yield attributed to cover cropping has been found to intensify with the extent of soil coverage by a permanent cover crop [103,146–149]. At a high-rainfall site in western Australia, altering the width of a perennial/annual cover crop mix significantly affected vine vigor and yield [135]. An inverse relationship was noted between vine vigor and cover crop width. Maximum vine vigor occurred in the absence of a cover crop, while vigor diminished with cover widths of 1.6 m and 2.4 m in the mid-row, where they competed for soil moisture. Ref. [147] conducted an impressive 17-year study comparing the effects of fully bare soil (treated with herbicides) and a grassed treatment with over 50% permanent cover. They observed a significant reduction in the number of vine roots in the interrow, particularly in the upper soil layers, but an increase near the row. Under permanent grass cover, there was an increase in organic matter, nitrogen, exchangeable K, pH, and soil moisture at field capacity, while bulk density and soil mechanical resistance decreased. In a study comparing bare soil with partial and complete permanent native grass in Chardonnay grown in Australia, Ref. [148] found that increased floor cover reduced water and nutrient availability to the vines. This reduction in soil moisture was linked to a significantly diminished uptake of nutrients, particularly nitrogen. The extent of this effect was site-dependent, with sward-vine competition for water being more severe in the dry, hot climate of Wagga Wagga compared to the cooler Tumbarumba site. Floor covers altered canopy architecture and reduced vine vigor and yield at both sites, but only after treatments had been in place for two or three years. Notably, at Wagga Wagga, the yield reduction in the complete cover crop treatment was 45.8% compared to the bare soil plots (four-year means).

The competition intensity between cover crops and grapevines is multifaceted, shaped by factors such as climate, soil depth, the extent of soil coverage by the cover crop, cover crop biomass, and the duration of cover cropping. Assessing the competition level between grapevine and grass root systems involves two main challenges: first, enhancing the current knowledge of the physical and chemical interactions when both root systems occupy the same soil space, and second, identifying the methods available to evaluate this competition.

In the realm of root-to-root interactions, it is widely recognized that differentiating between allelopathic effects and resource competition presents a significant challenge [25].

Festuca arundinacea, a frequently utilized cover crop, has demonstrated allelopathic effects when paired with certain woody plants [150]. However, in studies examining the allelopathic effects of winter cover crops on the growth of the grapevine rootstock 'VR043–43′, the most pronounced effects were noted with the extract from the aerial part of corn spurry (*Spergula arvensis* L.), followed by the aerial part of dandelion (*Taraxacum officinale* L.) [151] Overall, the limited research available indicates that allelopathy between grapevine and grass root systems is not a significant factor.

Conversely, numerous studies have focused on assessing the competition for resources between grapevines and associated grasses [86]. These investigations aim to understand the interactions that occur when the roots of these two species encounter each other and must determine the most beneficial strategy. It is crucial to differentiate between scenarios where both grapevine and grass roots occupy the soil strip beneath the trellis and situations where grapevine roots encounter grass roots during their lateral growth in a weed-free strip under the row, achieved through tillage, mulching, or herbicides.

In the first scenario, where competition is more immediate and intense, research indicates that grapevine roots tend to grow deeper but exhibit reduced longevity, a smaller proportion of fine roots, and a decreased total root length per unit of soil volume [104,152,153]. However, recent research conducted in South Australian vineyards [154] has demonstrated the potential of establishing under-vine coverage through spontaneous vegetation. In the long term, compared to the application of herbicides, this approach has enhanced the vineyard agro-ecosystem by improving soil phosphorus, water infiltration, and soil organic carbon [155], with minimal impact on yield and, at times, improved grape quality. In similar environments, comparable results were observed when under-vine management strategies, including straw mulch, herbicides, legume and grass mixes, fescue, and cocksfoot, were compared [156]. Notably, seed blends that included Medicago species significantly enhanced soil health without causing major yield constraints.

In the second scenario, where grapevine roots gradually invade a soil volume densely populated by grass roots, studies suggest that grapevine roots once again tend to spatially avoid grass roots and grow deeper as they approach the area of root system interaction [72,136,157–160]. This behavior might be advantageous to some extent, as grapevine roots can access a moistened soil horizon, thereby mitigating the effects of summer drought. Moreover, such avoidance could be beneficial in "forcing" the vine root to grow and reside in a designated soil volume under the trellis, thus facilitating the allocation and uptake of water and nutrients.

Methodologically, most research has assessed the extent of resource competition between the two root systems indirectly by examining factors such as vigor, vine capacity (including pruning weight or total leaf area), yield, and grape composition [25,77]. However, a more precise evaluation can be achieved by directly measuring gas exchange in grass and grapevine leaves or canopies, with a particular focus on water use variables. Due to methodological challenges, data on gas exchange measurements for cover crops remain limited. The study by [144] utilized a standard leaf cuvette from a portable gas exchange system, which is somewhat impractical for cover crop measurements. Recent advancements have led to the development of larger, self-constructed chambers that can be placed on the ground to increase the measured surface area for both tilled and grassed soils [161,162]. Additionally, a new low-cost, closed-type device has been designed for rapid cover crop measurements (Figure 5). In the realm of grapevines, evaluating the physiological effects of various soil management techniques often depends on individual leaf measurements of water status and gas exchange. However, extensive research spanning eight years in Australia [159] and four years in Italy [136] has revealed that, despite notable differences in vigor, yield, and the final composition of grapes, changes in single leaf water status and gas exchange were relatively sporadic and/or inconsistent. Previous studies have effectively shown that even precise single leaf sampling may not accurately represent the entire canopy level due to the complex interactions (such as age, light exposure, and health status) that a group of leaves inevitably initiates [163–165].

Figure 5. (**Left**) A schematic illustration of the components of a closed-type chamber used for evapotranspiration readings from soil portions. (**Center**) A measurement being taken on a section of bare soil. (**Right**) A measurement being taken on a cover crop grown in a pot. Images courtesy of the authors.

A study employing a novel approach, which involved planting vines with "split" roots in two pots and measuring gas exchange across the entire canopy, is depicted in Figure 6 [105]. This research aimed to achieve three primary objectives: (i) to "simulate" under-row grass cover with varying levels of competition that develops alongside the vine during its first year after planting; (ii) to quantify how this pre-treatment affects growth and photosynthetic functionality in the second year; and (iii) to determine the time required for the vine to recover from this "competitive shock" once the antagonism is removed, such as by clearing the sod with herbicide.

Figure 7A illustrates the first point, showing that when vine vigor—measured by total, main, and lateral pruning weight—is plotted against the amount of mowed dry biomass from treatments described in Figure 7B, there is a notable decrease in each vigor component. Interestingly, the treatment involving one pot cultivated and one with FA ground cover exerts a competitive effect nearly equivalent to that of both pots sown with the more "docile" *Festuca ovina* (FO) (Figure 7B). This pre-conditioning is dramatically reflected in the canopy's photosynthesis rate measured the following year (Figure 7C), which, between DOY 155 and 178 (4–27 June), decreases almost directly in proportion to the extent of ground cover (none, one, or both pots) and the type of management (cultivated or covered with FA and FO). Specifically, the percentage reduction of NCER/vine was 27% (GT-FO), 35% (GT-FA), 49% (GG-FO), and 73% (GG-FA). When competition is suddenly removed by weeding at GG 182 (1 July) (Figure 7C), after about 50–60 days, all treatments that were totally or partially covered show a recovery in photosynthesis that even surpasses the values reached in the cultivated control. Finally, this work highlights an important general finding: it is evident that when turf competition against the vine is strong, WUE also falls dramatically (Figure 7D); when competition is alleviated or removed, WUE rises. The reason for this mechanism seems intuitive: under strong competition, photosynthesis is limited by two main factors: (i) the formation of leaves with lower photosynthetic potential and (ii) water and nutrient competition. Meanwhile, under competition, transpiration is limited less than proportionally compared to photosynthesis because it is primarily controlled by the vapor pressure deficit (VPD).

Figure 6. (**A**) A close-up of a vine newly positioned in spring 2020, with its root system divided between two adjacent 40 L pots; (**B**) a photograph taken on 1 July 2020 shows the full establishment of the cover crops sown on 7 May; (**C**) an image captured a week after herbicide application, where the red arrow points to a vine previously grassed with *Festuca arundinacea*, clearly illustrating the vine's very stunted development. The green arrow indicates a vine under the GG-FAs treatment, where the newly sown cover crop is beginning to establish; (**D**) a detail of the herbicide's effect. Data taken from [105].

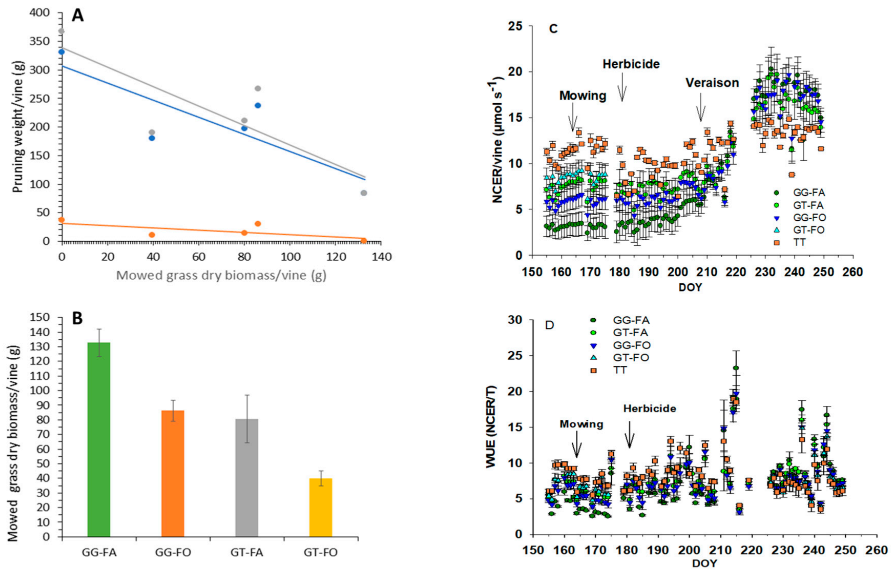


Figure 7. (**A**) Linear regression between mowed cover crop dry biomass (g) per vine (x) and main (blue), lateral (orange), and total (grey) pruning weights per vine. Linear regressions were all significant at p = 0.01 and had the following equations: $y = -0.2028x + 31.76$, $R^2 = 0.46$ (lateral pruning weight); $y = -1.5046x + 307.4$, $R^2 = 0.71$ (main pruning weight); $y = -1.7073x + 339.2$, $R^2 = 0.69$ (total pruning weight). (**B**) Data means ($n = 3$) of mowed cover crop dry biomass (g) per vine in the 2020 treatments. Hand mowing at 4 cm height was performed 19 August 2020 (DOY 231). (**C**) Net CO_2 carbon exchange rate (NCER) per vine daily monitored in 2021 on GG-FA, GT-FA, GG-GO, GT-FO, and TT treatments from DOY 155–175 (first experiment) and DOY 169–249 (second experiment). Each daily NCER derives from dawn to dusk averaging of instantaneous values. Arrows indicate dates of cover crop moving and herbicide application. Daily NCER/vine means ± SE are calculated on the three vine replicates per treatment. (**D**) Canopy water use efficiency (NCER/T) monitored in 2021 on GG-FA, GT-FA, GG-GO, GT-FO, and TT treatments from DOY 155–175 (first experiment) and DOY 169–249 (second experiment). Data taken from: [105].

5. Cover Crop Water Use

Designing a vineyard ecosystem that integrates cover cropping while minimizing competition for water and nutrients necessitates at least two levels of information: (i) Understanding the water use rates of the main species and cultivars under various environmental conditions. This objective, in turn, highlights the need for equipment capable of providing fast and reliable readings of soil/cover crop ET. (ii) Regardless of whether the vineyard grass is native or sown, the primary method to limit its water use is periodic mowing. Therefore, quantifying the water savings achieved through this practice is essential. Successfully addressing these two goals allows for the precise tuning of the seasonal water balance in a vineyard ecosystem, based on the following components: (i) soil evaporation; (ii) transpiration due to the amount of light intercepted by the canopy; and (iii) transpiration related to the presence of a grass cover [166–168].

