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REVIEW ARTICLES

Regenerative viticulture and climate change resilience

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ABSTRACT

Regenerative viticulture (RV) draws on disciplines and concepts such as ecology, agroecology, functional biodiversity, ecosystem services and permaculture, integrated into vineyard management to enhance both production and environmental outcomes. Its core aims are to regenerate vineyard soils and biodiversity, support vine health, enhance vineyard ecological conditions and resilience, and mitigate climate change. The purpose of this review was to evaluate the literature concerning individual, yet often interconnected components of, and approaches to RV, including soil management, cover crops, weeds, pests and diseases, and livestock integration, to establish current knowledge and inform future research opportunities. Where sufficient evidence was available, we also address the impact of RV related practices on vineyard performance, and grape and wine quality characteristics. The review found literature and science supporting viticulture's potential for: soil and biodiversity regeneration, carbon sequestration, land cooling, ecological enhancements, and soil water holding capacity improvements. There is less consensus regarding the impact of RV approaches on grape yield, wine quality and greenhouse gas (GHG) emissions, as well as a lack of vineyard-based evidence demonstrating the efficacy of biostimulants and Biological Control Agents (BCAs). Research covering a range of regional or context specific environments regarding regenerative approaches or practices are limited, particularly when seeking to address opportunities for, and impacts of whole vineyard systems change–this is a complex area that has not yet been fully addressed. Findings illustrate the emerging status of RV as a researched and/or applied concept, and this review supports those establishing RV systems and contributes to evidence-based RV approaches. It also supports policymakers by highlighting aspects of RV that contribute to the provision and protection of ecosystem services, climate change mitigation and vineyard resilience, fostering opportunities in viticulture.

KEYWORDS: carbon sequestration, climate change resilience, climate change mitigation, ecosystem services, functional biodiversity, regenerative viticulture, vineyard soils

INTRODUCTION

Regenerative viticulture is a term adapted from regenerative agriculture (RA), which focuses on leveraging ecological processes within an agricultural system to improve the health of the entire farm (Khangura *et al.*, 2023). The main goals of RA are to increase biological activity (above and below ground), augment soil health, improve nutrient cycling, and restore ecological functions while maintaining crop production and quality (Khangura *et al.*, 2023). These goals require more than simply substituting conventional inputs with organic ones and are not delivered through a didactic technological package with a list of practices to be followed, but rather through a whole farm systems change approach. RV is an emerging term being applied to the elective use of management strategies and vineyard practices that aim to regenerate vineyard soils and biodiversity, support vine health, enhance vineyard ecological conditions and resilience, and mitigate climate change. In the framework of this review, resilience refers to the ability of grapevines and vineyards to defend against, and survive climate-related events such as flooding, excess water, drought, heatwaves or emerging pests and diseases.

Unlike some agroecological or ecosystem development approaches, such as agroforestry or rewilding, which have established descriptors (Massaccesi *et al.*, 2019), no legal or regulatory definition of RV exists. Owing to this absence of an 'accepted' definition of RV, and a lack of peer reviewed studies focused on RV systems, this review evaluates literature that encompasses the individual yet interconnected practical approaches to RV and the science behind them. This review is the first to evaluate viticulture practices in terms of their potential to contribute to the aims of RV (Figure 1). These selected practices are the application of organic amendments; biological stimulants and BCAs; cover cropping; alternative weed management methods; and strategies to enhance functional biodiversity (including livestock integration).

MATERIALS AND METHODS

A scoping review method was applied using principles from the Preferred Reporting Items for Systematic review and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) (Tricco *et al.*, 2018) to identify scientific literature related to RV practices, and to evaluate and summarise the available evidence. A scoping review examines a broad research question or topic, aiming to identify and map available evidence for a specific area (Verdejo *et al.*, 2021). In this review, the question was: 'what science exists to support the efficacy of practices used in RV systems or approaches?'. We first identified common themes relating to RV (Table S1) through discussions with grape growers who were adopting regenerative approaches to viticulture, and members of the Regenerative Viticulture Foundation. We refined these themes into specific topics, and then key words and terms, which were subsequently used for the literature (peer reviewed publications) search. The process and search criteria are set out in the supplementary material (Table S1 and Figure S1). We conducted the initial key word search on Google Scholar and subsequently some limited secondary sources of information were used to support findings. Information from sixty-four references were used in the tables (31) and figures (33) in this review. The criteria for selection or rejection of literature are detailed in Table 1. The resulting literature was separated into sub-sections for this review structure, using the aims of RV (Figure 1) as a guide. Where topics were not studied in a vineyard setting, research focused on other crops has been included. The objective was to establish current RV practices that are based on evidence from scientific studies, and to identify further research needs within the topics covered in the review.

