



Defining and Managing for Healthy Vineyard Soils, Intersections With the Concept of Terroir

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The use of sustainable soil management practices is becoming common in wine growing regions around the world in response to an increased awareness of the value of soil health to maintain environmental quality, crop yield, and grape quality. In spite of this, little information is available on the meaning of soil health within a viticultural context, the effects of soil management practices on soil health and the consequences for grape quality and the expression of the terroir. In this review we discuss interrelated dynamic physical, chemical, and biological properties associated with soil health and how they could be important in the expression of the terroir. We focus on the use of cover crops and compost application, two practices commonly used in vineyard soils, and how they affect these physical, chemical and biological aspects of soil health, grape quality and the expression of the terroir. Finally, we discuss research gaps, and best management practices to reduce possible tradeoffs associated with these practices such as the emission of greenhouse gasses.

Keywords: sustainable soil management, viticulture, C sequestration, compost, cover crops, soil quality

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INTRODUCTION

Increasing awareness that soils are a non-renewable resource and the prevailing role of soils in climate change mitigation have spurred worldwide efforts to protect and improve soil health. Recent estimates indicate that 36 billion tons of soil are lost annually due to water and wind erosion alone (Borrelli et al., 2017). Besides erosion, soils are threatened by soil organic matter (SOM) loss, soil nutrient imbalances, salinization and sodification, soil sealing and land intake, loss of soil biodiversity, contamination, acidification, compaction, and waterlogging (FAO and ITPS, 2015). The term “Soil Health” has been co-opted by governmental and non-governmental organizations, academic institutions, industry and grassroot organizations alike in an effort to raise awareness of soil conservation and protect soils from degradation (Karlen et al., 2019). This urgency to protect soils has been further strengthened by their potential to store carbon (C) that would otherwise be emitted into the atmosphere as carbon dioxide (CO₂), thereby offering an appealing pathway for climate change mitigation (Lal, 2004; Paustian et al., 2016). France announced the four Per mille Initiative at the Climate Summit in Paris in 2015, aimed at reducing greenhouse gas (GHG) emissions and increasing food security by increasing soil organic carbon (SOC) concentrations by four permille worldwide (Minasny et al., 2017). Similar initiatives have followed, including California’s Healthy Soils Program which was launched in 2017 (Ross, 2016).

Conservation of soils and soil ecosystem services has been proposed as a key strategy to attain the United Nations Sustainable Development Goals by 2030 (Keesstra et al., 2016, 2018), and implemented in the European Union through payment for ecosystem services in rural development programs (Galati et al., 2016).

Under these initiatives, management practices that increase sequestration of SOC are promoted or incentivized. Much of the research on soil health and C sequestration have focused on cereal cropping systems in temperate climate zones (Fine et al., 2017). Given important differences between vineyards and cereal cropping systems, it is pertinent to evaluate soil health in the context of vineyard soils in particular and discuss the implications for the winemaking industry.

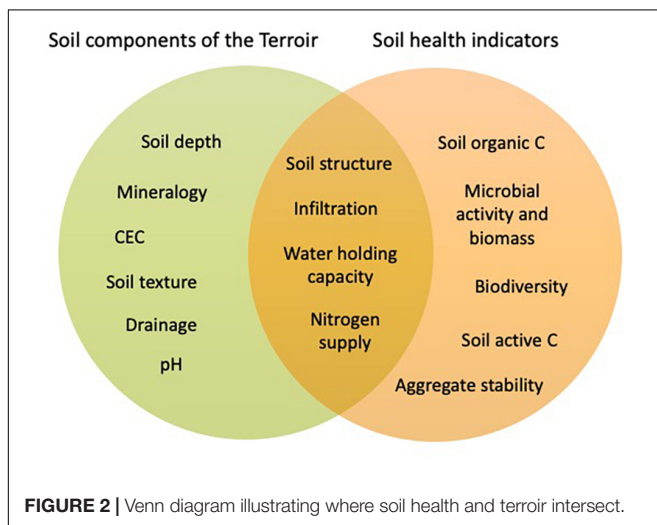
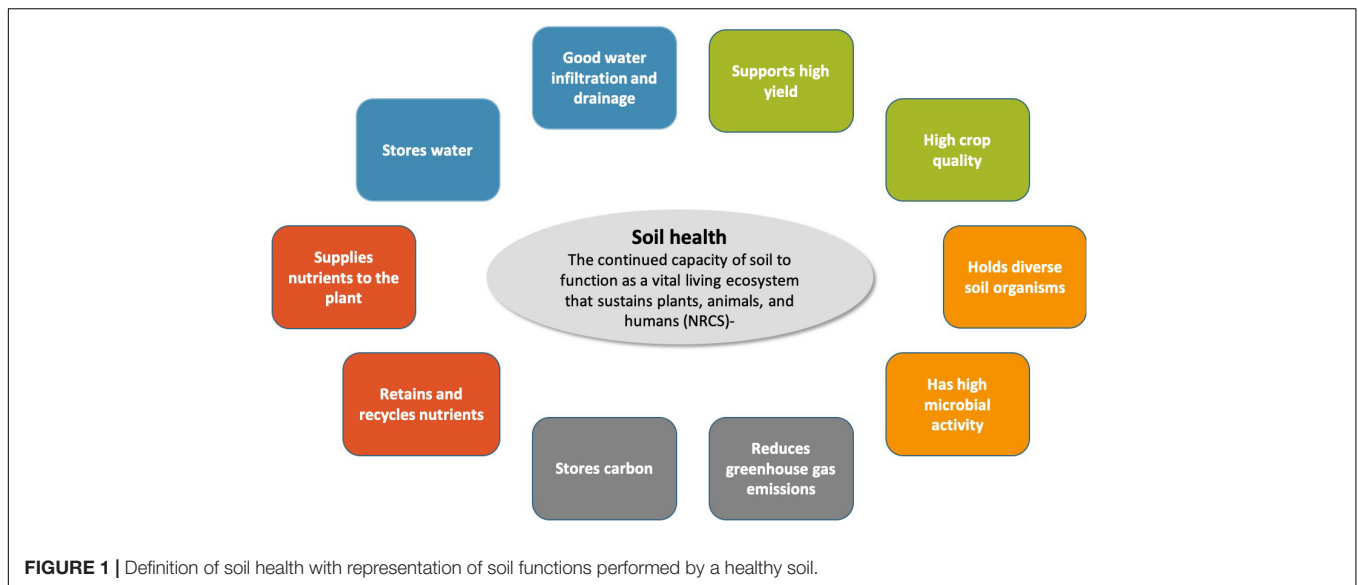
Vineyards in the old world were often established on marginal land, reserving the most fertile soils for cultivation of cereals, and other food crops (Martínez-Casasnovas and Ramos, 2006; Blavet et al., 2009), while extensive availability of land in the new world offered deep, alluvial, fertile soils for vineyard establishment (White, 2015). As a result, vineyards arguably occupy a broader range of soil types than any other crop. Due to microclimatic effects on winegrape quality, vineyards are often established on slopes, taking advantage of the hill's aspect to optimize solar radiation for the crop (White, 2015). Vineyards on slopes and marginal lands especially are at elevated risk for soil degradation, causing declines in soil quality and fertility, reduced water infiltration and storage, impaired quality of ground and surface water, diminished air quality, and risks associated with climate change mitigation and adaptation. Meanwhile, vineyards have a relatively low nitrogen (N) requirement, implying a low risk for N pollution associated with N fertilization compared to other crops (Williams, 1999). Moreover, as perennial crops with a relatively deep root system, vineyard soils were suggested to have great potential to sequester C (Suddick et al., 2013). Viticulture practices often aim to optimize wine grape quality rather than yield, as winemakers seek to bring out the flavors of a specific terroir, while consumers increasingly value sustainable practices in their decision process when buying wines (Schäufele and Hamm, 2017). As such, many questions remain on how to balance soil management to optimize soil health and the expression of terroir. Therefore, the objectives of this review are to (1) explore where soil characteristics for soil health and fine wine terroir intersect; (2) synthesize the literature on how cover crops and compost application affect soil health and terroir in vineyards; and (3) identify knowledge gaps in the management of cover crops, compost application and other novel practices to improve soil health and terroir.