There are various methods for measuring evapo-transpiration (ET) fluxes from a soil section, whether bare or covered with grass, each offering its own advantages and limitations. One method to determine cover crop ET is through gravimetric analysis using a mini-lysimeter (ML). This approach serves as an alternative to field lysimeters and is particularly useful in confined spaces, such as those between vine rows [169,170]. An ML consists of a container filled with a soil core, covered with vegetation identical to that of the surrounding area, and inserted into the ground until it is level with the adjacent soil surface. These containers, which can be plastic pots [106], must have holes at the bottom to allow water drainage. In this method, MLs are irrigated, and after allowing time for excess water to drain, they are weighed multiple times over the following days. The reduction in mass between weighing is attributed to ET.

Micrometeorological techniques, such as eddy covariance, offer alternative methods for measuring cover crop ET. These techniques have the distinct advantage of allowing continuous measurements without disturbing the field's micro-environment (i.e., an indirect method) [171]. However, this approach is not suitable for small-scale experiments. In contrast, chamber enclosure remains a non-invasive technique for small-scale measurements [172]. In this method, a transparent chamber is placed over vegetation or soil, and gas fluxes are estimated by observing changes in gas concentrations within the chamber. Typically, chamber methods are divided into two categories: closed and open chambers [173,174].

In an open chamber, gas is continuously pumped in and out through openings, and the difference in water vapor concentration between the chamber's inlet and outlet is measured to determine the ET flux. These measurements can be taken continuously over a period ranging from a few days to the entire growing season. However, complex systems are necessary to maintain the micro-climate inside the chamber reasonably close to ambient conditions [175,176]. Additionally, the portability of open chambers is usually limited, and the airflow supplied to the chambers must be carefully measured [177]. Although [161] successfully used an open-chamber system to determine the water use of *Festuca arundinacea* in a vineyard, a closed chamber has been designed to better meet portability needs [178,179], allowing it to be quickly moved among various sampling locations in the field. A closed-chamber system estimates gas fluxes by measuring the rate of change in gas concentrations within the chamber air over a short period while the chamber is sealed. To minimize changes in the canopy micro-climate induced by the chamber, rapid measurements for brief periods (i.e., about 1–2 min) should be employed [179].

A groundbreaking piece of equipment has recently been introduced and patented by [142], employing an Internet of Things (IoT) approach. This small, closed-type chamber (Figure 5) exhibited a remarkably close linear relationship between gravimetric and chamber values during both laboratory and outdoor calibration runs, with R^2 values of 0.96 and 0.99, respectively, within the ranges of 0–0.8 mm h^{-1} (lab) and 0–23 mm d^{-1} (outdoor). The optimal measurement time window was identified as 60 s after "time zero," which is set 15 s following chamber positioning.

Under all conditions, chamber heating never exceeded 2 °C above the air temperature. The true innovation of the proposed device lies in its IoT application, as the total cost of the necessary components does not exceed 200 euros. Its compact size and flexibility make it an ideal tool for rapid multipoint readings of soil and grass water losses in the field.

Primarily due to limitations in equipment availability, portability, and flexibility, the dataset on grass water use is indeed not extensive. Water consumption is influenced, on one hand, by each species and cultivar's ability to produce a certain amount of fresh biomass or transpiring surface area within a given timeframe, and on the other hand, by the specific transpiration rate. The most recent and largest dataset [180], utilizing the new closed-type chamber unit on 15 cover crop species grown in pots, has demonstrated a linear increase in cover crop ET with LAI up to about 6–7, after which it tends to saturate (Figure 8). This finding leads to a practical recommendation: particularly when the sward consists of a mixture of legumes, once the growth in height surpasses a certain LAI value (6–7 m^2 m^{-2}), the water loss through the sward does not increase proportionally and, in fact, tends to level off (Figure 8). If, as is often the case, the presence of legumes is associated with the use of green manure to enhance the soil's organic nitrogen supply through incorporation, the objective of maximizing biomass does not appear to conflict with the need to limit water consumption during temporary cover cropping.

Table 2. Aboveground dry biomass (ADB) clipped at the first mowing event, the corresponding leaf area surface index (LAI), and water use per leaf area unit (ET_{LEAF}) of all cover crops tested.

Cover Crop Group	Cover Crop Species	ADB ($g\ m^{-2}$)	LAI ($m^2\ m^{-2}$)	ET_{LEAF} ($mm\ m^{-2}\ day^{-1}$)
Legumes	*Trifolium michelianum (TM)*	750.0 a	12.4 a	1.81 d
	Medicago polymorpha (MP)	274.3 c	2.5 c	4.92 bc
	Medicago lupulina (ML)	503.3 b	5.1 b	4.05 bcd
	Medicago truncatula (MT)	641.2 a	5.4 b	3.40 bcd
	Lotus corniculatus (LC)	660.7 a	5.3 b	3.65 cd
Grasses	*Festuca arundinacea (FA)*	161.8 cd	1.5 cd	8.83 a
	Festuca ovina (FO)	48.4 d	1.0 cd	7.75 a
	Festuca rubra commutate (FRC)	125.3 cd	1.2 cd	8.54 a
	Poa pratensis (PP)	108.6 cd	1.3 cd	8.12 a
	Lolium perenne (LP)	106.8 cd	1.2 cd	9.22 a
Creeping	*Glecoma hederacea * (GH)*	89.6 d	0.8 cd	3.68 bcd
	*Hieracium pilosella * (HP)*	0.0 d	–	3.86 bcd
	*Dichondra repens * (DR)*	0.0 d	–	5.46 b
	Sagina subulate (SS)	0.0 d	–	–
	Trifolium subterraneum (TS)	23.2 d	0.2 d	2.74 * bcd

Within each cover crop group of five, lowercase letters indicate significant differences among species (SNK test, $p < 0.05$). * indicates ET_{LEAF} based on LAI estimated through photo analysis as creeping plants were not mowed.

However, if the data reported in Figure 8 are reconsidered, expressing water use not in relation to the LAI at maximum growth but rather per unit of leaf surface area (e.g., m^2) removed during mowing, the scenario changes significantly (Table 1). The three leguminous species, which are highly dissipative on a per soil unit basis, exhibit rates of 1.8–3.6 $mm \cdot m^{-2} \cdot day^{-1}$, whereas all the grasses increase to values between 7 and 9.5 $mm \cdot m^{-2} \cdot day^{-1}$. For instance, the figure for *Festuca ovina* (7.75 $mm \cdot m^{-2} \cdot day^{-1}$) is not markedly different from that for *Festuca arundinacea* (8.83 $mm \cdot m^{-2} \cdot day^{-1}$). This situation leads to at least three considerations of significant practical relevance: (i) with equal LAI, at least among the 15 tested species, the water consumption of a grass mixture is nearly double that of a legume mixture; (ii) among grasses, the tendency for transpiration—likely linked to leaf anatomy, stomatal density, etc.—does not vary much between species and thus responds almost linearly to the biomass formed (hence the greater dispersion for *Festuca arundinacea*); (iii) if allowed to grow freely, some legumes, under soil conditions that do not yet present water limitations, may, despite their relatively low specific transpiration rates, significantly deplete the usable soil water reserve due to the high biomass produced.

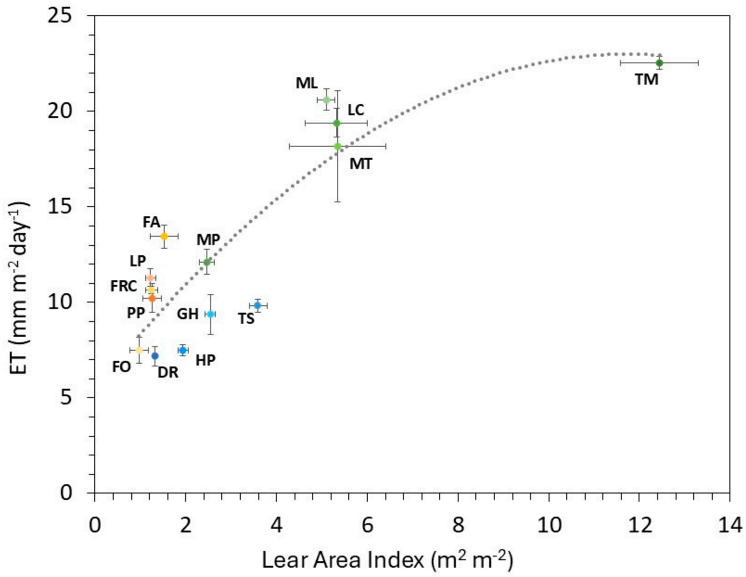


Figure 8. Quadratic regression of leaf area index (LAI, $m^2\ m^{-2}$) vs. cover crop evapotranspiration per unit of soil (ET, mm day^{-1}). Each data point is mean value ± SE (n = 4). The quadratic model equation is $y = -0.128x^2 + 2.9968x + 5.4716$, $R^2 = 0.76$. Data. Correspondence between cover crop label and full names can be found in Table 2.

The second item warranting significant attention is the extent and dynamics of water conservation following the mowing of cover crops. As noted by [135], during wet seasons, cover crops can be left undisturbed with a large leaf area. However, in dry seasons, mowing to remove leaves can effectively reduce cover ET. The height at which the crops are cut is crucial and not arbitrary: Ref. [181] found that cutting wallaby grass and weeping grass to 10 cm above the ground maximized both root and shoot biomass, whereas cutting to 2 cm diminished plant survival. In an inter-row sward of *Festuca arundinacea* var. barfelix, which had grown to about 18 cm in height, corresponding to an LAI of 5 $m^2\ m^{-2}$, mowing reduced the cover to approximately 5 cm in height (LAI = 2 $m^2\ m^{-2}$). This resulted in a reduction of the sward's transpiration by 29 to 45%, depending on the amount of dry biomass removed, which in this specific test ranged from 140 to 320 g m^{-2} [161]. The same study further indicates that, 19 days post-mowing, the sward's transpiration had already returned to levels similar to those before mowing [161]. Using the same 15 grass species described in Table 2, Ref. [180] evaluated the dynamics of water loss 4-day pre-mowing and 2, 8, 17, and 25 days post-mowing (Figure 9). The results highlight distinct behaviors among the three groups: within legumes, the drop in ET two days after mowing was significant, peaking at −73% in *Trifolium michelianum*. Even 25 days post-mowing, the ET reduction remained quite consistent, except for *Lotus corniculatus*, which had already returned to pre-mowing levels 17 days after the grass cut. Among grasses, the largest ET reduction two days after mowing (−25%) was observed in *Festuca arundinacea*. Subsequent samplings indicated that most grasses progressively recovered their water use, and data collected 17 days post-mowing confirmed that all GR had regained pre-mowing ET rates. The management of the five creeping species suggests that any canopy shortening is avoided until the cover begins to overflow the pot surface. This status was achieved only by *Glecoma hederacea* (GH) and *Trifolium subterraneum* (TS). ET data presented in Figure 8 and Table 1 strongly support the assumption that all CR species maintain good water-saving characteristics. For three of them (DR, HP, and SS), pre-mowing ET rates were slightly lower than those measured in the control, with less than 400 g $H_2O \cdot pot^{-1} \cdot day^{-1}$ used.