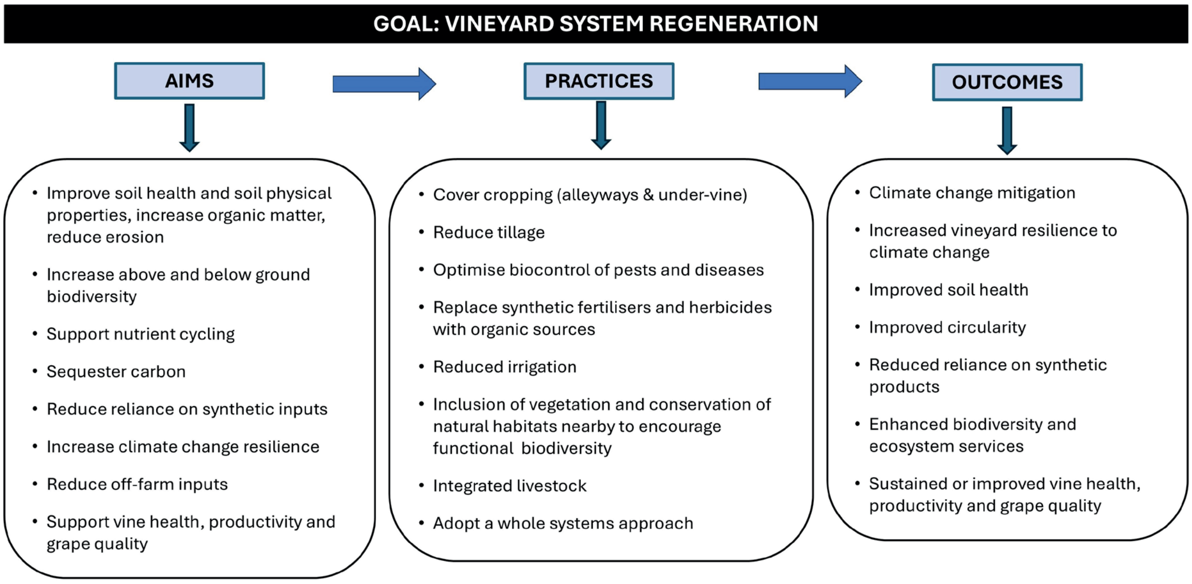

FIGURE 1. The principal goals of regenerative viticulture, the practices employed to achieve them and their potential impacts.

This figure was created using information from Calleja-Cervantes *et al.* (2015), Cataldo *et al.* (2020), Khangura *et al.* (2023), and Villat and Nicholas (2024).

TABLE 1. A summary of the criteria that determined the inclusion or the rejection of scientific literature in this review.

Inclusion criteria	Exclusion / rejection criteria
• Resilience, climate change mitigation and sustainable approaches to vineyard management within RV themes. • Studies on grapevines, or studies on other crops where there was insufficient research related to viticulture on the topic.	• Papers that did not mention practices relating to regenerative viticulture (*i.e.* improving the resilience, climate change mitigation and sustainability of vineyards), or papers where this was not the focus. • Papers based solely on modelling without experimental field or laboratory data. • Papers published more than 15 years ago, unless no recent studies on the topic have been published. • Publications about crops that do not include grapevines, unless there are insufficient papers on grapevines available for the practice in question.

VITICULTURE PRACTICES AND THEIR POTENTIAL TO SUPPORT THE AIMS OF RV

Composts, biochar, and other organic soil amendments

Reducing or discontinuing the use of synthetic fertilisers is promoted in RV because they can be detrimental to soil health and are associated with high GHG emissions. Organic-based soil amendments, such as composts and biochar, can both provide an alternative source of vine nutrients, with several additional beneficial outcomes for RV goals including weed suppression and soil health improvement.