WHERE SOIL HEALTH MANAGEMENT AND THE EXPRESSION OF TERROIR INTERSECT

The concept of soil health or soil quality has been of concern to soil scientists and agronomists for decades. Various attempts have been made to define soil health and identify metrics and frameworks to quantify the health status of a

soil (Karlen and Rice, 2015; Bünemann et al., 2018; Stewart et al., 2018). The United States Natural Resources Conservation Services (NRCS) defined soil health as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans,” an adaptation of the earlier definition of soil quality by Doran (1994). A key component in this definition is the importance of soil functions; a healthy soil does not only show certain properties, these properties link to the capacity of the soil to perform functions or deliver ecosystem services that benefit humankind (Doran, 1994; Haygarth and Ritz, 2009). In this review, we adopted previously proposed concepts of soil functions (Schulte et al., 2014; Vogel et al., 2019), and envision a healthy soil to (1) support high yield and crop quality, (2) have good water infiltration and the capacity to store water, (3) retain and recycle nutrients efficiently, while supplying nutrients in correspondence with crop demand, (4) store C and reduce GHG emissions, and (5) support diverse microorganisms and high biological activity (Figure 1). The capacity of a soil to perform these soil functions can be assessed by a suite of chemical, physical, and biological soil health indicators; however, a standardized approach to assess soil health remains elusive (Fine et al., 2017; Stewart et al., 2018; Vogel et al., 2019).

For the objective of winemaking, the most important soil function to be optimized is support of high crop quality. It is well known that soils influence the quality of winegrapes; in fact, the impact of the soil, when combined with climate, topography and grapevine variety, is referred to as the terroir effect (Van Leeuwen et al., 2018). When we consider the soil component of the terroir effect in relation to soil health, it is helpful to distinguish (i) inherent (or use-invariant) soil properties from (ii) dynamic or manageable soil properties (Wienhold et al., 2004; Karlen et al., 2019). The soil component of terroir has been linked to factors such as soil depth and mineralogy (White, 2015), which would be considered inherent soil properties, while other studies have found effects of soil nutrient supply, soil moisture, and soil temperature on winegrape quality (Van Leeuwen et al., 2018), which are considered dynamic soil properties. In this review, we deem that soil health is reigned by dynamic soil properties, and that a healthy soil is a soil that performs soil functions to its maximum capacity. This is in line with Fine et al. (2017), who proposed scoring schemes for soil health indicators based on soil texture groups, as implemented in Cornell's comprehensive soil health assessment. It also resonates with Vogel et al. (2019), who considered that each soil has a limited potential to deliver a certain soil function, and that soil health assessment should reflect the status of a soil relative to its potential. As such, soil health and terroir are expected to intersect with respect to the dynamic soil components of terroir (Figure 2). Because crop quality is one of the functions performed by a healthy soil, we postulate that a healthy vineyard soil must optimally express its terroir. While the concept of terroir and its relationship with crop quality is well understood and deeply engrained in the context of wine production, the concept of soil health has recently gained acceptance by growers worldwide (Brevik et al., 2019) and there is an urgent need to reconcile these two concepts. Here, we discuss how dynamic soil properties of terroir intersect with soil health.



Soil Temperature

Van Leeuwen et al. (2018) proposed that cool soils may be an advantage in warm climates because they can slightly delay ripeness, thereby enhancing certain flavors. Soil temperature is greatly affected by soil color; light colors have a high albedo effect which keeps the soil relatively cool. Soil color can be described as an inherent soil property. However, light colors on the soil surface can be achieved by management practices such as mulching and leaving cover crop residue on the surface (Teasdale and Mohler, 1993). While soil temperature appears relevant to terroir, it has not been commonly associated with soil health assessment. Management practices that decrease soil temperature, however, are greatly promoted in regard to other soil health functions.

Soil Chemical Fertility

It can be argued that soils of the best terroirs should be characterized by a stable and well balanced nutrient supply, able

to assure the target qualitative result without massive integration of fertilizers (Costantini and Bucelli, 2014). Experience shows that these soils are often characterized by only moderate chemical fertility. Correlations between the mineral composition in soils and wine has been used with mixed success to identify the geographic origin of wines (Versari et al., 2014; Pepi et al., 2017). Yet, scientific evidence linking soil chemical properties to grape and wine quality is scarce. Maltman (2013) argues that the minerals in wine are typically metallic cations at minuscule concentrations that lack flavor, and only distantly relate to vineyard geological minerals. Meanwhile, plant nutrients play an important role in plant physiology and metabolism. Mackenzie and Christy (2005) found that grape juice properties such as Baumé and titratable acidity (TA) were correlated with several plant-available trace elements in the soil, most notably Ca, Sr, Ba, Pb, and Si. Potassium content of soil has been found to have an effect on must acidity (Costantini and Bucelli, 2014), and manganese has been correlated with phenolics in grape berries (Bramley and Janik, 2005). While mechanisms underlying these correlations are lacking, the results suggest that soil cation chemistry does have an influence on wine grape composition. We increasingly understand how soil biological processes govern the availability of plant essential and beneficial nutrients and acknowledge that soil management has the potential to modify these processes. In particular, increased popularity of organic amendments such as composts in vineyards could greatly affect the availability of essential and beneficial plant nutrients. Hence, it likely behooves viculturalists to better understand how managing soil nutrient supply can optimize the soil chemistry related expression of terroir.

Soil Nitrogen Supply and Retention

Nitrogen is one of the most limiting nutrients for plant growth, and by far the dominant nutrient applied as fertilizer to cropping systems worldwide. As ensuring high N supply is considered a

type of insurance for high crop production, it is not surprising that average N use efficiencies (i.e., the amount of applied N taken up by the crop) are as low as 50% (Ladha et al., 2005). N not taken up by the plant is commonly lost from the soil-plant system through leaching or gaseous emission (**Figure 3A**). While an adequate supply of N is crucial for good crop productivity, the overapplication of N fertilizer over the last decades has caused large losses of N to the environment with alarming consequences for air and water resources (Rockström et al., 2009).

Soil NO_3^- concentrations are typically shown on soil test reports and have been used to monitor the availability of N for the plant. Good nutrient stewardship keeps soil NO_3^- concentrations high enough to meet crop N demand, and low enough to reduce the risk of N loss to the environment. However, improved understanding of the N cycle increasingly demonstrates that NO_3^- is not a static pool waiting to be taken up by the plant. Instead, soil NH_4^+ and NO_3^- pools can be very dynamic, reliant on rapid mineralization, nitrification and immobilization rates that continuously produce and consume new plant available N (Drinkwater and Snapp, 2007; Bowles et al., 2015). In this scenario, plants successfully compete with microorganisms for the use of newly mineralized plant available N, and soil NO_3^- concentrations can likely be kept much lower than previously thought, further reducing N losses to the environment (**Figure 3B**). Following this paradigm shift, a healthy soil supplies N when the plant needs it and retains N during periods of low plant demand by cycling it efficiently through a thriving soil food web.

In most cropping systems, the success of this new paradigm is subject to the ability of the plant to compete with microorganisms for soil available N. In wine grape production, however, the story is even more complicated. As for most crops, N plays a major role in many biological functions and processes and is therefore a highly abundant and often limiting nutrient in grapevine production. Winegrapes remove about 22–56 kg of N ha^{-1} through harvest (Williams, 1999), and this value serves as an indication of the minimum amount of N that should be replenished annually. In addition, a great amount of N is invested in the growth of trunk, roots, leaves and shoots. Although a fraction of this N is reabsorbed into permanent structures when plants go dormant or recycled in the soil-plant system with leaf fall and pruning, vegetative growth does imply additional N demand. Meanwhile, excessive N availability can boost vigor, negatively impacting sink-source relationships in the vine and the canopy microclimate, all of which can lead to loss of grape yield and quality (Wheeler and Pickering, 2003; White et al., 2007). Moreover, N nutrition also directly affects the form and concentration of yeast assimilable nitrogen (YAN) in the grapes, with further implications for wine quality (Bell and Henschke, 2005; Reynard et al., 2011). It is clear that to balance vine health and grape quality, vineyard N status must be managed very carefully.