Gaining a better understanding of water usage rates from either native or sown cover crop species in vineyards enables the integration of this data into the vineyard ecosystem's seasonal water budget. One of the few studies that delineates these sources of water loss within a vineyard ecosystem is reported by [168] This three-year study, conducted in an Albariño vineyard in Galicia, Spain, utilized a spur cordon training system with 3 m spacing between rows and 1.5 m spacing within rows. The vineyard was maintained with permanent cover cropping between rows, with the grass cover mowed approximately four times per season. The study found that, on average over the three years, the total transpiration of the vineyard ecosystem was 392 mm/year, with contributions from soil, canopy, and grass cover accounting for 13%, 48%, and 39%, respectively. It is important to note that this research was conducted under non-limiting water conditions, as evidenced by the necessity of four mowings to reduce competition from the spontaneous grass cover.

A second example simulates the seasonal water consumption for three different locations in the Rheingau region of Germany, detailing separate entries for canopy transpiration, evapotranspiration from covered soil, and evaporation from bare (tilled) soil [182]. The vineyard known as ER (Ehrenfels) presents a particularly striking case with its steep slope, southern exposure, shallow soil, and row spacing of 2.5 m, of which 2.1 m are covered by permanent spontaneous grass. Under these conditions, the grass cover transpires the majority of the available water even before vine transpiration becomes significant. This can lead to early water stress in springs with little rainfall, affecting shoot growth and flowering. Additionally, in the ongoing effort to quantify the water consumption of various components within the vineyard ecosystem, mixed approaches are gaining traction. This involves integrating water balance modeling with high-resolution multispectral and thermal imaging to distinguish the water consumption of covered versus uncovered soil patches. In one such application [183]) conducted on a Bobal vineyard in the Valencia area of Spain, it was discovered that a mulching strategy reduced seasonal water consumption by 28% compared to a tilled control.

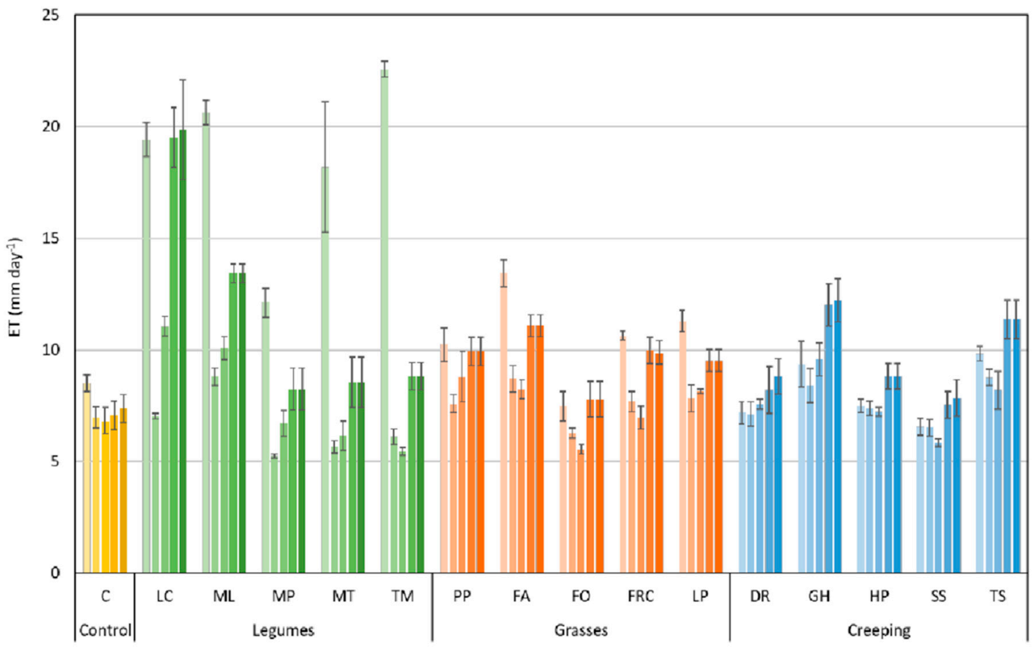


Figure 9. Vertical bars represent the daily water use as referred to unit of soil (ET, mm day^{-1}) for the bare soil (yellow) and all the cover crop species as divided into creeping plants (shades of blue), legumes (shades of green), and grasses (shades of orange). Evapotranspiration was measured through a gravimetric method before (i.e., −4 days) and at 2, 8, 17, and 25 days after mowing. Within each treatment, vertical bar sequence corresponds to progressive date of measurement. ET data are mean values ± SE (n = 4). Correspondence between cover crop label and full names can be found in Table 2. Data taken from [184].

The recognition that the annual water balance of the vineyard ecosystem must consider both major components—canopy and soil, with the latter potentially managed differently—has recently spurred even sophisticated methodological approaches [185]. In this study, conducted over two years in a covered vineyard in South Tyrol, methods such as eddy-covariance and direct measurements of grass cover and vine transpiration were combined to distinguish the evapotranspiration contributions of the canopy and the "under-canopy." Two main findings emerged: under specific climatic conditions marked by high seasonal variability, the fraction of transpiration attributable to the canopy accounted for 77–79% of the entire ecosystem's transpiration, averaging around 3.4 mm/day. Notably, after intense rainfall events, canopy transpiration was predominantly higher, while the contribution of the "under-canopy" component increased as drier conditions set in.

6. Planning a Vineyard for the Best Compromise Between Tillage and Cover Crops

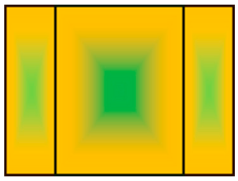
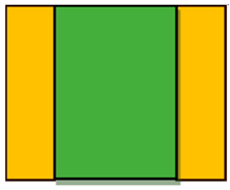
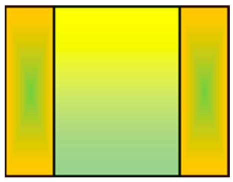
To limit the number of case studies, we will concentrate our hypotheses on warm-hot climates, specifically examining cases A and B (dry farming) and C (irrigation available). The first proposed protocol (A) is outlined in Table 3, which offers a schematic representation of the under-row and between-row areas, complete with appropriate color coding. Ideally, the annual time span is divided into three phases, each with its own rationale: (a) from mid-October to mid-April, it is highly recommended to have pre-emergence before the cold season, relying on microtherm species [186,187]. This strategy promotes a more robust and solid establishment by mid-April, when the spraying season against downy mildew typically begins. The first two weeks of April also present the highest risk for frost, and a soil featuring a mix of tillage and short grass might be a good setup. (b) From mid-April to the end of June, tractor passages may be frequent, and grass competition for water must be controlled to prevent early water stress, which could significantly impact the final yield. (c) From July to mid-October, the two months of July and August have a high likelihood of meteorological drought, necessitating minimized grass water use. During the latter part of this period, some regrowth is expected to facilitate harvest operations.

Table 3 also presents dynamic seasonal management strategies for both the between-row and under-row areas. Generally, the management of the between-row space is based on the ability of microtherm grasses to thrive in a temperate climate, exhibiting optimal growth rates between 15 and 25 °C. These grasses can endure harsh winter temperatures while maintaining their green color, although they may temporarily yellow in the summer. When protocol 1 is set for a dry-farmed environment and the between-row space is predominantly "grassed," the under-row management should adopt a more conservative approach to soil management. This involves primarily relying on light tillage, which allows for the growth of spotty native vegetation in the spring and fall, particularly when abundant precipitation increases the likelihood of surface runoff and erosion.

Protocol B (Table 4), designed for dry-farmed conditions, adopts a distinct approach by focusing on the sowing, growth, and termination of a temporary winter cover crop. Recent studies [93,188] have highlighted that the floristic composition, pedoclimate conditions, and termination dates are key factors influencing the advantages and disadvantages of this method. Implementing a sown winter cover crop in each alley often poses significant challenges to cultural practices, such as spraying and desuckering, before termination. It also increases frost risk and leads to substantial soil water uptake, potentially exacerbating summer drought. On the other hand, expected benefits include improved soil structure, reduced spore splashing from the soil to the vine, and enhanced nutrition, particularly when legumes are part of the mix. The method of termination is crucial, with interrow rolling or sub-row mulching serving as viable alternatives to the traditional green manure practice.

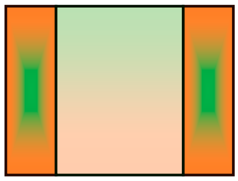
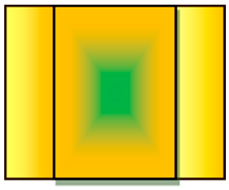
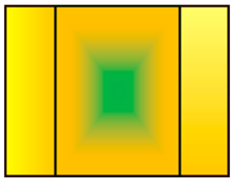
Case B, as outlined in Table 4, anticipates the adoption of the sub-row mulching method, where grass clippings are mechanically gathered under the row to create a permanent layer of dead, dry mulch. This approach, provided there is sufficient material placed under the row, offers an excellent natural solution for controlling native weeds. In Case B, the management of soil between the rows is quite dynamic, varying with the chosen termination type—tilled for GM, mulched for R, and short grass for SRM. The same applies to the soil management under the row, where the SRM option is preferred. This method represents a sustainable solution by implementing a natural mulch under the row, essentially reusing a vineyard by-product, the sward of the winter cover crop.

Table 3. Protocol of seasonal vineyard floor management based on the sowing, in the fall, of a blend of micro-term grasses. Conditions imply a temperate-warm climate and the absence of irrigation. Tillage = ; live grass cover ; dry grass cover . Combinations of two colors means co-existence of two different soil management practices.

Time Periods	Between-Rows	Under the Row	Notes	Color Codes
Mid-October–mid April	Mechanical sowing of a mixture of microtherm grass species such as *Agrostis stolonifera*, *Festuca rubra “commutata”*, *Festuca ribra “ribra”*, *Festuca longifolia*, *Lolium perenne*, *Poa pratensis*	Natural cover in winter and light tillage early March	Not less than 100 kg/ha to favor establishment and resistance to trampling	
Mid April–end of June	Sown cover firmly established	Light tillage	Allow vineyard access for spraying, eventual fertilizers application and for mechanical trunk desuckering	
July–mid October	Microtherm cover crop typically yellows and tends to partially re-establish early fall	Light tillage or allow short native crop	➢ It might favor grapevine roots to colonize deeper and moistened soil layers ➢ Limited water competition in summer	

Case C stands apart from the previous cases by scheduling the use of irrigation water (Table 5). This approach is notably original [156,189] as it involves intentionally cultivating an under-row cover crop with several advantageous characteristics: (i) rapid and dense growth to suppress the aggressiveness of other native weeds; (ii) development of a dense yet shallow root system that encourages spatial separation from the deeper grapevine roots; (iii) a perennial nature, eliminating the need for reseeding or new transplants; and (iv) low maintenance requirements. Managing such cover crops involves refraining from mowing until the cover extends beyond the under-row strip and begins to encroach on the alley.

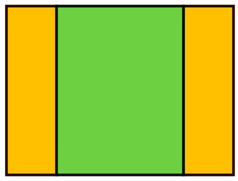
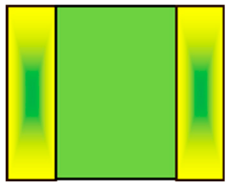
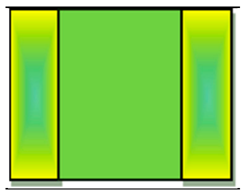
Table 4. Protocol of seasonal vineyard floor management based on the sowing, in the fall, of a temporary winter cover crop. Conditions imply a temperate-warm climate and the absence of irrigation. Tillage = ; live grass cover ; dry grass cover . Combinations of two colors means co-existence of two different soil management practices. * The sub-row mulching termination type is represented.