1. Soil health

Soil health is widely considered to be a central focus of RV. "Soil health" is commonly defined as the ability of soil to perform ecosystem services and functions, such as nutrient cycling, carbon (C) storage, and sustaining air and water quality, in addition to supporting plant and animal health (Doran, 1996). Soil health can be measured using a range of indicators, which include physical, chemical, and biological soil properties (Figure 2). Vineyard management activities such as tillage and chemical inputs can drive processes that threaten soil health such as soil erosion, salinisation, acidification and soil structural decline (Evangelista *et al.*, 2023).

2. Vineyard soil health and organic amendments

Soil microbial communities contribute towards soil health primarily through their roles in soil nutrient cycling, soil aggregation, and C sequestration which occurs predominantly through the contribution of microbial necromass to soil organic matter (SOM) (Zhang *et al.*, 2023; Figure 3). In vineyards, the soil microbiome can also act as reservoir from which vines select certain beneficial microbes that enter via the root system and ultimately form the grapevine-associated microbiome (including those colonising grapes, leaves and flowers) (Zarraonaindia *et al.*, 2015).

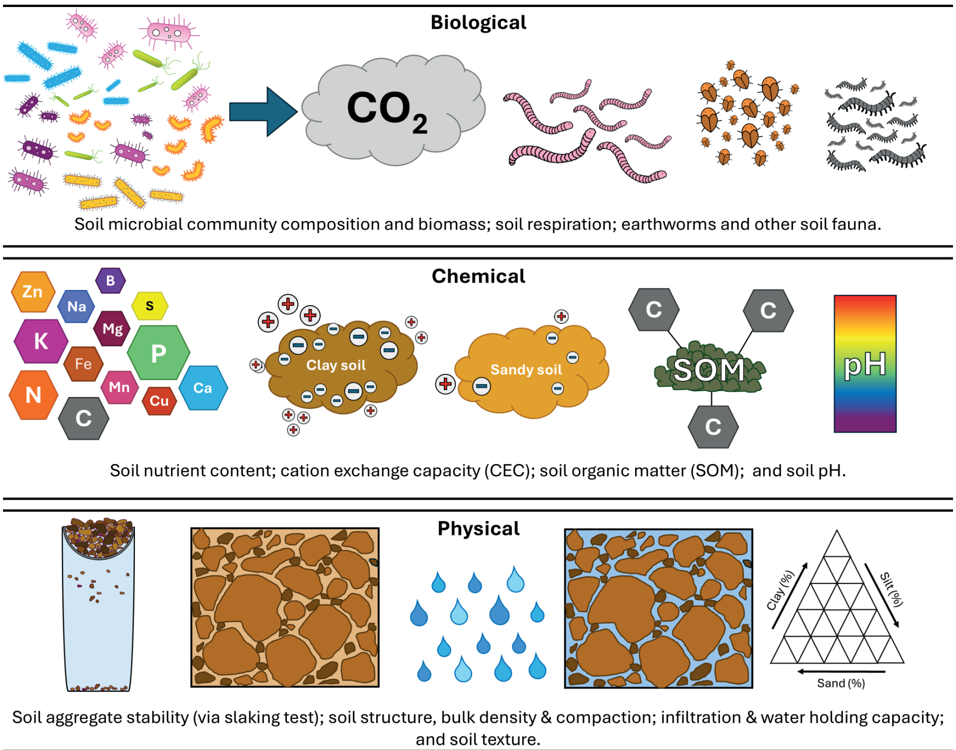

FIGURE 2. Biological, chemical and physical soil properties commonly used to assess soil health.
The sources used to create this figure were Lal (2016); Huber *et al.* (2024) and Zhang *et al.* (2023).