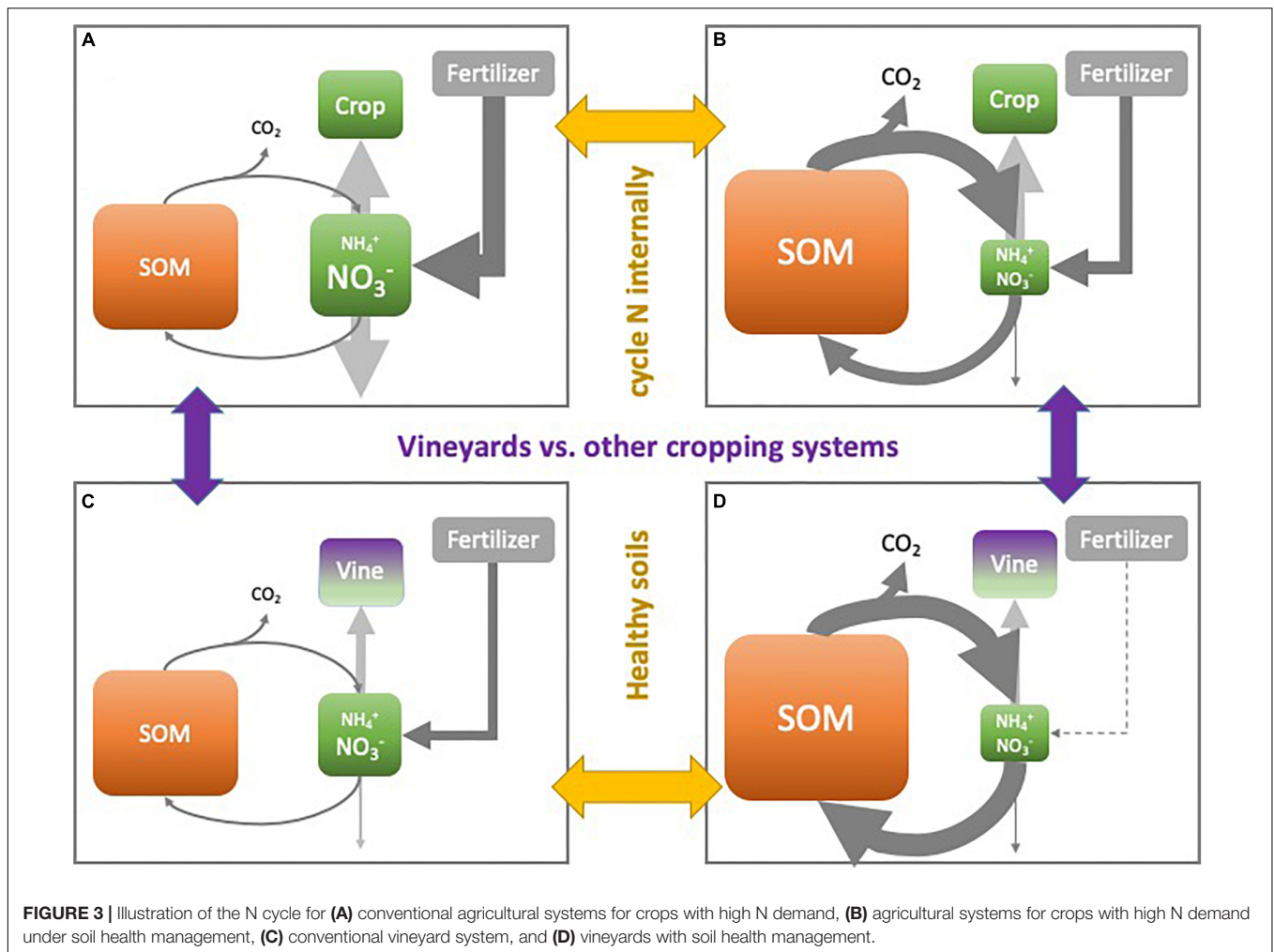
Traditionally, excessive availability of N in vineyards is avoided by delivering N in small doses when vine N demand is greatest (**Figure 3C**). When building SOM and soil health,

however, care must be taken that this does not inadvertently lead to an increase in the soil's capacity to supply N, thereby promoting vine vigor and loss of wine grape quality. As the balance between N mineralization and immobilization is governed to a great extent by the availability of C relative to N (Booth et al., 2005), C-rich organic inputs such as straw amendments have been proposed as one strategy to manage excessive N supply in healthy soils (Wheeler and Pickering, 2003) (**Figure 3D**). Alternatively, non-legume cover crops have been used to remove excessive soil NO_3^- , by increasing competition with the vines for available N (Wheeler and Pickering, 2003; Van Leeuwen et al., 2018).

Water Availability and Drainage

In wine grape cultivation, it is important to carefully manage water availability and drainage in order to ensure vine health as well as wine grape quality. Excessive water availability can promote vigor and cause direct and indirect negative effects on wine grape quality (Wheeler and Pickering, 2003; White et al., 2007). Therefore, high wine grape quality is often expressed under mild water stress, as found on well-drained soils or as a result of deficit irrigation. If water stress becomes too severe, however, vine health, yield as well as wine grape quality are jeopardized. This is particularly relevant for vineyards in Mediterranean climates where water scarcity can become an issue, especially in the light of climate change (Medrano et al., 2015; Mirás-Avalos et al., 2017).

Whether a vineyard experiences excessive water supply or severe water stress depends on the climate, the cultivar, the rootstock, irrigation management, canopy management, soil type, as well as soil health management (Medrano et al., 2015). Various soil properties affect soil water regulation, most notoriously water holding capacity, plant available water, and hydraulic conductivity. Water holding capacity is the water the soil can hold on to against gravitational forces. The water holding capacity reflects the amount of water in the soil at a matric potential of approximately -33 kPa. Permanent wilting point is reached at a matric potential of approximately $-1,500$ kPa. At this point, water left in the soil is strongly held by capillary forces and unavailable to the plant. Therefore, plant available water is defined as the amount of water observed between field capacity and permanent wilting point. Finer textured soils have a greater water holding capacity compared to coarser textured soils (**Figure 4**). Meanwhile, the greatest plant available water is typically observed in silt loams and silty clay loams. In finer soil texture classes, plant available water decreases as the water left in the soil at the permanent wilting point increases. Even though water holding capacity and plant available water are predominately determined by soil texture class, building soil health by increasing SOM and improving soil structure has the capacity to increase water holding capacity and plant available water (Kern, 1995; Olness and Archer, 2005). While water holding capacity and plant available water are important metrics for water storage, hydraulic conductivity describes the ease with which water can move through the soil. Hydraulic conductivity is greatly affected by texture and soil moisture. Hydraulic conductivity is typically greater in coarse textured



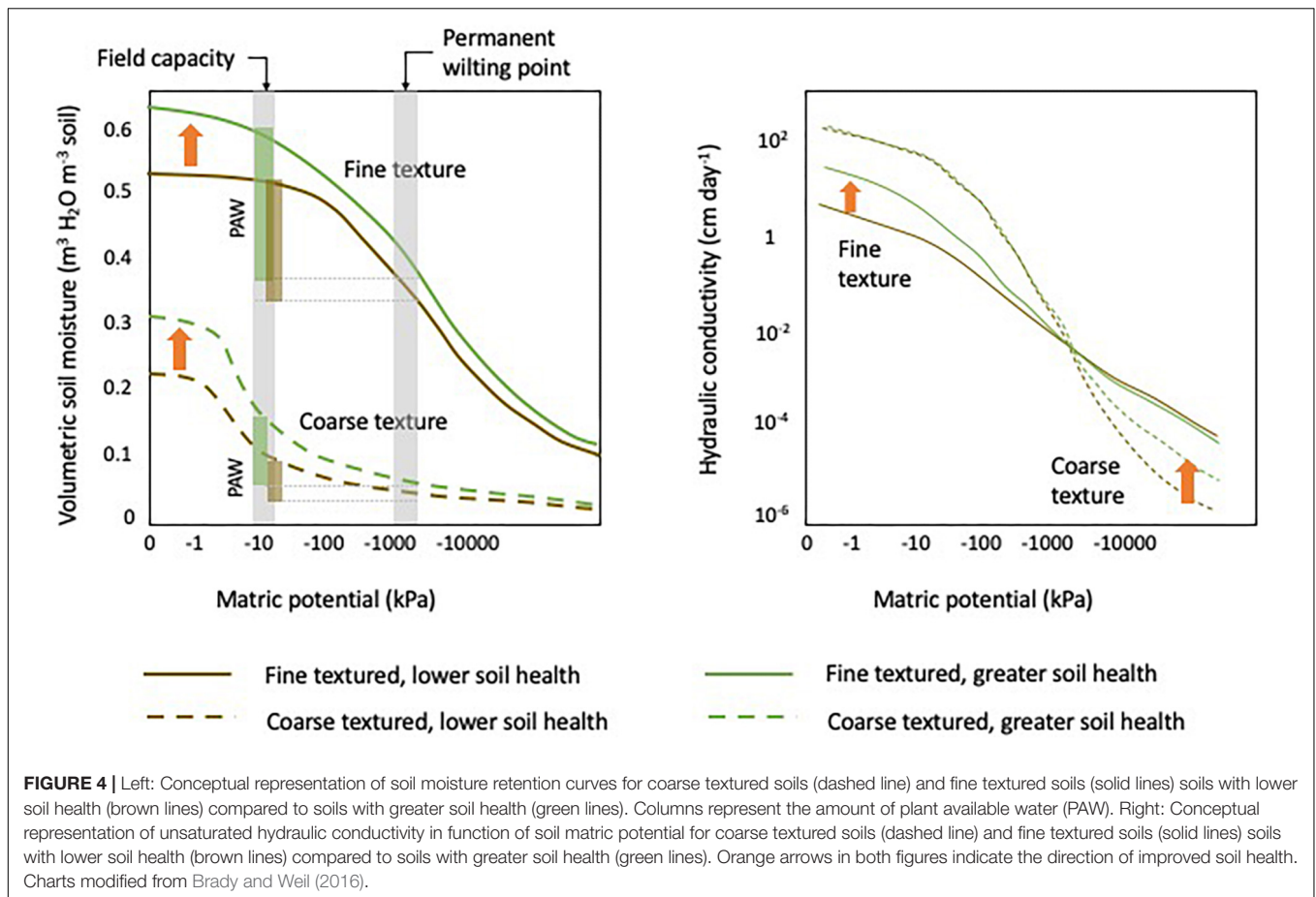
soils under very wet conditions but as the soil becomes dryer it decreases sharply and, at low soil moisture conditions, hydraulic conductivity is lower than in fine textured soils (Figure 4). In addition to the inherent property soil texture, manageable soil properties including SOM content and soil structure have been shown to affect hydraulic conductivity (Vereecken, 1995).