Time Periods	Between-Rows	Under the Row	Notes	Color Coding
Mid-October–mid April	Mechanical sowing of a balanced mix (grasses, legumes, and some Brassicaceae)	Natural cover in winter and light tillage early March	Not less than 80 kg/ha to favor establishment and resistance to trampling. Sowing one interrow every two is a viable option to allow machine transit for spring operations.	
Mid April–end of June *	Spring termination with three options: ➢ Green manure (GM) ➢ Interrow rolling (R) ➢ Sub-row mulching (SRM)	Light tillage or dead grass mulching depending on chosen termination	Type of termination provides flexibility in terms of ➢ Indirect N supply ➢ Water and nutrient competition with vines ➢ Amount of biomass for mulching	* 
July–mid October *	Depending on spring termination it can show up as ➢ Tilled (GM) ➢ Mulched (R) ➢ Short grass (SRM)	Light tillage or dead grass mulching depending on chosen termination	➢ It might favor grapevine roots to colonize deeper and moistened soil layers ➢ Limited water competition in summer ➢ Dead sub row grass mulching might partially invade from native grass	

This solution is also attractive under dry-farmed conditions. A recent study conducted in the Oltrepò Pavese wine district (Northern Italy) compared the speed of establishment and within-season durability of Glecoma hederaceae (GH) and Trifolium subterraneum (TS) covers against herbicides (H) and native grass (NG) control treatments in a mature Riesling vineyard (Pelusi et al., in print). While TS exhibited a progressive decline in active soil coverage (from 85% on 5 June to 6% on 23 October), indicating a gradual reduction in vegetative ground cover after the biomass dried down, GH achieved over 90% ground cover during the same period, surpassing the average soil coverage recorded in NG (around 86%). Notably, despite the slightly higher soil coverage, GH used 13% less water than NV and also demonstrated a shallow root system (root dry weight = 1.03 mg/cm3 at a depth of 0–10 cm), whereas NV showed greater rooting depth, with RDW peaking between 20 and 40 cm (0.49 mg/cm^3).

An even more extreme version of functional under-trellis cover cropping is presented by [154], who maintained undisturbed spontaneous under-vine vegetation for five years in two southern Australian irrigated vineyards (McLaren Vale and Eden Valley) for comparison with herbicide and cultivation treatments. Notably, yield per vine remained unaffected at both sites, while in Eden Valley, reduced vigor led to improved grape composition at harvest. At the same location, the spontaneous vegetation also altered the under-vine plant community, increasing the prevalence of perennial grasses compared to the higher proportion of broad-leaf, fast-growing species that tend to dominate under herbicide and cultivation treatments.

Table 5. Protocol of seasonal vineyard floor management based on allowing native vegetation controlled by periodic mowing between rows and sowing a creeping and suffocating cover crop under the row. Conditions imply a temperate-warm climate and the presence of irrigation. Tillage: ; live grass cover: ; dry grass cover: . Combinations of two colors means co-existence of two different soil management practices.

Time Periods	Between-Rows	Under the Row	Notes	Color Coding
Mid-October until mid April	Maintain native grass	➢ Sowing a creeping suffocating cover crop able to prevail, over years, over native grasses. ➢ Goal is to achieve a dense yet shallow root system with physical separation from the bulk of grapevine roots	➢ Suitable species might be ➢ *Glecoma hederacea, Hieracium pilosella, Trifolium subterraneum, Dactilis glomerate, Rytidosperma geniculatum, Medicago littoralis and Medicago truncatula, Festuca rubra and Trifolium fragiferum* ➢ Some species might need transplanting (e.g., *H. pilosella*)	
Mid April–end of June	Maintain native grass and control growth by moving (not less that 5 cm tall)	Assist growth with N, irrigation and perform hand removal of large size weeds.		
July–mid October	Maintain native grass	Assess fraction of soil colonization and evaluate option for re-seeding or thickening	➢ Allow heavy machinery transit for harvest	

7. Conclusions

Our investigation into techniques that could help find the optimal balance between vineyard soil tillage (e.g., cultivation) and grass covers (either native or sown) reveals several key insights:

- Under cool and wet growing conditions, the conflict between these two techniques is minimal. Cover crops offer numerous agro-ecological benefits and can serve as a vital tool for vine balance. They help control vegetative vigor, prevent excessive yields, and significantly enhance overall grape composition.
- In warm to hot climates, transitioning from tillage to cover crops becomes more complex due to the potential competition for water and nutrients, with the needs

of the associated vines taking precedence. Additionally, the increasing severity and frequency of meteorological droughts suggest that under dry farming conditions, light tillage might still be advisable.

- Several methods and approaches are now available to regulate the degree of competition that a cover might exert on the associated vines: (i) limit the spatial extension and growth of native grassing; (ii) regardless of which part of the vineyard is cover cropped (i.e., between rows or under vines), a good strategy is to achieve root double layering, meaning the topsoil (0–15 cm) is densely colonized by grass roots, while the underlying layers are dominated by grapevine roots, including some tap roots that may ensure survival during extreme summer drought; (iii) if an artificial sod is chosen, preference should be given to microtherm species that have a growth lag in summer with the potential to recover in the fall.
- The general impression is that "soil management" is still viewed as a fairly standard practice that does not require any "design and management strategy" and is, in most cases, left to the free growth of native vegetation, with competition reduced by periodic mowing.
- Part of the contradiction between tillage and cover crops can be resolved if "no tillage" is understood to mean the use of mulching practices. This advanced method remains largely underutilized in vineyards. Progress could be achieved by overcoming the well-known challenges of sourcing, distributing, maintaining, and disposing of mulching material through natural solutions like interrow rolling or sub-row mulching.
- There is also a growing interest in alternative management of the under-vine strip, which is still traditionally managed with herbicides or tillage. Among the various approaches, which should consider the availability of blue water, the intentional sowing of low-maintenance, suffocating creeping cover crops that can control native weeds and limit water use is gaining attention. Where irrigation is available, allowing spontaneous vegetation to grow and observing whether it leads to a beneficial plant community that gradually isolates aggressive broadleaf species is another option.

Author Contributions: Conceptualization: S.P.; writing—original draft preparation: S.P.; writing—review and editing: H.T., G.C., F.P.; data curation: H.T., G.C., F.P., S.P.; formal analysis: H.T., G.C., F.P., S.P.; data analysis: H.T., G.C., F.P.; literature review: H.T., G.C., F.P., S.P.; visualization: S.P.; supervision: S.P. All authors agree to be accountable for any aspect of the work, to ensure accuracy and integrity. All authors have read and agreed to the published version of the manuscript.

Funding: Università Cattolica del Sacro Cuore contributed to the funding of this research project and its publication (Bandi Interni Sedi Padane 2025, Linea D3.1.b).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Giffard, B.; Winter, S.; Guidoni, S.; Nicolai, A.; Castaldini, M.; Cluzeau, D.; Coll, P.; Cortet, J.; Le Cadre, E.; D'errico, G.; et al. Vineyard management and its impacts on soil biodiversity, functions, and ecosystem services. *Front. Ecol. Evol.* **2022**, *10*, 850272. [CrossRef]
2. Rodrigo-Comino, J. Five decades of soil erosion research in "terroir". The State-of-the-Art. *Earth-Sci. Rev.* **2018**, *179*, 436–447. [CrossRef]
3. Prosdocimi, M.; Cerdà, A.; Tarolli, P. Soil water erosion on Mediterranean vineyards: A review. *Catena* **2016**, *141*, 1–21. [CrossRef]
4. Rodrigo Comino, J.; Iserloh, T.; Morvan, X.; Malam Issa, O.; Naisse, C.; Keesstra, S.D.; Cerdà, A.; Prosdocimi, M.; Arnáez, J.; Lasanta, T.; et al. Soil erosion processes in European vineyards: A qualitative comparison of rainfall simulation measurements in Germany, Spain and France. *Hydrology* **2016**, *3*, 6. [CrossRef]
5. Gristina, L.; Novara, A.; Minacapilli, M. Rethinking vineyard ground management to counter soil tillage erosion. *Soil Tillage Res.* **2022**, *217*, 105275. [CrossRef]

6. Novara, A.; Gristina, L.; Saladino, S.; Santoro, A.; Cerdà, A. Soil erosion assessment on tillage and alternative soil managements in a Sicilian vineyard. *Soil Tillage Res.* **2011**, *117*, 140–147. [CrossRef]
7. Peregrina, F.; Pérez-Álvarez, E.P.; Colina, M.; García-Escudero, E. Cover crops and tillage influence soil organic matter and nitrogen availability in a semi-arid vineyard. *Arch. Agron. Soil Sci.* **2012**, *58* (Suppl. S1), SS95–SS102. [CrossRef]
8. Zehetner, F.; Djukic, I.; Hofmann, R.; Kühnen, L.; Rampazzo-Todorovic, G.; Gerzabek, M.H.; Soja, G. Soil organic carbon and microbial communities respond to vineyard management. *Soil Use Manag.* **2015**, *31*, 528–533. [CrossRef]
9. Emmerling, C.; Schloter, M.; Hartmann, A.; Kandeler, E. Functional diversity of soil organisms—A review of recent research activities in Germany. *J. Plant Nutr. Soil Sci.* **2002**, *165*, 408–420. [CrossRef]
10. Hendgen, M.; Hoppe, B.; Döring, J.; Friedel, M.; Kauer, R.; Frisch, M.; Dahl, A.; Kellner, H. Effects of different management regimes on microbial biodiversity in vineyard soils. *Sci. Rep.* **2018**, *8*, 9393. [CrossRef]
11. Cavani, L.; Manici, L.M.; Caputo, F.; Peruzzi, E.; Ciavatta, C. Ecological restoration of a copper polluted vineyard: Long-term impact of farmland abandonment on soil bio-chemical properties and microbial communities. *J. Environ. Manag.* **2016**, *182*, 37–47. [CrossRef]
12. Jackson, L.E.; Bowles, T.M.; Hodson, A.K.; Lazcano, C. Soil microbial-root and microbial-rhizosphere processes to increase nitrogen availability and retention in agroecosystems. *Curr. Opin. Environ. Sustain.* **2012**, *4*, 517–522. [CrossRef]
13. Duret, M.; Wallner, A.; Besaury, L.; Aziz, A. Diversity and functional features of the root-associated bacteriome are dependent on grapevine susceptibility to Plasmopara viticola. *Environ. Microbiome* **2025**, *20*, 30. [CrossRef]
14. Xue, T.; Zhang, L.; Yang, F.; Cheng, C.; Wang, J.; Sang, Q.; Yang, S.; Zhao, X.; Zhang, L. Carbon sink and soil organic carbon sequestration mechanisms in vineyards. *J. Clean. Prod.* **2024**, *469*, 143217. [CrossRef]
15. Vrsic, S.; Ivancic, A.; Pulko, B.; Valdhuber, J. Effect of soil management systems on erosion and nutrition loss in vineyards on steep slopes. *J. Environ. Biol.* **2011**, *32*, 289.
16. Louchart, X.; Voltz, M.; Andrieux, P.; Moussa, R. Herbicide transport to surface waters at field and watershed scales in a Mediterranean vineyard area. *J. Environ. Qual.* **2001**, *30*, 982–991. [CrossRef]
17. Ying, G.-G.; Williams, B. Dissipation of herbicides in soil and grapes in a South Australian vineyard. *Agric. Ecosyst. Environ.* **2000**, *78*, 283–289. [CrossRef]
18. Derpsch, R.; Franzluebbers, A.; Duiker, S.; Reicosky, D.; Koeller, K.; Friedrich, T.; Sturny, W.; Sá, J.; Weiss, K. Why do we need to standardize no-tillage research? *Soil Tillage Res.* **2014**, *137*, 16–22. [CrossRef]
19. Peixoto, D.S.; da Silva, L.d.C.M.; de Melo, L.B.B.; Azevedo, R.P.; Araújo, B.C.L.; de Carvalho, T.S.; Moreira, S.G.; Curi, N.; Silva, B.M. Occasional tillage in no-tillage systems: A global meta-analysis. *Sci. Total Environ.* **2020**, *745*, 140887. [CrossRef]
20. Van Huyssteen, L.; Weber, H. The effect of conventional and minimum tillage practices on some soil properties in a dryland vineyard. *S. Afr. J. Enol. Vitic.* **1980**, *1*, 35–45. [CrossRef]
21. Dobrei, A.; Nistor, E. Tillage practices in the context of climate change and a sustainable viticulture. *Not. Sci. Biol.* **2015**, *7*, 500–504. [CrossRef]
22. Runge, T.; Latacz-Lohmann, U.; Schaller, L.; Todorova, K.; Daugbjerg, C.; Termansen, M.; Liira, J.; Le Gloux, F.; Dupraz, P.; Leppanen, J.; et al. Implementation of Eco-schemes in Fifteen European Union Member States. *EuroChoices* **2022**, *21*, 19–27. [CrossRef]
23. Noun, G.; Lo Cascio, M.; Spano, D.; Marras, S.; Sirca, C. Plant-Based Methodologies and Approaches for Estimating Plant Water Status of Mediterranean Tree Species: A Semi-Systematic Review. *Agronomy* **2022**, *12*, 2127. [CrossRef]
24. Burg, P.; Čížková, A.; Mašán, V.; Sedlar, A.; Matwijczuk, A.; Souček, J. The effect of mulch materials on selected soil properties, yield and grape quality in vineyards under central European conditions. *Agronomy* **2022**, *12*, 1862. [CrossRef]
25. Guerra, B.; Steenwerth, K. Influence of floor management technique on grapevine growth, disease pressure, and juice and wine composition: A review. *Am. J. Enol. Vitic.* **2012**, *63*, 149–164. [CrossRef]
26. Visconti, F.; Lopez, R.; Olego, M.A. The health of vineyard soils: Towards a sustainable viticulture. *Horticulturae* **2024**, *10*, 154. [CrossRef]
27. Manzone, M.; Demeneghi, M.; Marucco, P.; Grella, M.; Balsari, P. Technical solutions for under-row weed control in vineyards: Efficacy, costs and environmental aspects analysis. *J. Agric. Eng.* **2020**, *51*, 36–42. [CrossRef]
28. Mainardis, M.; Boscutti, F.; Rubio Cebolla, M.d.M.; Pergher, G. Comparison between flaming, mowing and tillage weed control in the vineyard: Effects on plant community, diversity and abundance. *PLoS ONE* **2020**, *15*, e0238396. [CrossRef]
29. Steenwerth, K.L.; Calderón-Orellana, A.; Hanifin, R.C.; Storm, C.; McElrone, A.J. Effects of various vineyard floor management techniques on weed community shifts and grapevine water relations. *Am. J. Enol. Vitic.* **2016**, *67*, 153–162. [CrossRef]
30. Coulouma, G.; Boizard, H.; Trotoux, G.; Lagacherie, P.; Richard, G. Effect of deep tillage for vineyard establishment on soil structure: A case study in Southern France. *Soil Tillage Res.* **2006**, *88*, 132–143. [CrossRef]
31. Lagacherie, P.; Coulouma, G.; Ariagno, P.; Virat, P.; Boizard, H.; Richard, G. Spatial variability of soil compaction over a vineyard region in relation with soils and cultivation operations. *Geoderma* **2006**, *134*, 207–216. [CrossRef]