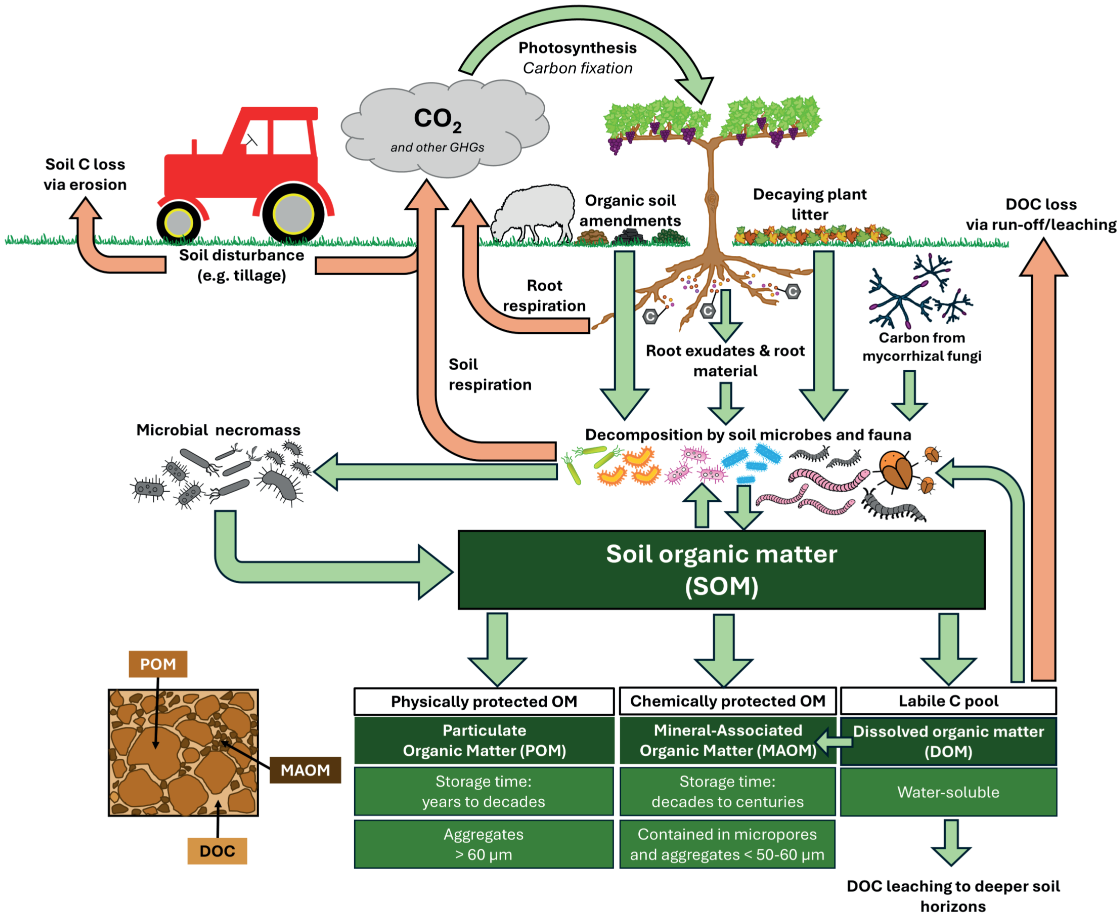

FIGURE 3. The soil carbon cycle and the potential impacts of vineyard management practices.

This figure is based on information sourced from Lützow *et al.* (2006); Bhattacharyya *et al.* (2022); Cortufo and Lavallee (2022); Keiblinger *et al.* (2023); Villat and Nicholas (2024); and Wu *et al.* (2024).

Studies have indicated that the grape microbiota can affect wine aroma profiles, including the compound rotundone in Shiraz grapes (Gupta *et al.*, 2019; Liu *et al.*, 2020). Therefore, vineyard practices that alter the soil microbiome as a result of their impact on soil properties such as pH and SOM content, could have an indirect but significant effect on the characteristics of wine (Hendgen *et al.*, 2018), although further research in this area is required. Cover cropping, organic amendments and cultivation are all known to alter soil microbial communities, although the extent of their impact varies with soil types and climate (Chou *et al.*, 2018; Vukicevich *et al.*, 2018).

The application of organic soil amendments, particularly those produced on-farm, is an approach used in RV to promote soil nutrient status, water management, SOM and C content (Figure 3). Those commonly used in vineyards include biochar, composts (*e.g.*, vermicompost and mushroom compost), farmyard manure, cuttings from vine pruning, and winery waste products, although the latter two may carry a risk of harbouring vine pests or pathogens. Studies have reported that the repeated application of composts and manures to vineyards at or above rates of approximately 4 t ha^{-1} $year^{-1}$ fresh weight over several (+5) years can result in significant increases in soil nutrients (nitrogen (N), phosphorous (P), potassium (K)), SOM content and microbial biomass (Calleja-Cervantes *et al.*, 2015; Gaiotti *et al.*, 2017; Mondini *et al.*, 2018).

The composting process is an important step in unlocking the potential beneficial effects of vine pruning cuttings on soil health parameters as Pike *et al.* (2023) reported that incorporating them, without prior composting, into the alleyways of a vineyard in South Australia over thirteen years had limited impact on soil C and nutrients. Another potential use of vine cuttings is to produce biochar via the process of pyrolysis (combustion in the partial or total absence of oxygen). Biochar is a highly stable material, meaning that the C it contains can be stored over long periods without the risk of decomposition, thus enhancing soil C sequestration while also improving soil fertility (Cárdenas-Aguiar *et al.*, 2023).