From a soils water balance perspective, soil water supply is determined by infiltration rate, storage, drainage, runoff, and evapotranspiration (Figure 5). In a fine-textured soil, the amount of water stored in the soil may be compromised if runoff is high relative to infiltration. In contrast, water supply may be excessive in fine textured soils in wetter climates, due to the high water holding capacity of fine textured soils (Van Leeuwen et al., 2018). Soil health management can be tailored to improve infiltration and water storage in dry climates; or mitigate excessive water storage in fine textured soils by improving hydraulic conductivity and drainage or promoting evapotranspiration in wetter climates. Meanwhile, the low water holding capacity of coarse textured soils causes increased risk for severe water stress in dry climates. Here, soil health management can increase water holding capacity and

help mitigate severe water stress (Medrano et al., 2015). As such, soil health management regarding water regulation can greatly impact the terroir effect.

Soil Biodiversity

There is a growing interest in the role of the soil microbiome not only for grapevine health and nutrition but also for wine quality. The soil microbiome includes all microorganisms that can be found in soil, including archaea, bacteria, viruses, fungi, protists, and other microbial eukaryotes (Fierer, 2017). For most of the history of viticulture, and agriculture in general, soil microbes were mostly seen as something negative (i.e., pathogens), and efforts to improve wine quality were mostly focused on grapevine genetics and soil cultural practices, with little consideration for the soil and plant microbiome. The increasing availability, affordability and use of molecular techniques is revealing the existence of a great amount of biodiversity in the soil, the root–soil interface (the rhizosphere) and the plant itself with beneficial functions for plants (Vandenkoornhuys et al., 2015). Soil microbial communities support key ecological processes and are directly responsible for the provision of the most important soil ecosystem services such as decomposition, mineralization of

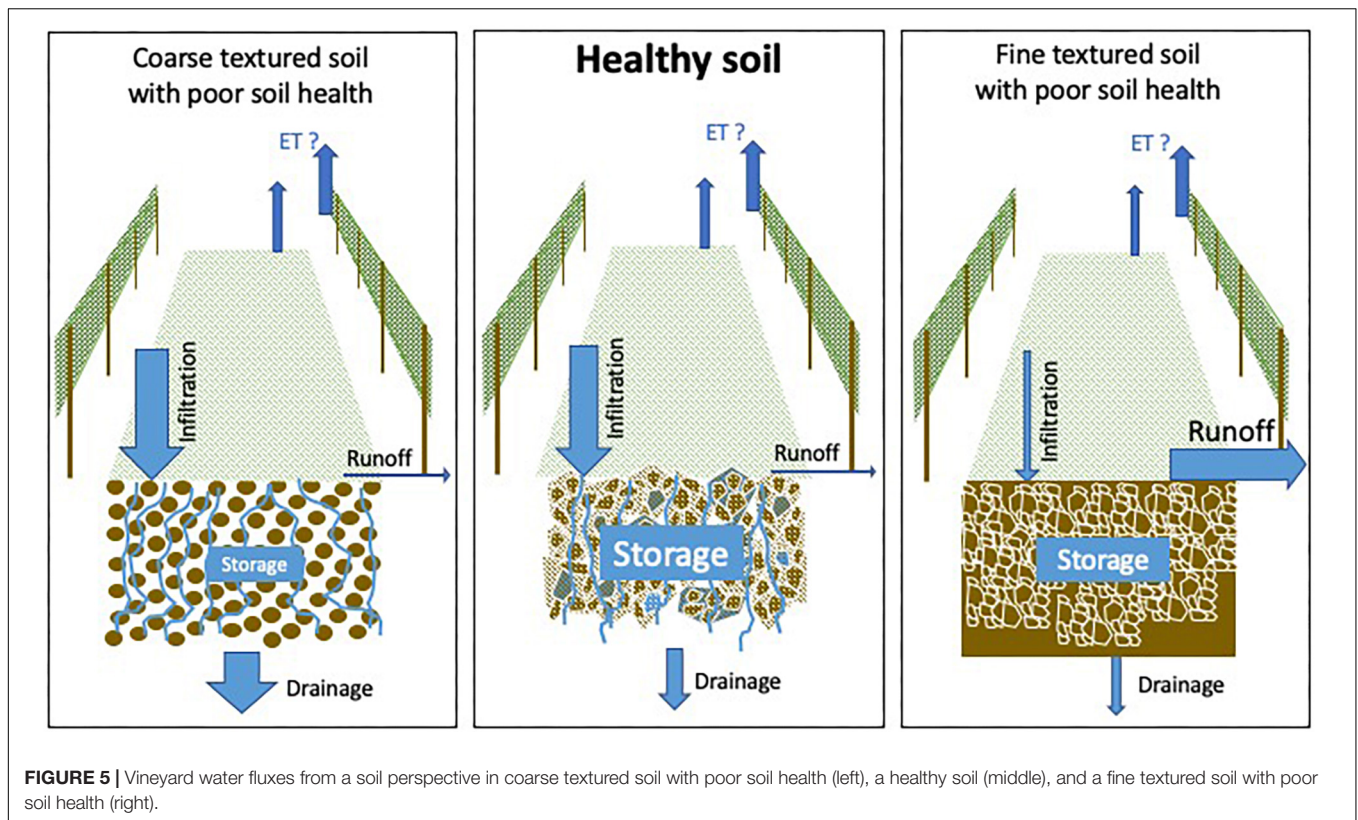


plant nutrients, atmospheric N fixation and C sequestration, all of them of high relevance for agricultural production (Bardgett and van der Putten, 2014; Fierer, 2017). Plants with adequate nutrition may be more resistant to biotic stress; in addition, soil microorganisms are known to support plant health by competing with pathogenic microorganisms for soil resources, production of antibiotic substances, or triggering of plant defenses, the so-called induced systemic resistance (Berendsen et al., 2012). But the role of the soil microbiome in wine production goes beyond supporting the typical functions of a healthy soil, wine making is essentially a microbial process in which the whole grape microbiome in early fermentation stage, including both bacteria and fungi, drives fermentation performance and the chemical characteristics of the finished wine (Bokulich et al., 2013; Belda et al., 2017). The microbial community of the winegrapes is known to share several microbial taxa with the soil, which suggests that soil may serve as a reservoir for grape microorganisms that are carried over into the fermentation stage (Zarraonaindia et al., 2015). Soil microorganisms may colonize the grapes through different pathways, such as the migration of root endophytes, dust, rain splashes, or people during harvesting and other management events (Gilbert et al., 2014). Therefore both the soil and grape microbiome are as important as the grape varietal, the soil type or the climate in regulating the organoleptic properties of wine, and show

a strong biogeographical pattern that allows to differentiate between wine growing regions and even vineyards (Bokulich et al., 2016; Belda et al., 2017). This has led several scientists to propose the concept of the *microbial terroir* (Belda et al., 2017) opening a new and promising research field in which the soil and plant microbiome could be manipulated to support plant health, fermentation and produce optimal organoleptic wine properties. This would be achieved through management for a healthy soil microbiome as an integral part of the soil ecosystem to achieve the maximum expression of the terroir. Recent evidence shows that practices such as cover cropping results in significant changes in the soil microbiome, potentially altering the grape microbiome and wine quality (Burns et al., 2016). Yet, Chou et al. (2018) found little change in the grape microbiome with soil management practices such as herbicide application or cultivation for vegetation removal under the vine.