32. Linares, R.; de la Fuente, M.; Junquera, P.; Lissarrague, J.R.; Baeza, P. Effects of soil management in vineyard on soil physical and chemical characteristics. *BIO Web Conf.* **2014**, *3*, 01008. [CrossRef]
33. Minardi, I.; Tezza, L.; Pitacco, A.; Valenti, L.; Coppo, L.; Ghiglieno, I. Evaluation of nitrous oxide emissions from vineyard soil: Effect of organic fertilisation and tillage. *J. Clean. Prod.* **2022**, *380*, 134557. [CrossRef]
34. Biddoccu, M.; Ferraris, S.; Cavallo, E.; Opsi, F.; Previati, M.; Canone, D. Hillslope vineyard rainfall-runoff measurements in relation to soil infiltration and water content. *Procedia Environ. Sci.* **2013**, *19*, 351–360. [CrossRef]
35. Marques, M.; Ruiz-Colmenero, M.; Bienes, R.; García-Díaz, A.; Sastre, B. Effects of a permanent soil cover on water dynamics and wine characteristics in a steep vineyard in the Central Spain. *Air Soil Water Res.* **2020**, *13*, 1178622120948069. [CrossRef]
36. Ozpinar, S.; Ozpinar, A.; Cay, A. Soil management effect on soil properties in traditional and mechanized vineyards under a semiarid Mediterranean environment. *Soil Tillage Res.* **2018**, *178*, 198–208. [CrossRef]
37. Sharley, D.J.; Hoffmann, A.A.; Thomson, L.J. The effects of soil tillage on beneficial invertebrates within the vineyard. *Agric. For. Entomol.* **2008**, *10*, 233–243. [CrossRef]
38. Blanco-Pérez, R.; Sáenz-Romo, M.G.; Vicente-Díez, I.; Ibáñez-Pascual, S.; Martínez-Villar, E.; Marco-Mancebón, V.S.; Pérez-Moreno, I.; Campos-Herrera, R. Impact of vineyard ground cover management on the occurrence and activity of entomopathogenic nematodes and associated soil organisms. *Agric. Ecosyst. Environ.* **2020**, *301*, 107028. [CrossRef]
39. Uzman, D.; Pliester, J.; Leyer, I.; Entling, M.H.; Reineke, A. Drivers of entomopathogenic fungi presence in organic and conventional vineyard soils. *Appl. Soil Ecol.* **2019**, *133*, 89–97. [CrossRef]
40. Pfingstmann, A.; Paredes, D.; Buchholz, J.; Querner, P.; Bauer, T.; Strauss, P.; Kratschmer, S.; Winter, S.; Zaller, J. Contrasting effects of tillage and landscape structure on spiders and springtails in vineyards. *Sustainability* **2019**, *11*, 2095. [CrossRef]
41. Liebhard, G.; Guzman, G.; Gomez, J.A.; Winter, S.; Zaller, J.G.; Bauer, T.; Nicolai, A.; Cluzeau, D.; Popescu, D.; Bunea, C.I. Vineyard cover crop management strategies and their effect on soil properties across Europe. *Eur. J. Soil Sci.* **2024**, *75*, e13573. [CrossRef]
42. Catania, P.; Badalucco, L.; Laudicina, V.A.; Vallone, M. Effects of tilling methods on soil penetration resistance, organic carbon and water stable aggregates in a vineyard of semiarid Mediterranean environment. *Environ. Earth Sci.* **2018**, *77*, 348. [CrossRef]
43. Novara, A.; Stallone, G.; Cerdà, A.; Gristina, L. The effect of shallow tillage on soil erosion in a semi-arid vineyard. *Agronomy* **2019**, *9*, 257. [CrossRef]
44. Lieskovský, J.; Kenderessy, P. Modelling the effect of vegetation cover and different tillage practices on soil erosion in vineyards: A case study in Vráble (Slovakia) using WATEM/SEDEM. *Land Degrad. Dev.* **2014**, *25*, 288–296. [CrossRef]
45. Straffelini, E.; Pijl, A.; Otto, S.; Marchesini, E.; Pitacco, A.; Tarolli, P. A high-resolution physical modelling approach to assess runoff and soil erosion in vineyards under different soil managements. *Soil Tillage Res.* **2022**, *222*, 105418. [CrossRef]
46. Raclot, D.; Le Bissonnais, Y.; Louchart, X.; Andrieux, P.; Moussa, R.; Voltz, M. Soil tillage and scale effects on erosion from fields to catchment in a Mediterranean vineyard area. *Agric. Ecosyst. Environ.* **2009**, *134*, 201–210. [CrossRef]
47. Biddoccu, M.; Ferraris, S.; Opsi, F.; Cavallo, E. Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North–West Italy). *Soil Tillage Res.* **2016**, *155*, 176–189. [CrossRef]
48. Capello, G.; Biddoccu, M.; Ferraris, S.; Cavallo, E. Effects of tractor passes on hydrological and soil erosion processes in tilled and grassed vineyards. *Water* **2019**, *11*, 2118. [CrossRef]
49. Bogunovic, I.; Bilandzija, D.; Andabaka, Z.; Stupic, D.; Rodrigo Comino, J.; Cacic, M.; Brezinscak, L.; Maletic, E.; Pereira, P. Soil compaction under different management practices in a Croatian vineyard. *Arab. J. Geosci.* **2017**, *10*, 340. [CrossRef]
50. Van Dijck, S.; Van Asch, T.W. Compaction of loamy soils due to tractor traffic in vineyards and orchards and its effect on infiltration in southern France. *Soil Tillage Res.* **2002**, *63*, 141–153. [CrossRef]
51. Pessina, D.; Tadini, V.; Galli, L.E. Soil compaction in Northern Italian vineyards: Challenges and mitigation strategies. *J. Agric. Eng.* **2025**, *56*, 41–49. [CrossRef]
52. Bonifacio, E.; Said-Pullicino, D.; Stanchi, S.; Potenza, M.; Belmonte, S.A.; Celi, L. Soil and management effects on aggregation and organic matter dynamics in vineyards. *Soil Tillage Res.* **2024**, *240*, 106077. [CrossRef]
53. Belmonte, S.A.; Luisella, C.; Stahel, R.J.; Bonifacio, E.; Novello, V.; Zanini, E.; Steenwerth, K.L. Effect of long-term soil management on the mutual interaction among soil organic matter, microbial activity and aggregate stability in a vineyard. *Pedosphere* **2018**, *28*, 288–298. [CrossRef]
54. Mondello, V.; Larignon, P.; Armengol, J.; Kortekamp, A.; Vaczy, K.; Prezman, F.; Serrano, E.; Rego, C.; Mugnai, L.; Fontaine, F. Management of grapevine trunk diseases. *Phytopathol. Mediterr.* **2018**, *57*, 369–383.
55. Marras, S.; Masia, S.; Duce, P.; Spano, D.; Sirca, C. Carbon footprint assessment on a mature vineyard. *Agric. For. Meteorol.* **2015**, *214*, 350–356. [CrossRef]
56. Ghiglieno, I.; Simonetto, A.; Facciano, L.; Tonni, M.; Donna, P.; Valenti, L.; Gilioli, G. Comparing the Carbon Footprint of Conventional and Organic Vineyards in Northern Italy. *Sustainability* **2023**, *15*, 5252. [CrossRef]
57. Wolff, M.W.; Alsina, M.M.; Stockert, C.M.; Khalsa, S.D.S.; Smart, D.R. Minimum tillage of a cover crop lowers net GWP and sequesters soil carbon in a California vineyard. *Soil Tillage Res.* **2018**, *175*, 244–254. [CrossRef]