Soil Carbon Sequestration and Greenhouse Gas Emissions

Soil C sequestration has been promoted as a powerful strategy to mitigate climate change (Lal, 2004). In most soils, the predominant form of C is organic C. Soils serve as a sink for atmospheric CO_2 when management practices that increase SOC stocks are adopted. Soil C sequestration hinges on the balance



between C inputs and losses from decomposition. Soil C inputs can be increased through organic amendments or cover crops, but the net effect on SOC stocks depends on how much of the C that enters the soil is ultimately retained. Relatively stable SOC pools are typically thought to be chemically protected (binding with clay and silt minerals), physical protected (occlusion into soil aggregates), or biochemically stabilized (condensation of recalcitrant C compounds) (Six et al., 2000). Moreover, rather than a pool of inherently stable and chemically unique compounds, evidence has mounted that SOM is a continuum of progressively decomposing organic compounds processed through the soil food web (Lehmann and Kleber, 2015; Kögel-Knabner, 2017). Therefore, C sequestration requires continuous management of the turnover and volume of organic compounds and warrants further research into balancing both stocks and flows of organic matter (Lehmann and Kleber, 2015).

When building SOC stocks as a means to mitigate climate change, one must also consider tradeoffs from GHG emissions, most notably the potent GHG nitrous oxide (N_2O). N_2O is produced predominately by nitrifying and denitrifying microorganisms in the soil and stimulated by anthropogenic and natural disturbances such as fertilizer and organic amendment inputs, rain events, irrigation, and tillage (Butterbach-Bahl et al., 2013; Verhoeven et al., 2017). While building SOC stocks is a slow process that may take 5–10 years before a measurable management impacts are observed, responses of N_2O emissions to management changes are much more instantaneous. The net effect of management on GHG emission reductions takes the

balance between changes in SOC stocks and changes in N_2O emissions over multiple years.

Several studies assessing the C balance of vineyards have found that vineyards have great potential for storing C (Kroodsma and Field, 2006; Suddick et al., 2013; Brunori et al., 2016; Scandellari et al., 2016). Kroodsma and Field (2006) estimated that $68 \text{ g C m}^{-2} \text{ year}^{-1}$ could be sequestered by converting annual cropping systems to vineyard agroecosystems in California. Nevertheless, the potential of vineyards to sequester C depends on soil physical characteristics, the grapevine's biological properties, as well as management practices in the vineyard (Brunori et al., 2016; Vicente-Vicente et al., 2016). Most measurements of N_2O emissions in vineyards have taken place in Mediterranean climates. Under these environmental conditions, N_2O emissions in vineyards are relatively small compared to potential to sequester SOC (Garland et al., 2011; Longbottom and Petrie, 2015). Nevertheless, N_2O emissions from vineyards can be further reduced by modifying the timing of N fertilizer application, offsetting soil and cover-cropping activities in the tractor row in relation to forecasted precipitation and minimizing floor management activity in the fall is also recommended (Longbottom and Petrie, 2015; Verhoeven et al., 2017).

What does this all mean for terroir? Soil C sequestration and GHG emissions will unlikely have a direct effect on terroir. However, it is well-known that SOC is essential for maintaining a good soil structure, retaining nutrients, and supporting an active soil food web, all of which have been linked to terroir. Moreover, market research shows that wine

consumers increasingly value sustainability in wine production, especially among higher spenders and wine experts (Pomarici, 2016; Schäufele and Hamm, 2017). In a recent review of articles published between 2000 and March 2016 (Schäufele and Hamm, 2017) found that a considerable number of consumers across different countries reported a willingness to pay a premium for wine with characteristics of sustainable production and that sustainability cues were often perceived as quality indicators.

As a next step, efforts should be focused on establishing the spatial variability and mapping of soil C and soil biodiversity as components of soil and the terroir (Vaudour et al., 2015). Furthermore, it is important to understand how soil management commonly used to support soil health in wine grape production, will affect the expression of the terroir.

COVER CROPS AND COVER CROP MANAGEMENT FOR IMPROVED VINEYARD SOIL HEALTH AND EXPRESSION OF TERROIR

Cover crops are traditionally used in the vineyard interrow to prevent soil degradation and erosion (Battany and Grismer, 2000; Ruiz-Colmenero et al., 2013; Novara et al., 2018), a practice that is being increasingly incentivized in most of the wine growing regions of the world such as California or the Mediterranean countries of Europe, where soil degradation is a pressing issue (Rodrigo-Comino, 2018; Rodrigo-Comino et al., 2018). Moreover, cover crops provide multiple other services, depending on the plant species used, such as acting as catch crops, fodder or green manure (Ramírez-García et al., 2015). Additionally, several recent meta-analyses show that cover crops support ecosystem services such as above- and below-ground biodiversity, pest control, C sequestration and soil fertility (Vicente-Vicente et al., 2016; Bowles et al., 2017; Winter et al., 2018; Shackelford et al., 2019). Many of the ecosystem services provided by cover crops are mediated through effects on soil physical, chemical and biological properties that support soil health and that may affect the expression of the terroir.

Even though the use of cover crops to manage soil fertility dates back to the Roman empire, this practice was mostly abandoned after the green revolution and widespread availability of synthetic fertilizers (Dunn et al., 2016). Today, in spite of the increasing evidence of the benefits for soil health, adoption rates are still very low due to the contrasting perceptions of producers on the actual benefits provided by cover crops, concerns over water and nutrient usage (especially in arid regions), and lack of adequate management strategies (Dunn et al., 2016; Schütte and Bergmann, 2019). Furthermore, cover crops can act as vectors or increase susceptibility of vines to plant diseases (Forte et al., 2010; Muscas et al., 2017). These issues limit the adoption of this practice and drive the active removal of vegetation in the vineyard interrow through the use of tillage and/or herbicides with negative consequences for soil health. As consumers demand sustainable products and are willing to pay the premium of sustainably grown wine, air and water quality regulations are

imposed, growers are forced to consider the use of cover crops. Thus, there is a strong need for a careful synthesis of the potential benefits of this practice and how management decisions can reduce potential drawbacks.

Cover crops protect the soil from the eroding action of raindrops preventing soil erosion and runoff (Battany and Grismer, 2000), but they also improve infiltration rates (Gulick et al., 1994; Biddoccu et al., 2017) which is particularly important for vineyards established on steep slopes with higher erosion rates (Ruiz-Colmenero et al., 2013; Rodrigo-Comino, 2018). Higher infiltration, lower runoff and erosion rates in cover cropped vineyards lead to lower nitrate runoff and therefore the increase in nutrient retention (García-Díaz et al., 2017). Higher infiltration has been attributed to the increase in SOM, improvement of structure, including aggregate stability and pore connectivity (Aljibury and Christensen, 1972; Ruiz-Colmenero et al., 2013). Cover crop termination by mowing increases infiltration rates by 45% as compared to tillage (Ruiz-Colmenero et al., 2013). It is also well known that vineyards under cover crops and with a better soil structure store more water than soils without permanent vegetation cover or tilled (García-Díaz et al., 2017; López-Vicente and Álvarez, 2018).

Improvements in soil structure, pore connectivity and water holding capacity are interrelated soil properties which are directly affected by the growth of plant roots and input of organic matter not only through aboveground biomass incorporation but mostly through root turnover and root exudates released from living roots (Sokol et al., 2019). More than half of the plant biomass is belowground, which constitutes a large input of C directly into the soil; the release of root exudates constitutes a constant drip of C that feeds the rhizosphere microbial community leading to the formation of stable C-mineral associations, which contribute to further aggregate formation (Sokol and Bradford, 2019). In Mediterranean climates cover crop growth occurs during the wet season (fall and winter) and afterward, during the dry season, annual cover crops die down whereas perennial plants go into dormancy. Even though this stops root exudation, the role of roots in maintaining root structure during the dry season is still highly relevant, as dead roots hold together and preserve microbially created macroaggregates (Blankinship et al., 2016). As a result, total soil organic C and aggregate stability increases in vineyard soils with cover crops as compared to bare soil (Guzmán et al., 2019); these increases are more pronounced in the upper centimeters of soil (Wolff et al., 2018) and seem to depend on cover crop management; for instance, certain cover crop mixes result in higher C sequestration rates and increases in soil C and improvements in soil structure are higher if cover crop is not tilled (Winter et al., 2018; Novara et al., 2019).

Above and belowground C inputs by cover crops influence the structure of the soil microbial community, increasing microbial biomass and changing the species composition. Burns et al. (2016) observed that cover crop presence and species drove soil microbial community composition and consistently resulted in distinctive bacterial and archaeal soil communities throughout 19 vineyards in Napa Valley, California. As mentioned earlier, the soil microbiome has important implications, not only for nutrient cycling and soil health in general, but also for the health, yield

and quality of the grapevine, and it is currently regarded as an important component of the terroir (Belda et al., 2017).

In addition to changes in the structure of the soil microbial community, cover crop C inputs increase microbial activity, soil respiration and CO₂ efflux as compared to non-cover cropped and tilled vineyard soils (Steenwerth and Belina, 2008b). N inputs with leguminous cover crops could increase the amount of available N in the soil and therefore nitrification and denitrification rates that lead to the production and release of N₂O, a potent GHG (Garland et al., 2011). Increase in CO₂ and N₂O emissions to the atmosphere could offset the potential environmental benefits of cover crops. Nevertheless, the amount of total C sequestered in plant biomass and the increase in soil C usually exceeds the increased CO₂ emissions under cover crops (Wolff et al., 2018). Emissions of N₂O from vineyard soils are usually small but can be increased by soil management practices that affect soil nutrient content, labile C and moisture (Verhoeven et al., 2019). Reductions in N₂O emissions from cover cropped soils could be potentially achieved through the selection of the cover crop mix to reduce the presence of legumes or the choice of cover crop termination method (tilling, mowing, or grazing), however, no clear differences have been observed yet in this respect (Garland et al., 2011; Wolff et al., 2018).

Changes in soil microbiome, physical and chemical properties could have significant impacts to vine vegetative growth, yields, grape and must quality, by changing water and nutrient availability. Cover crops can reduce N uptake during grapevine vegetative growth and reduce vigor and N nutritional status, increasing the anthocyanin and polyphenols contents in the grapes and therefore having a positive impact in must quality (Pérez-Álvarez et al., 2013).

Nevertheless, cover crops can also be large sources of plant-available N if the mix contains legumes (Novara et al., 2019). In addition to improving soil nutrient status, potential nitrification, N mineralization and denitrification can be up to 2–4-fold greater in cover crop soils than in bare soils under tillage showing increased nutrient turnover and availability (Steenwerth and Belina, 2008a). Higher N availability under legume cover crops results in larger vine vegetative growth and reduced polyphenol in grapes as compared to non-legume cover crops (Muscas et al., 2017).

Finally, high transpiration rates in the cover crop can reduce water availability for grapevines; while this may be convenient in humid regions to regulate growth, reduce vigor and avoid negative impacts to must quality, in Mediterranean arid climates it may induce water stress in the grapevine (Celette et al., 2008; Celette and Gary, 2013). Water stress can have beneficial effects for grapevine health and must quality when it is not excessive, as it reduces vegetative growth and increases anthocyanins and polyphenol contents in the grapes (Monteiro and Lopes, 2007).

In spite of the above, several studies have seen little differences between cover cropped and non-cover cropped grapevines, suggesting that this practice does not seem to negatively affect crop vine yield and quality overall (Sweet and Schreiner, 2010; Steenwerth et al., 2013; Pérez-Bermúdez et al., 2016; Winter et al., 2018; Wolff et al., 2018), and that negative effects can be reduced by management decisions. For instance, no tilling the cover crops

can reduce grapevine N uptake as compared to tilling (Steenwerth et al., 2013). Fertilizer and irrigation management, mowing the cover crop at budbreak or reducing the sowing density can reduce competition between grapevines and cover crops in dryer and warmer growing regions (Tesic et al., 2007; Delpuech and Metay, 2018). Younger vines may also be more sensitive to water and nutrient stress in the presence of cover crops, as they don't have a sufficiently developed root system to explore different parts of the soil profile or store nutrients (Celette et al., 2008).

COMPOST USE AND MANAGEMENT FOR IMPROVED VINEYARD SOIL HEALTH AND EXPRESSION OF TERROIR

One widely adopted method to improve soil health in vineyards is through the application of composts or other organic input materials (Morlat and Chaussod, 2008; Brown and Cotton, 2011; Gaiotti et al., 2017). Increases in SOC and SOM from compost addition underlie most of the biological, chemical, and physical impacts to vineyard soils we will review in the following sections. SOC or SOM are universally increased from compost additions in vineyard soils (Pinamonti, 1998; Korboulewsky et al., 2002; Ramos and López-Acevedo, 2004; Morlat and Chaussod, 2008; Brown and Cotton, 2011; Bustamante et al., 2011; Peregrina et al., 2012; Rubio et al., 2013; Calleja-Cervantes et al., 2015a,b; Gaiotti et al., 2017; Mondini et al., 2018). Higher rates of compost addition typically result in greater treatment effects between compost treated soils and controls or grower standard NPK fertilizer practices (Korboulewsky et al., 2002; Morlat and Chaussod, 2008; Peregrina et al., 2012; Mondini et al., 2018). Both short term applications (Larchevêque et al., 2006; Rubio et al., 2013) and long-term applications (Morlat and Chaussod, 2008; Calleja-Cervantes et al., 2015a,b) result in increases in SOC/SOM in compost treated plots. The amount of SOM increases linearly with the amount of C applied in composts (Mondini et al., 2018). The longer the continued application, the stronger the treatment effect with time (Morlat and Chaussod, 2008). Soil C is the basis of the soil food web and increases in SOC from compost addition typically increases the size of the microbial biomass (Bustamante et al., 2011; Rubio et al., 2013; Wilson et al., 2016), although not always (Gaiotti et al., 2017). Increases in SOM lead to increases in total N, absolute amounts of organic N as well as inorganic N from mineralization (Larchevêque et al., 2006; Morlat and Chaussod, 2008; Calleja-Cervantes et al., 2015a; Gaiotti et al., 2017). Additions of compost derived C can influence P dynamics through competitive inhibition of P sorption sites by organic acid anions, as well as providing a source of mineral and organic P (Hue, 1992; Korboulewsky et al., 2002; Hunt et al., 2007; Wilson et al., 2016). Increases in SOC lead to better soil aggregation, infiltration and water holding capacity and reduced bulk density (Celik et al., 2004; Morlat and Chaussod, 2008; Brown and Cotton, 2011; Salomé et al., 2016; Ramos, 2017). Further, compost additions have been suggested as a potential C sequestration practice (Calleja-Cervantes et al., 2015a; Longbottom and Petrie, 2015), although N₂O (denitrification) and CO₂ (respiration) emissions may be increased in compost treated plots as compared

to controls or grower standard NPK practices (Calleja-Cervantes et al., 2015a). Thus, many of the improvements to soil health and the manifestation of terroir from compost additions to be discussed here are rooted in the addition of C and increases to SOC/SOM from compost addition.

Addition of composts routinely increases soil microbial biomass carbon (MBC) and respiration as measured by CO₂ evolution (Bustamante et al., 2011; Rubio et al., 2013; Wilson et al., 2016; Gaiotti et al., 2017). An increase in the size and activity of the microbial biomass can have beneficial effects to nutrient cycling, especially in degraded soils (Ros, 2003; Lazcano et al., 2013). Compost application can also change the structure of the soil microbial community; for instance, in a calcareous vineyard sheep compost enhanced soil microbial activity and shifted bacterial composition from oligotrophic to copiotrophic, as shown by differences in 16S rRNA gene sequences (Calleja-Cervantes et al., 2015a). A robust and diverse microbial community is a hallmark of healthy soils. However, changes in the soil microbial community resulting from application of composts can be different for different soil types. For example, organic inputs increased MBC in fine textured non-calcareous soils, but not in calcareous soils in France (Salomé et al., 2016). Increases in MBC are tied to the rate of C applied, but less to the source of C. Inputs from diverse composts (mushroom compost, farmyard manure, and vine pruning waste compost) had a similar response in MBC. Increases in the rate of C applied from composts applied lead to incremental increases in MBC (Morlat and Chaussod, 2008; Peregrina et al., 2012). Both single doses, and long-term applications increases MBC (Morlat and Chaussod, 2008; Rubio et al., 2013). Other investigations have reported no response or a modest non-significant responses of compost addition to MBC (Nendel and Reuter, 2007; Gaiotti et al., 2017). Differences in the magnitude of the MBC response from compost addition is tied to the antecedent soil health, particularly the physical and biological conditions, as well as the source and rate of compost additions (Gaiotti et al., 2017). More research is needed to connect compost addition rates, soil types and soil health objectives and potential benefits from increased MBC.