58. Longbottom, M.; Petrie, P. Role of vineyard practices in generating and mitigating greenhouse gas emissions. *Aust. J. Grape Wine Res.* **2015**, *21*, 522–536. [CrossRef]
59. Pessina, D.; Galli, L.E.; Santoro, S.; Facchinetti, D. Sustainability of machinery traffic in vineyard. *Sustainability* **2021**, *13*, 2475. [CrossRef]
60. Schütte, R.; Plaas, E.; Gómez, J.A.; Guzmán, G. Profitability of erosion control with cover crops in European vineyards under consideration of environmental costs. *Environ. Dev.* **2020**, *35*, 100521. [CrossRef]
61. Ruiz-Colmenero, M.; Bienes, R.; Eldridge, D.; Marques, M. Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. *Catena* **2013**, *104*, 153–160. [CrossRef]
62. López-Vicente, M.; Calvo-Seas, E.; Álvarez, S.; Cerdà, A. Effectiveness of cover crops to reduce loss of soil organic matter in a rainfed vineyard. *Land* **2020**, *9*, 230. [CrossRef]
63. Gómez, J.; Llewellyn, C.; Basch, G.; Sutton, P.; Dyson, J.; Jones, C. The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. *Soil Use Manag.* **2011**, *27*, 502–514. [CrossRef]
64. Langdale, G.; Blevins, R.; Karlen, D.; McCool, D.; Nearing, M.; Skidmore, E.; Thomas, A.; Tyler, D.; Williams, J. Cover crop effects on soil erosion by wind and water. *Cover Crops Clean Water* **1991**, 15–22.
65. Novara, A.; Gristina, L.; Guaitoli, F.; Santoro, A.; Cerdà, A. Managing soil nitrate with cover crops and buffer strips in Sicilian vineyards. *Solid Earth* **2013**, *4*, 255–262. [CrossRef]
66. García-Díaz, A.; Bienes, R.; Sastre, B.; Novara, A.; Gristina, L.; Cerda, A. Nitrogen losses in vineyards under different types of soil groundcover. A field runoff simulator approach in central Spain. *Agric. Ecosyst. Environ.* **2017**, *236*, 256–267. [CrossRef]
67. Clothier, B.; Green, S. The Leaching and Runoff of Nutrients from Vineyards. In *Science and Policy: Nutrient Management Challenges for the Next Generation*; Massey University: Palmerston North, New Zealand, 2017.
68. Barlow, K.; Bond, W.; Holzapfel, B.; Smith, J.; Hutton, R. Nitrogen concentrations in soil solution and surface run-off on irrigated vineyards in Australia. *Aust. J. Grape Wine Res.* **2009**, *15*, 131–143. [CrossRef]
69. Cock, G. Soil structural conditions of vineyards under two soil management systems. *Aust. J. Exp. Agric.* **1985**, *25*, 450–454. [CrossRef]
70. Steenwerth, K.; Belina, K. Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem. *Appl. Soil Ecol.* **2008**, *40*, 359–369. [CrossRef]
71. McGourty, G.T.; Reganold, J.P. Managing vineyard soil organic matter with cover crops. In *Proceedings of the Soil Environment and Vine Mineral Nutrition Symposium, San Diego, CA, USA, 29–30 June 2004*; American Society for Enology and Viticulture: Davis, CA, USA, 2005.
72. Celette, F.; Gaudin, R.; Gary, C. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. *Eur. J. Agron.* **2008**, *29*, 153–162. [CrossRef]
73. Gulick, S.; Grimes, D.; Munk, D.; Goldhamer, D. Cover-crop-enhanced water infiltration of a slowly permeable fine sandy loam. *Soil Sci. Soc. Am. J.* **1994**, *58*, 1539–1546. [CrossRef]
74. Lanari, V.; Pallotti, L.; Lattanzi, T.; Silvestroni, O. Grapevine Root Distribution and Density in Deep Soil Layers Under Different Soil Management Practices. *Plants* **2025**, *14*, 1823. [CrossRef]
75. Centinari, M. Impacts of under-trellis cover crops. *Aust. New Zealand Grapegrow. Winemak.* **2017**, *638*, 33–34.
76. Bernaschina, Y.; Fresia, P.; Garaycochea, S.; Leoni, C. Permanent cover crop as a strategy to promote soil health and vineyard performance. *Environ. Sustain.* **2023**, *6*, 243–258. [CrossRef]
77. Abad, J.; de Mendoza, I.H.; Marín, D.; Orcaray, L.; Santesteban, L.G. Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard. *OENO One* **2021**, *55*, 295–312. [CrossRef]
78. Winter, S.; Bauer, T.; Strauss, P.; Kratschmer, S.; Paredes, D.; Popescu, D.; Landa, B.; Guzmán, G.; Gómez, J.A.; Guernion, M.; et al. Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: A meta-analysis. *J. Appl. Ecol.* **2018**, *55*, 2484–2495. [CrossRef] [PubMed]
79. Bruggisser, O.T.; Schmidt-Entling, M.H.; Bacher, S. Effects of vineyard management on biodiversity at three trophic levels. *Biol. Conserv.* **2010**, *143*, 1521–1528. [CrossRef]
80. Puig-Montserrat, X.; Stefanescu, C.; Torre, I.; Palet, J.; Fabregas, E.; Dantart, J.; Arrizabalaga, A.; Flaquer, C. Effects of organic and conventional crop management on vineyard biodiversity. *Agric. Ecosyst. Environ.* **2017**, *243*, 19–26. [CrossRef]
81. Hasanaliyeva, G.; Furiosi, M.; Rossi, V.; Caffi, T. Cover crops lower the dispersal of grapevine foliar pathogens from the ground and contribute to early-season disease management. *Front. Plant Sci.* **2024**, *15*, 1498848. [CrossRef]
82. Mahaffee, W.F.; Margairaz, F.; Ulmer, L.; Bailey, B.N.; Stoll, R. Catching spores: Linking epidemiology, pathogen biology, and physics to ground-based airborne inoculum monitoring. *Plant Dis.* **2023**, *107*, 13–33. [CrossRef]
83. Xi, Z.-M.; Tao, Y.-S.; Zhang, L.; Li, H. Impact of cover crops in vineyard on the aroma compounds of *Vitis vinifera* L. cv Cabernet Sauvignon wine. *Food Chem.* **2011**, *127*, 516–522. [CrossRef]
84. Pérez-Álvarez, E.P.; García-Escudero, E.; Peregrina, F. Soil nutrient availability under cover crops: Effects on vines, must, and wine in a Tempranillo vineyard. *Am. J. Enol. Vitic.* **2015**, *66*, 311–320. [CrossRef]

85. Lopes, C.; Monteiro, A.; Machado, J.; Fernandes, N.; Araújo, A. Cover cropping in a sloping non-irrigated vineyard: II–Effects on vegetative growth, yield, berry and wine quality of 'Cabernet Sauvignon'grapevines. *Ciência Téc.* **2008**, *23*, 37–43.
86. Abad, J.; de Mendoza, I.H.; Marín, D.; Orcaray, L.; Santesteban, L.G. Cover crops in viticulture. A systematic review (2): Implications on vineyard agronomic performance. *OENO One* **2021**, *55*, 1–27. [CrossRef]
87. Mihály, Z.; Olimpia, B.; Miklós, S.; Zita, D. Grassy and herbaceous interrow cover crops in European vineyards: A review of their Short-Term effects on water management and regulating ecosystem services. *Land* **2025**, *14*, 1526. [CrossRef]
88. Jacometti, M.A.; Wratten, S.D.; Walter, M. Enhancing ecosystem services in vineyards: Using cover crops to decrease botrytis bunch rot severity. *Int. J. Agric. Sustain.* **2007**, *5*, 305–314. [CrossRef]
89. Sáenz-Romo, M.G.; Veas-Bernal, A.; Martínez-García, H.; Campos-Herrera, R.; Ibanez-Pascual, S.; Martínez-Villar, E.; Perez-Moreno, I.; Marco-Mancebón, V.S. Ground cover management in a Mediterranean vineyard: Impact on insect abundance and diversity. *Agric. Ecosyst. Environ.* **2019**, *283*, 106571. [CrossRef]
90. Sáenz-Romo, M.G.; Veas-Bernal, A.; Martínez-García, H.; Ibáñez-Pascual, S.; Martínez-Villar, E.; Campos-Herrera, R.; Marco-Mancebón, V.S.; Pérez-Moreno, I. Effects of ground cover management on insect predators and pests in a Mediterranean vineyard. *Insects* **2019**, *10*, 421. [CrossRef]
91. Danne, A.; Thomson, L.; Sharley, D.; Penfold, C.; Hoffmann, A. Effects of native grass cover crops on beneficial and pest invertebrates in Australian vineyards. *Environ. Entomol.* **2010**, *39*, 970–978. [CrossRef]
92. Geldenhuys, M.; Gaigher, R.; Pryke, J.; Samways, M. Diverse herbaceous cover crops promote vineyard arthropod diversity across different management regimes. *Agric. Ecosyst. Environ.* **2021**, *307*, 107222. [CrossRef]
93. Pelusi, F.; Gatti, M.; Cunial, L.; Zozzo, F.D.; Santelli, S.; Poni, S. Effects of Winter Cover Crop Mixture and Termination on the Performance and Physiology of cv. Barbera (*Vitis vinifera* L.) Grapevines. *Aust. J. Grape Wine Res.* **2025**, *2025*, 4271832. [CrossRef]
94. Chou, M.-Y.; Vanden Heuvel, J.E. Annual under-vine cover crops mitigate vine vigor in a mature and vigorous cabernet franc vineyard. *Am. J. Enol. Vitic.* **2019**, *70*, 98–108. [CrossRef]
95. Griesser, M.; Steiner, M.; Pingel, M.; Uzman, D.; Preda, C.; Giffard, B.; Tolle, P.; Memedemin, D.; Forneck, A.; Reineke, A.; et al. General trends of different inter-row vegetation management affecting vine vigor and grape quality across European vineyards. *Agric. Ecosyst. Environ.* **2022**, *338*, 108073. [CrossRef]
96. Giese, G.; Velasco-Cruz, C.; Roberts, L.; Heitman, J.; Wolf, T.K. Complete vineyard floor cover crops favorably limit grapevine vegetative growth. *Sci. Hortic.* **2014**, *170*, 256–266. [CrossRef]
97. Bavougian, C.M.; Read, P.E. Mulch and groundcover effects on soil temperature and moisture, surface reflectance, grapevine water potential, and vineyard weed management. *PeerJ* **2018**, *6*, e5082. [CrossRef] [PubMed]
98. Agam, N.; Kustas, W.; Alfieri, J.; Gao, F.; McKee, L.; Prueger, J.; Hipps, L. Micro-scale spatial variability in soil heat flux (SHF) in a wine-grape vineyard. *Irrig. Sci.* **2019**, *37*, 253–268. [CrossRef]
99. Costa, J.M.; Egipto, R.; Aguiar, F.C.; Marques, P.; Nogales, A.; Madeira, M. The role of soil temperature in mediterranean vineyards in a climate change context. *Front. Plant Sci.* **2023**, *14*, 1145137. [CrossRef] [PubMed]
100. Novara, A.; Minacapilli, M.; Santoro, A.; Rodrigo-Comino, J.; Carrubba, A.; Sarno, M.; Venezia, G.; Gristina, L. Real cover crops contribution to soil organic carbon sequestration in sloping vineyard. *Sci. Total Environ.* **2019**, *652*, 300–306. [CrossRef]
101. Payen, F.T.; Sykes, A.; Aitkenhead, M.; Alexander, P.; Moran, D.; MacLeod, M. Soil organic carbon sequestration rates in vineyard agroecosystems under different soil management practices: A meta-analysis. *J. Clean. Prod.* **2021**, *290*, 125736. [CrossRef]
102. Zumkeller, M.; Yu, R.; Torres, N.; Marigliano, L.E.; Zaccaria, D.; Kurtural, S.K. Site characteristics determine the effectiveness of tillage and cover crops on the net ecosystem carbon balance in California vineyard agroecosystems. *Front. Plant Sci.* **2022**, *13*, 1024606. [CrossRef]
103. Delpuech, X.; Metay, A. Adapting cover crop soil coverage to soil depth to limit competition for water in a Mediterranean vineyard. *Eur. J. Agron.* **2018**, *97*, 60–69. [CrossRef]
104. Klodd, A.; Eissenstat, D.; Wolf, T.; Centinari, M. Coping with cover crop competition in mature grapevines. *Plant Soil* **2016**, *400*, 391–402. [CrossRef]
105. Stefano, P.; Caterina, C.; Eugenio, M.; Stefano, S.; Matteo, G.; Frioni, T. A whole-canopy approach to assess varying effects of cover crop vs grapevine competition and recovery. *Sci. Hortic.* **2024**, *327*, 112854. [CrossRef]
106. Centinari, M.; Filippetti, I.; Bauerle, T.; Allegro, G.; Valentini, G.; Poni, S. Cover crop water use in relation to vineyard floor management practices. *Am. J. Enol. Vitic.* **2013**, *64*, 522–526. [CrossRef]
107. Capri, C.; Fiorini, A.; Gatti, M.; Richards, A.; Poni, S. Screening of cover crop species for sustainable vineyard floor management. In Proceedings of the XXXI International Horticultural Congress (IHC2022): International Symposium on the Vitivinicultural Sector: Which Tools to 1370, Angers, France, 14 August 2022.
108. Sulas, L.; Mercenaro, L.; Campesi, G.; Nieddu, G. Different cover crops affect nitrogen fluxes in mediterranean vineyard. *Agron. J.* **2017**, *109*, 2579–2585. [CrossRef]