Compost application routinely increases soil N, and this increase is incremental with compost application rate (Korboulesky et al., 2002; Peregrina et al., 2012). Peregrina et al. (2012) reported increases in N and SOC with increases in the rate of fresh and composted mushroom substrate applied. Application of various sources of organic materials, including composted sewage sludges, mushroom composts, composted cattle manure, winery wastes and pruning wastes routinely increase soil total N (Larchevêque et al., 2006; Morlat and Chaussod, 2008; Calleja-Cervantes et al., 2015a; Gaiotti et al., 2017). Mugnai et al. (2012) reported an increase in total N over a positive control (NPK) following 9 years of compost grape waste application, with NH₄-N favored over NO₃-N in compost treated plots, with the opposite true in the mineral nutrient positive control (grower standard NPK practice). Long term and continuous applications of cattle manure in excess of crop demand, may result in N build up, N leaching and potential suppressive effects on yield and quality (Morlat and Chaussod, 2008; Morlat and Symoneaux, 2008). While application of

composts and other organic materials generally increases soil total N, differences exist in the amounts of organic N versus inorganic N, as well as the timing of release soluble N from mineralization of added organic inputs.

Initial compost applications result in a quick pulse of inorganic N followed by a prolonged period of elevated organic N. Synchronizing mineralization of compost N and the timing of high N demand in winegrapes is an area of ongoing investigation. In a 3-year study applying a range of compost types to a calcareous soil, Bustamante et al. (2011) reported that diverse sources of compost result in an initial spike in soluble N that is tempered with time, while organic N tends to remain elevated. They concluded that excess N was not observed in the soil, suggesting that the pulse of inorganic N following mineralization was utilized by the vines. Similar results were reported by Rubio et al. (2013), after application of a variety of compost sources including pruning wastes, winery wastes (pumice), sheep manure, cattle manure and mixes of manures and pumice. Similarly, application of vermicompost and vine shoot compost led to an initial large increases in extractable N, with subsequent applications leading to progressively smaller increases in extractable N, but higher values of microbial biomass N (Mondini et al., 2018). Potentially, initial applications of compost lead to initial increases in inorganic N before the additional C increased the size of the microbial biomass, and additional N resources are either assimilated into the microbial biomass, taken up by vines or lost through denitrification (Korboulesky et al., 2002) applied three rates of sewage sludge to a French vineyard and reported an initial spike in inorganic N (NO₃ and NH₄), which subsided with increased application. Broadly, amounts of N remain elevated in compost treated plots compared to controls, and inorganic and organic N increased incrementally with compost application rate.

In winegrapes N uptake has been observed in two major periods, one from budbreak to veraison, and the second post-harvest, with as much as 34% of the total seasonal N uptake in this period (Conradie, 2017). N pulses following compost application are likely to be utilized by the vine, especially if N deficiencies exists. Winegrapes benefit from an extensive established root system such that the soluble N pulse following application can be utilized by vines at budbreak into flowering, whereas spring N pulses may be lost in shallow rooted row crop systems. This is particularly true if a restorative effect is desired from application of compost to established vines, where roots are eager for fresh nutrient inputs. For example, in an investigation of compost application rates to a degraded vineyard soil with established, underperforming vines, compost application in the dormant season resulted in a significant increase petiole N in the following growing season, with this increase incremental with application rate (significant dose response). Application of composts to established vines will result in uptake of the initial pulse of soluble N. Conversely large applications of high N composts (composted manures) at preplant may result in losses of N to the environment.

Soil phosphorus (P) is typically increased as the result of compost application (Korboulesky et al., 2002; Morlat and Chaussod, 2008; Bustamante et al., 2011; Wilson et al., 2016),

due to many factors including the additional P applied in the compost, the chelation of active Al or Ca by organic acids and other decomposition products, and competitive inhibition of P-sorption sites by organic acid anions (Hue, 1992; Delgado et al., 2002). Winegrapes have relatively low P demands (Schreiner and Osborne, 2018). The combined effect of relatively low P demand, and increased P availability due to P sorption inhibition, can lead to excess P following compost application (Korboulesky et al., 2002; Wilson et al., 2016). Care should be taken, especially when composts or other organic materials are applied to meet N demands, that excess P is not applied (Korboulesky et al., 2002). Nonetheless, P deficiency in winegrapes has been reported in certain soil types with less than 10 mg P per kg soil (Olsen-P) (Skinner et al., 1988). P deficiency can lead to reduced fruit set, yields, and vegetative growth (Skinner et al., 1988). Yield reduction from P deficiency is likely due to deleterious effects on the initiation and differentiation of bud primordia. P deficiency is manifest in blotchy red interveins, which can be mistaken for leafroll disease or red blotch disease. Soil P dynamics are directly tied to the soil component of terroir, with certain soil types, particularly red, clay rich soils from high Fe/Al parent materials (basalts and andesites), and volcanic ash soils, exhibiting P deficiency and higher P sorption capacities. In these instances, compost application can be a favorable management strategy to relieve P deficiency, due to the combined beneficial effect of applied SOM and applied P. Management of P deficiency in winegrapes is largely driven by the terroir of the soil, as influenced by pedogenesis. For example, weathered soils derived from low P lithologies, such as granite, may be P deficient, but also have low P fixation capacities, and hence would respond well to P applications (Wilson et al., 2016, 2017). Conversely, P deficient soils with high P sorption capacities, such as volcanic ash soils, will require higher applications of compost to overcome the P fixation capacity. In most instances applying composts to meet P demand will result in lower P sorption capacities, and higher P availability, than mineral fertilizers alone due to competitive inhibition of anion sorption sites (Hue, 1992; Hunt et al., 2007; Wilson et al., 2016). The management of P, both with and without composts, is dependent on the terroir of the site, as manifested by soil genesis, particularly soil mineralogy and acidity/alkalinity.

In winegrapes, reduced K supply can lead to premature leaf drop, and negative effects on yield and vegetative growth (Christensen and Peacock, 2000). Potassium is the major cation in grape juice and musts and has a significant effect on juice pH (Mpelasoka et al., 2003). Excess K has been connected to undesirably high wine pH, reduced wine stability and declines in color quality (Mpelasoka et al., 2003). Excessive K in berries may lead to lower levels of the more desirable tartaric acid, altering the perception of flavor (Mpelasoka et al., 2003). In a wide range of studies with many different sources, compost application usually increases soil extractable K. Many different types of composts, cattle manures, winery wastes, sheep manures, municipal solid wastes, garden green waste mulches, mushroom composts, and mixes of these materials result in elevated K status in soils (Pinamonti, 1998; Larchevêque et al., 2006; Morlat and Chaussod, 2008; Bustamante et al., 2011; Chan and Fahey, 2011; Calleja-Cervantes et al., 2015a,b). This is particularly true for

composts with a significant proportion of winery wastes which are higher in soluble K, and composts derived from manures (Bustamante et al., 2008; Rubio et al., 2013). Compost application leads to incremental increases in soil K, with very high levels of soil K corresponding to higher application rates (Morlat and Chaussod, 2008; Chan and Fahey, 2011).

When available, vines tend to uptake excess K, such that when soil K was increased from compost addition, plant tissue K also increases (Pinamonti, 1998; Morlat and Chaussod, 2008; Chan and Fahey, 2011). Given that berries are strong sinks for K, excess K supplied to vines results in larger amounts of K in berries (Pinamonti, 1998; Mpelasoka et al., 2003; Morlat and Symoneaux, 2008; Chan and Fahey, 2011). The strongest effect of compost applications to vineyard soils on wine quality may be from K supply, with increased K observed in grapes and musts as the result of compost addition (Pinamonti, 1998; Morlat and Symoneaux, 2008). With respect to terroir, Chan and Fahey (2011) noted that the treatment effect of composts on berry K was much less than the site effect on berry K. This suggests that, especially with respect to K, the inherent terroir, related to soil mineralogy and parent material, may be a greater factor in soil, vine and berry K status than the K applied in composts. However, further research is required to understand the variability in soil and vine K status attributable to variability in site characteristics and terroir. While several studies report increased berry K from increased extractable soil K following compost addition (Rubio et al., 2013) observed significant increases in soil K, but not in berry K. Conversely, lower rates of vermicompost and compost additions did not result in increased soil K status nor vine K status (Martinez et al., 2018). Mpelasoka et al. (2003) notes that the relationship between K supply in soils and K in berries and tissues is not always absolute. Differences in application rate, source, timing, irrigation, as well as vine parameters such as root architecture and the initial plant nutrient status will influence the uptake and availability of K. Given the significant variability in K status of soils due to differences in their terroir and pedogenic environment (mineralogy and parent material) as well as the effect of composts on soil K status, significant knowledge gaps exists connecting antecedent soil K, K supplied in composts, and the connection between soil K, berry K, must K, and wine quality.

In vineyard soils, increases in organic C from compost addition improve many soil physical properties. For example, in Mediterranean-type soils, compost additions increase aggregate stability (Celik et al., 2004; Kong et al., 2005; Goulet et al., 2006). The organic C fraction of soils is lighter than the mineral fraction and compost additions to vineyard soils typically reduce the soil bulk density (Celik et al., 2004; Morlat and Chaussod, 2008; Brown and Cotton, 2011; Salomé et al., 2016; Ramos, 2017). Both reductions in bulk density and improved aggregation lead to improved soil porosity, with improved porosity reported following compost addition (Pérès et al., 1998; Pinamonti, 1998). Soil temperature fluctuations are also reduced from application of compost mulches, especially compared to plastic row covers (Pinamonti, 1998). Improvements to soil structure and aggregation as well as improvements to porosity, lead to improvements in soil water holding capacity. Improved water holding capacity following compost addition is widely

reported (Pinamonti, 1998; Morlat and Chaussod, 2008; Brown and Cotton, 2011; Ramos, 2017; Mondini et al., 2018). Of all soil properties, soil water has the most significant effect on vine growth, vigor, berry formation and subsequent effects on wine quality (Keller, 2005, 2010). Excess water, which leads to excess shoot growth, has been linked to declines in wine quality (Hepner et al., 1985; Wheeler and Pickering, 2003). However, concerns over climate change, drought and water use efficiency suggest that improvements to soil water holding capacity following compost addition are likely to be beneficial dependent on soil type and edaphic conditions. For example, Ramos (2017) reported significant improvements to soil water holding capacity and infiltration rate following compost addition to degraded vineyard soils, with the positive effects of compost addition on per vine yield stronger in drier years. These data suggest that, in degraded soils low in organic matter, increasing SOC from composts addition may provide some resilience to drought conditions. Similarly, in degraded vineyard soils application of vine shoot composts, but not vermicompost, lead to improved soil water holding capacity (Mondini et al., 2018). Dependent on the rate and amount of compost, compost application can be expected to improve soil water holding capacity, especially with repeated applications of high C sources. Increases in soil water holding capacity following compost addition can have significant effects on vine performance. Care should be taken by viticulturalists to mediate irrigation practices following sustained application of composts. Nonetheless, compost addition to vineyard soils is promising to mitigate soil drought and improve water use efficiency. Changes and improvements to vine water use efficiency following application of diverse sources of compost requires further investigation.

Improvements to vineyard soil health are generally consistent following compost application, improving soil biological, chemical, and physical characteristics. However, there is a view among viticulturalists that compost applications may have a negative effect on quality due to excess vigor and an imbalance between shoot growth and yield, and that the clear benefits to vineyard soil health from compost application may be outweighed by the negative effects on vine balance and grape quality. Yet, this is not borne out of the available data. For example, several studies have shown no significant changes to vine balance or juice quality following compost application (Pinamonti, 1998; Bartoli and Dousset, 2011; Mugnai et al., 2012; Mondini et al., 2018). Mugnai et al. (2012) applied municipal green waste compost to a chardonnay vineyard in the Tuscany region of Italy and conclude that, using measures of both leaf area and leaf chlorophyll, excess vigor, yields, and grape quality were not significantly affected by compost addition. Similarly, Pinamonti (1998) report no negative effects to vine balance (yields/pruning weights), total soluble solids (TSS) or pH following compost addition. Where improved water status is implicated in yield or shoot growth increases in some studies (Pinamonti, 1998; Ramos, 2017), soil N status drives increased yields and shoot growth in others. (Gaiotti et al., 2017) applied composted cattle manure and composted vine pruning wastes over a 5-year period and reported significant increases in vine growth and yield, without significant changes to vine balance

(per vine yield/pruning weights). They note increased vigor in treatments containing composted cattle manure, a result they ascribe to faster mineralization rates, and more available N. In a similar, but single season study Rubio et al. (2013) applied diverse composts (citrus waste, winery waste, composted cattle manure, vine pruning wastes, and combinations of materials) and reported increases to yields, especially for mixes containing composted cattle manure, a response they also attribute to the elevated soil N status. With respect to juice chemistry, TSS was unaffected and the total polyphenol index was influenced by compost treatment, but trends were unclear. While increased N status led to increased yield in some studies, excess N was implicated in yield decline in others (Morlat, 2008). There, sustained applications of high rates (20 t ha⁻¹ for 28 years) of relatively high N composted manures had a negative effect on yields and pruning weights, potentially due to N toxicity. Conversely, lower application rates of vine pruning compost (with higher C:N ratios) had a positive effect on yields and pruning weights. Nonetheless, no changes were reported to vine balance after 28 years of continued compost application from any source trialed. With respect to juice chemistry, Morlat (2008) report that total anthocyanins and TSS were decreased, while pH and K⁺ were increased in berries following addition of high rates of composted manures. In contrast, in a 3-year investigation of irrigation strategies with and without compost addition, (Cirigliano et al., 2017) found improved anthocyanin and other polyphenol contents in berries following compost addition compared to treatments without compost. Their data suggest that in drip irrigated Mediterranean-type climates, compost application can improve grape quality over irrigation alone, perhaps due to better infiltration and water holding capacity in compost treated vines. Contrasting results on the impact of composts on vine growth and yield, as well as on grape quality, especially polyphenol compositions, requires further investigation.

Compost applications can lead to improved yields and pruning weights, without detrimental effects to grape quality (pH, TSS, and TA), although effects to anthocyanins and other polyphenols are unclear. Increases in yields and pruning weights are tied to increases in soil water status and soil N status. Evaluating the existing soil conditions, as well as available water for irrigation and yield and quality objectives, ultimately informs the compost approach adopted. For example, in established normally performing vineyards, success has been accomplished with lower N inputs, such as vine pruning waste composts (Morlat, 2008; Morlat and Chaussod, 2008; Gaiotti et al., 2017). If a significant yield response is desired, or if soils are degraded, composts richer in plant available nutrients can be applied with success (Ramos, 2017; Mondini et al., 2018). The beneficial effect of compost application on yields in drought years noted by Mondini et al. (2018) and Ramos (2017) highlights a potentially significant benefit from compost addition in the face of water shortages and requires further investigation. Broadly, more research is needed to quantify yield, pruning weight, and grape quality responses from application of diverse composts in a variety of soil types, to solidify our understanding of the effect of composts in viticulture.

CONCLUSION

As we increase our understanding of the fundamental role of soils and soil health in long term climate regulation, crop yields and quality, there is an urgent need to understand how the dynamic and inherent aspects of soil health may overlap with the concept of terroir in wine grape production. In this review we show that, because of their impact on vine health and grape quality, the physical, chemical, and biological aspects of soil health overlap clearly with the soil related aspects of the *terroir*. Furthermore, we find potential for the expansion of the terroir concept by incorporating dynamic aspects of soil health such as SOM, soil C and soil biota which influence vine performance, potentially affecting wine quality. In spite of this, there are no crop specific guidelines or reference values that would help growers manage soil health for an optimum expression of the terroir. These guidelines need to be established by defining the meaning and main functions of a healthy soil in grapevines as compared to other crops and incorporating regional variability and site-specific needs.

Conservation of soil health needs to be prioritized rather than restoration of degraded soils. The use of cover crops and compost, supports the physical, chemical, and biological aspects of soil health, therefore contributing to the expression of the soil related aspects of the terroir. However, there are outstanding knowledge gaps that need to be addressed in order to implement grapevine specific best management practices. In particular, more

information is needed on different cover crop species and mixes, their effects on vine nutrient and water uptake, the suitability of to boost different aspects of a healthy soil, and the consequences for grape and wine quality. In regard to the use of cover crops, we need a better understanding of the effects of different termination strategies (mowing, tilling, and grazing) and timing on soil health, crop yield and quality. Compost application clearly improves soil health, yet there is large variability in the observed effects potentially associated with the use of different feedstocks, placement, application rate and timing. The role of these factors needs to be understood in order to manage soil health for the maximum expression of the terroir.

AUTHOR CONTRIBUTIONS

CL and CD developed the idea for this review manuscript. CL, SW, and CD performed the literature review, and discussed and collected the data.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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