109. Pérez-Álvarez, E.P.; Garde-Cerdán, T.; Santamaría, P.; García-Escudero, E.; Peregrina, F. Influence of two different cover crops on soil N availability, N nutritional status, and grape yeast-assimilable N (YAN) in a cv. Tempranillo vineyard. *Plant Soil* **2015**, *390*, 143–156. [CrossRef]
110. Brunetto, G.; Lorensini, F.; Ceretta, C.A.; Avelar Ferreira, P.A.; da Rosa Couto, R.; De Conti, L.; Nara Ciotta, M.; Kulmann, M.; Schneider, R.O.; Michelon Somavilla, L. Contribution of mineral N to young grapevine in the presence or absence of cover crops. *J. Soil Sci. Plant Nutr.* **2017**, *17*, 570–580. [CrossRef]
111. Messiga, A.J.; Gallant, K.S.; Sharifi, M.; Hammermeister, A.; Fuller, K.; Tango, M.; Fillmore, S. Grape yield and quality response to cover crops and amendments in a vineyard in Nova Scotia, Canada. *Am. J. Enol. Vitic.* **2016**, *67*, 77–85. [CrossRef]
112. Muscas, E.; Cocco, A.; Mercenaro, L.; Cabras, M.; Lentini, A.; Porqueddu, C.; Nieddu, G. Effects of vineyard floor cover crops on grapevine vigor, yield, and fruit quality, and the development of the vine mealybug under a Mediterranean climate. *Agric. Ecosyst. Environ.* **2017**, *237*, 203–212. [CrossRef]
113. Irvin, N.; Hagler, J.; Hoddle, M. Measuring natural enemy dispersal from cover crops in a California vineyard. *Biol. Control* **2018**, *126*, 15–25. [CrossRef]
114. Bau, L.; Chassaing, T. Impact assessment of cover crops on the risk of frost in the Anjou vineyard: Original language of the article: English. *IVES Tech. Rev. Vine Wine* **2025**. [CrossRef]
115. Baillet, V.; Symoneaux, R.; Renaud-Gentié, C. Life Cycle Assessment of Spring Frost Protection Methods: High and Contrasted Environmental Consequences in Vineyard Management. *Sustainability* **2025**, *17*, 7835. [CrossRef]
116. Zumkeller, M.; Torres, N.; Yu, R.; Kurtural, K. Permanent Cover Cropping with Reduced Tillage Increased Resiliency of Wine Grape Vineyards to Climate Change. In Proceedings of the Terclim2022 | XIVth International Terroir Congress 2nd ClimWine Symposium, Bordeaux, France, 3–8 July 2022.
117. Merot, A.; Smits, N. Explaining yield dynamics during vineyard conversion to organic farming. *Eur. J. Agron.* **2024**, *153*, 127068. [CrossRef]
118. La Torre, A.; Talocci, S.; Spera, G.; Valori, R. Control of downy mildew on grapes in organic viticulture. *Commun Agric. Appl. Biol. Sci.* **2008**, *73*, 169–178.
119. Poeydebat, C.; Courchinoux, E.; Demeaux, I.; Rodriguez, M.; Chataigner, A.; Lelievre, M.; Goutouly, J.-P.; Rossi, J.-P.; Raynal, M.; Deliere, L. Quantitative assessment and spatial distribution of Plasmopara viticola oospores in vineyard soil. *BioRxiv* **2024**. [CrossRef]
120. Sharley, D.; Thomson, L. Determining the effects of vineyard soil tillage on beneficial soil invertebrates. *Aust. New Zealand Grapegrow. Winemak.* **2005**, *499*, 44–46.
121. Paoletti, M.G. Using bioindicators based on biodiversity to assess landscape sustainability. In *Invertebrate Biodiversity as Bioindicators of Sustainable Landscapes*; Elsevier: Amsterdam, The Netherlands, 1999; pp. 1–18.
122. Rocher, L.; Blaya, R.; Blaise, C.; Bischoff, A.; Blight, O. Species and functional responses of ants to inter-row tillage and vegetation in organic Mediterranean vineyards. *Basic Appl. Ecol.* **2022**, *65*, 126–135. [CrossRef]
123. Rogiers, S.Y.; Greer, D.H.; Liu, Y.; Baby, T.; Xiao, Z. Impact of climate change on grape berry ripening: An assessment of adaptation strategies for the Australian vineyard. *Front. Plant Sci.* **2022**, *13*, 1094633. [CrossRef] [PubMed]
124. Matlock, J.M.; Isaacs, R.; Grieshop, M. Tillage reduces survival of grape berry moth (*Lepidoptera: Tortricidae*), via burial rather than mechanical injury. *Environ. Entomol.* **2017**, *46*, 100–106. [CrossRef]
125. Donaldson, D.R.; Snyder, R.L.; Elmore, C.; Gallagher, S. Weed control influences vineyard minimum temperatures. *Am. J. Enol. Vitic.* **1993**, *44*, 431–434. [CrossRef]
126. Evans, R.G. The art of protecting grapevines from low temperature injury. In Proceedings of the American Society for Enology and Viticulture (ASEV) 50th Anniversary Annual Meeting, Seattle, WA, USA, 19–23 June 2000; pp. 60–72.
127. Poni, S.; Sabbatini, P.; Palliotti, A. Facing spring frost damage in grapevine: Recent developments and the role of delayed winter pruning–A review. *Am. J. Enol. Vitic.* **2022**, *73*, 211–226. [CrossRef]
128. Rochard, J. Arido-viticulture dans le contexte de changement climatique: Concept, bases pratiques et exemples des vignobles de Lanzarote et Santorin. *BIO Web Conf.* **2023**, *56*, 01001. [CrossRef]
129. Mekki, I.; Zitouna Chebbi, R.; Jacob, F.; Masmoudi, M.; Prévot, L.; Ben Mechlia, N.; Voltz, M.; Albergel, J. Water balance for different land use and crop sequences under semiarid environment. *Rev. Régions Arid.* **2014**, *35*, 769–777.
130. Wu, G.; Chen, J.; Shi, X.; Kim, J.S.; Xia, J.; Zhang, L. Impacts of global climate warming on meteorological and hydrological droughts and their propagations. *Earth′s Future* **2022**, *10*, e2021EF002542. [CrossRef]
131. Cruz, A.; Botelho, M.; Silvestre, J.; Castro, R. Soil management: Introduction of tillage in a vineyard with a long-term natural cover. *Ciência Técnica Vitivinícola* **2012**, *27*, 27–38.
132. Jordan, L.M.; Björkman, T.; Vanden Heuvel, J.E. Annual under-vine cover crops did not impact vine growth or fruit composition of mature cool-climate 'Riesling'grapevines. *HortTechnology* **2016**, *26*, 36–45. [CrossRef]
133. Fernando, M.; Scott, N.; Shrestha, A.; Gao, S.; Hale, L. A native plant species cover crop positively impacted vineyard water dynamics, soil health, and vine vigor. *Agric. Ecosyst. Environ.* **2024**, *367*, 108972. [CrossRef]

134. Intrieri, C.; Filippetti, I.; Lia, G.; Colucci, E.; Poni, S. Intra-row vineyard spacing and soil management, long-term field trial results with Cv. Pignoletto. *Pract. Winery Vineyard* **2005**, *26*, 76–87.
135. Penfold, C.; Collins, C. *Cover Crops and Water Use*; The University of Adelaide: Adelaide, Australia, 2012.
136. Gatti, M.; Garavani, A.; Squeri, C.; Capri, C.; Diti, I.; D'Ambrosio, R.; Frioni, T.; Scotti, C.; Poni, S. Inter-row floor management is a powerful factor for optimising vine balance in a non-irrigated organic Barbera vineyard in northern Italy. *Eur. J. Agron.* **2022**, *136*, 126490. [CrossRef]
137. Raiesi, F.; Kabiri, V. Carbon and nitrogen mineralization kinetics as affected by tillage systems in a calcareous loam soil. *Ecol. Eng.* **2017**, *106*, 24–34. [CrossRef]
138. Dobrei, A.; Alina, D.; Nistor, E.; Camen, D.; Sala, F. Improvement of soil physical and chemical properties with green manure for healthy vine and wine by-products. *Int. Multidiscip. Sci. GeoConference SGEM* **2016**, *2*, 157–164.
139. Perria, R.; Ciofini, A.; Petrucci, W.A.; D'Arcangelo, M.E.M.; Valentini, P.; Storchi, P.; Carella, G.; Pacetti, A.; Mugnai, L. A study on the efficiency of sustainable wine grape vineyard management strategies. *Agronomy* **2022**, *12*, 392. [CrossRef]
140. Li, W.; Brunner, P.; Franssen, H.-J.H.; Li, Z.; Wang, Z.; Zhang, Z.; Wang, W. Potential evaporation dynamics over saturated bare soil and an open water surface. *J. Hydrol.* **2020**, *590*, 125140. [CrossRef]
141. Wythers, K.; Lauenroth, W.; Paruelo, J. Bare-soil evaporation under semiarid field conditions. *Soil Sci. Soc. Am. J.* **1999**, *63*, 1341–1349. [CrossRef]
142. Capri, C.; Gatti, M.; Guadagna, P.; Del Zozzo, F.; Magnanini, E.; Poni, S. A low-cost portable chamber based on Arduino micro-controller for measuring cover crops water use. *Comput. Electron. Agric.* **2021**, *190*, 106361. [CrossRef]
143. Celette, F.; Gary, C. Dynamics of water and nitrogen stress along the grapevine cycle as affected by cover cropping. *Eur. J. Agron.* **2013**, *45*, 142–152. [CrossRef]
144. Lopes, C.; Monterio, A.; Rückert, F.E.; Gruber, B.; Steinberg, G.; Schultz, H.R. Transpiration of grapevines and co-habitating cover crop and weed species in a vineyard. A "snapshot" at diurnal trends. *Vitis* **2004**, *43*, 111–117.
145. Diti, I.; Legler, S.E.; Caffi, T.; Rossi, V.; Canali, G.; Bosso, A.; Cancila, E.; Anelli, S.; Trioli, G.; Kleshcheva, E.; et al. A new integrated approach for management of soil threats in the vineyard ecosystem. *Catena* **2020**, *195*, 104788. [CrossRef]
146. Del Zozzo, F.; Canavera, G.; Pagani, S.; Gatti, M.; Poni, S.; Frioni, T. Post-Spring Frost Canopy Recovery, Vine Balance, and Fruit Composition in cv. Barbera Grapevines. *Aust. J. Grape Wine Res.* **2022**, *2022*, 6596021. [CrossRef]
147. Morlat, R.; Jacquet, A. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. *Am. J. Enol. Vitic.* **2003**, *54*, 1–7. [CrossRef]
148. Tesic, D.; Keller, M.; Hutton, R.J. Influence of vineyard floor management practices on grapevine vegetative growth, yield, and fruit composition. *Am. J. Enol. Vitic.* **2007**, *58*, 1–11. [CrossRef]
149. Giese, G.; Wolf, T.K.; Velasco-Cruz, C.; Roberts, L.; Heitman, J. Cover crop and root pruning impacts on vegetative growth, crop yield components, and grape composition of Cabernet Sauvignon. *Am. J. Enol. Vitic.* **2015**, *66*, 212–226. [CrossRef]
150. Smith, M.W.; Wolf, M.E.; Cheary, B.S.; Carroll, B.L. Allelopathy of bermudagrass, tall fescue, redroot pigweed, and cutleaf evening primrose on pecan. *HortScience* **2001**, *36*, 1047–1048. [CrossRef]
151. Bettoni, I.P.; Gardin, T.P.P.; Rodrigues, O.T.; Feldberg, N.P.; Dalbó, M.A. Allelopathic potential of weed extracts on the growth of grapevine rootstock VR 043-43. *Rev. Agropecuária Catarin.* **2020**, *24*, 51–55.
152. Centinari, M.; Vanden Heuvel, J.; Goebel, M.; Smith, M.; Bauerle, T. Root-zone management practices impact above and belowground growth in C abernet F ranc grapevines. *Aust. J. Grape Wine Res.* **2016**, *22*, 137–148. [CrossRef]
153. Fleishman, S.M.; Bock, H.W.; Eissenstat, D.M.; Centinari, M. Undervine groundcover substantially increases shallow but not deep soil carbon in a temperate vineyard. *Agric. Ecosyst. Environ.* **2021**, *313*, 107362. [CrossRef]
154. Kesser, M.M.; Joubert, W.; Cavagnaro, T.R.; De Bei, R.; Collins, C. Long-term under-vine coverage by spontaneous vegetation changed plant community and soil dynamics without impacting yield at two South Australian vineyards. *Agric. Ecosyst. Environ.* **2023**, *356*, 108629. [CrossRef]
155. Marks, J.; Lines, T.; Penfold, C.; Cavagnaro, T. Cover crops and carbon stocks: How under-vine management influences SOC inputs and turnover in two vineyards. *Sci. Total Environ.* **2022**, *831*, 154800. [CrossRef]
156. Lines, T.; Penfold, C.; Marks, J.; Kesser, M.; Pagay, V.; Cavagnaro, T. Run for cover–the 'right'species of under-vine cover crops do not influence yield in an Australian vineyard. *OENO One* **2024**, *4*, 58. [CrossRef]
157. Penfold, M.C.; Collins, C. *Native Cover Crops in Viticulture*; Grape and Wine Research and Development Corporation: Adelaide, Australia, 2012.
158. Comas, L.H.; Anderson, L.J.; Dunst, R.M.; Lakso, A.N.; Eissenstat, D.M. Canopy and environmental control of root dynamics in a long-term study of Concord grape. *New Phytol.* **2005**, *167*, 829–840. [CrossRef]
159. RLinares Torres, R.; De La Fuente Lloreda, M.; Junquera Gonzalez, P.; Lissarrague García-Gutierrez, J.R.; Baeza Trujillo, P. Effect of soil management strategies on the characteristics of the grapevine root system in irrigated vineyards under semi? arid conditions. *Aust. J. Grape Wine Res.* **2018**, *24*, 439–449. [CrossRef]
160. Pool, R.; Lakso, A. *Cover Crop Management for Vineyards*; IPM Report: Adelaide, Australia, 1994; pp. 14–18.

161. Centinari, M.; Poni, S.; Filippetti, I.; Magnanini, E.; Intrieri, C. Evaluation of an open portable chamber system for measuring cover crop water use in a vineyard and comparison with a mini-lysimeter approach. *Agric. For. Meteorol.* **2009**, *149*, 1975–1982. [CrossRef]
162. Uliarte, E.M.; Schultz, H.R.; Frings, C.; Pfister, M.; Parera, C.A.; Raúl, F. Seasonal dynamics of CO_2 balance and water consumption of C3 and C4-type cover crops compared to bare soil in a suitability study for their use in vineyards in Germany and Argentina. *Agric. For. Meteorol.* **2013**, *181*, 1–16. [CrossRef]
163. Medrano, H.; Tomás, M.; Martorell, S.; Flexas, J.; Hernández, E.; Rosselló, J.; Pou, A.; Escalona, J.-M.; Bota, J. From leaf to whole-plant water use efficiency (WUE) in complex canopies: Limitations of leaf WUE as a selection target. *Crop J.* **2015**, *3*, 220–228. [CrossRef]
164. Poni, S.; Bernizzoni, F.; Civardi, S.; Gatti, M.; Porro, D.; Camin, F. Performance and water-use efficiency (single-leaf vs. whole-canopy) of well-watered and half-stressed split-root Lambrusco grapevines grown in Po Valley (Italy). *Agric. Ecosyst. Environ.* **2009**, *129*, 97–106. [CrossRef]
165. Smith, J.P.; Edwards, E.J.; Walker, A.R.; Gouot, J.C.; Barril, C.; Holzapfel, B.P. A whole canopy gas exchange system for the targeted manipulation of grapevine source-sink relations using sub-ambient CO_2. *BMC Plant Biol.* **2019**, *19*, 535. [CrossRef]
166. Darouich, H.; Ramos, T.B.; Pereira, L.S.; Rabino, D.; Bagagiolo, G.; Capello, G.; Simionesei, L.; Cavallo, E.; Biddoccu, M. Water use and soil water balance of Mediterranean vineyards under rainfed and drip irrigation management: Evapotranspiration partition and soil management modelling for resource conservation. *Water* **2022**, *14*, 554. [CrossRef]
167. Allen, R.G.; Pereira, L.S. Estimating crop coefficients from fraction of ground cover and height. *Irrig. Sci.* **2009**, *28*, 17–34. [CrossRef]
168. Fandiño, M.; Cancela, J.; Rey, B.; Martínez, E.; Rosa, R.; Pereira, L. Using the dual-Kc approach to model evapotranspiration of Albariño vineyards (*Vitis vinifera* L. cv. Albariño) with consideration of active ground cover. *Agric. Water Manag.* **2012**, *112*, 75–87. [CrossRef]
169. Bremer, D.J. Evaluation of microlysimeters used in turfgrass evapotranspiration studies using the dual-probe heat-pulse technique. *Agron. J.* **2003**, *95*, 1625–1632. [CrossRef]
170. Lakso, A.N.; Pool, R.M.; Dunst, R.; Fendinger, A. Comparison of two methods to evaluate water use by row middle cover crops in fruit plantings. *HortScience* **1995**, *30*, 820. [CrossRef]
171. Baldocchi, D. Measuring fluxes of trace gases and energy between ecosystems and the atmosphere–the state and future of the eddy covariance method. *Glob. Change Biol.* **2014**, *20*, 3600–3609. [CrossRef]
172. Steduto, P.; Çetinkökü, Ö.; Albrizio, R.; Kanber, R. Automated closed-system canopy-chamber for continuous field-crop monitoring of CO_2 and H_2O fluxes. *Agric. For. Meteorol.* **2002**, *111*, 171–186. [CrossRef]
173. Garcia, R.L.; Norman, J.M.; McDermitt, D.K. Measurements of canopy gas exchange using an open chamber system. *Remote Sens. Rev.* **1990**, *5*, 141–162. [CrossRef]
174. Wagner, S.; Reicosky, D. Closed-chamber effects on leaf temperature, canopy photosynthesis, and evapotranspiration. *Agron. J.* **1992**, *84*, 731–738. [CrossRef]
175. Corelli-Grappadelli, L.; Magnanini, E. A whole-tree system for gas-exchange studies. *HortScience* **1993**, *28*, 41–45. [CrossRef]
176. Poni, S.; Merli, M.C.; Magnanini, E.; Galbignani, M.; Bernizzoni, F.; Vercesi, A.; Gatti, M. An improved multichamber gas exchange system for determining whole-canopy water-use efficiency in grapevine. *Am. J. Enol. Vitic.* **2014**, *65*, 268–276. [CrossRef]
177. Hamel, P.; Mchugh, I.; Coutts, A.; Daly, E.; Beringer, J.; Fletcher, T.D. Automated chamber system to measure field evapotranspiration rates. *J. Hydrol. Eng.* **2015**, *20*, 04014037. [CrossRef]
178. Luo, C.; Wang, Z.; Sauer, T.J.; Helmers, M.J.; Horton, R. Portable canopy chamber measurements of evapotranspiration in corn, soybean, and reconstructed prairie. *Agric. Water Manag.* **2018**, *198*, 1–9. [CrossRef]
179. Nomura, K.; Yamasaki, Y.; Takada, A.; Sago, Y.; Yasutake, D.; Kitano, M. A new method of evaluating gas fluxes in a closed chamber system with theoretical consideration for dynamic characteristics of a concentration sensor. *Environ. Control Biol.* **2019**, *57*, 53–59. [CrossRef]
180. Capri, C.; Gatti, M.; Fiorini, A.; Ardenti, F.; Tabaglio, V.; Poni, S. A comparative study of fifteen cover crop species for orchard soil management: Water uptake, root density traits and soil aggregate stability. *Sci. Rep.* **2023**, *13*, 721. [CrossRef]
181. Nie, Z.; Zollinger, R.; Jacobs, J. Performance of 7 Australian native grasses from the temperate zone under a range of cutting and fertiliser regimes. *Crop Pasture Sci.* **2009**, *60*, 943–953. [CrossRef]
182. Marco, H.; Kahlen, K.; Voss-FelsKai, K.P.; Cast, C.S.; Ollat, N.; Vivin, P.; Loose, S.; Nsibi, M.; Schmid, J.; Strack, T.; et al. Towards grapevine root architectural models to adapt viticulture to drought. *Front. Plant Sci.* **2023**, *14*, 1162506. [CrossRef] [PubMed]
183. Ramírez-Cuesta, J.M.; Intrigliolo, D.S.; Lorite, I.J.; Moreno, M.A.; Vanella, D.; Ballesteros, R.; Hernández-López, D.; Buesa, I. Determining grapevine water use under different sustainable agronomic practices using METRIC-UAV surface energy balance model. *Agric. Water Manag.* **2023**, *281*, 108247. [CrossRef]
184. Capri, C. Vineyard Soil Management: New Sustainable Approaches. 2023. Available online: https://publicatt.unicatt.it/handle/10280/146611 (accessed on 11 August 2025).

185. Campos, F.B.; Callesen, T.O.; Gonzalez, C.V.; Alberti, G.; Montagnani, L.; Tagliavini, M.; Nelson, J.A.; Zanotelli, D. Evapotranspiration dynamics and partitioning in a grassed vineyard: Ecophysiological and computational modeling approaches. *Water Resour. Res.* **2025**, *61*, e2023WR035360. [CrossRef]
186. Annese, V.; Cazzato, E.; Corleto, A. Quantitative and qualitative traits of natural ecotypes of perennial grasses (*Dactylis glomerata* L., *Festuca arundinacea Schreb.*, *Phalaris tuberosa* L., *Brachypodium rupestre* (Host) R. et S.) collected in Southern Italy. *Genet. Resour. Crop Evol.* **2006**, *53*, 431–441. [CrossRef]
187. Gliga, A.; Rotar, I.; Buta, M.; Păcurar, F.; Balazsi, F. Floristic, ecologic and pedologic characterization of semi-natural hay meadows from rodna mountains. *Bull. USAMV Ser. Agric.* **2014**, *71*, 2. [CrossRef]
188. Cunial, L.; Diti, I.; Bonini, P.; Patelli, R.; Gatti, M.; Cola, G.; Bordoni, M.; Nguyen, T.N.A.; Meisina, C.; Confalonieri, R.; et al. Novel termination techniques of winter cover crops in the vineyard: Effects on physiology and performance of Pinot Noir and Malvasia di Candia aromatica grapevines. *Eur. J. Agron.* **2025**, *164*, 127514. [CrossRef]
189. Delabays, N.; Spring, J.-L.; Mermillod, G. Essai d'enherbement de la vigne avec des espèces peu concurrentielles: Aspects botaniques et malherbologiques. *Rev. Suisse Vitic. Arboric. Hortic.* **2006**, *38*, 343–354.