Organic amendments can have other soil health benefits such as enhanced aggregate stability and soil structure, which in turn promote soil water infiltration and water holding capacity (Laird *et al.*, 2010). Applications of a biochar produced from orchard pruning biomass (applied at 22 t ha^{-1} $year^{-1}$) to vine rows of a non-irrigated vineyard located on a shallow acidic sandy-clay-loam in central Italy were demonstrated to reduce soil bulk density and increase available soil water content, resulting in elevated vine leaf water potential (Baronti *et al.*, 2014). This effect of biochar is due in part to its porous structure, which facilitates water and air movement, thus benefiting water management and soil structure. Similarly, the application of composted manure at a rate of 40 t ha^{-1} to a vineyard in Spain resulted in higher infiltration rates and water holding capacity relative to untreated areas (Ramos, 2017). Organic amendments could therefore support the ability of vines to withstand heat or drought events, which are forecast to affect grape growing regions globally due to climate change (Santillán *et al.*, 2019). Conversely, a treatment comprising a mixture of pumice (50 t ha^{-1} yr^{-1}) and a straw and farm manure (50 t ha^{-1} yr^{-1}) was found to result in lower soil moisture content in two consecutive years in a Turkish vineyard when compared to the control (Tangolar *et al.*, 2020). This may be related to the specific properties of the vineyard soil or the applied treatments, as well as climatic factors, highlighting the contrasting impact organic amendments can have both on a temporal and spatial scale.

3. Vine performance, yield, and wine quality

Owing to their impact on soil health, organic soil amendments can have a significant impact on vine growth, yield and, in some cases, grape juice chemistry (*e.g.*, yeast assimilable nitrogen (YAN), titratable acidity (TA g/L) and phenolic compounds) (Reynard *et al.*, 2011). Treatments comprising a mixture of farm manure and pruning residue (50 t ha^{-1} $year^{-1}$) resulted in significantly higher grape yields and cluster weights, as well as significantly higher total soluble solids (TSS), pH and maturity index in grape juice after 2 years of applications in a vineyard in Turkey (Tangolar *et al.*, 2020). Gaiotti *et al.* (2017) also found applications of composts from vine pruning waste and cattle manure in a five-year study resulted in increased yield, with the pruning waste compost also stimulating vine root growth. However, while the application of both composts was associated with significantly higher YAN content in the grape juice, they also resulted in reduced TSS, total flavonoids, and total anthocyanins relative to the control. The authors suggest that in the case of the pruning waste compost treatment, these results could have been due to the increased root growth acting as a nutrient sink in competition with the developing fruit. However, the impacts of organic amendments do not always extend to grape juice. For instance, although applications of composted steer manure were found to increase the nutrient content of both soil (N, C, exchangeable K, calcium (Ca), manganese (Mn), and available P) and vine petioles (N, P, K), and increase yield in a vineyard in northern California, no effect was observed on the juice quality parameters (pH, TSS and TA) (Wilson *et al.*, 2021).

It is important that the impact of soil amendments on the nutrient status of the vineyard is carefully monitored to avoid adverse effects. For example, elevated concentrations of plant-available N can result in excessive vigour, as well as increased malic acid and lower anthocyanin content in juice, which can have a negative effect on red wine quality (Hilbert *et al.*, 2003). This can be avoided by using C-rich amendments, such as straw or composted vine cuttings from pruning. Compost treatments have also been found to increase the K content of grapes and musts (Chan & Fahey, 2011). This may be undesirable since excess K can be detrimental to wine quality, causing it to have a high pH, lower tartrate:malate ratio and reduced stability (Mpelasoka *et al.*, 2003). Thus, the nutritional status of both the soil and vine should be monitored throughout the growing season following compost applications, so that any deficiencies or excessive concentrations can be addressed. Wine chemistry and other non-target impacts like the leaching of nutrients from the compost should also be monitored, since the effects of composts are dependent, to some extent, on climate, soil type and other soil properties, and therefore their response may differ between vineyards.

4. Soil C sequestration and GHG emissions

Understanding if, and to what extent, agricultural land types can sequester C is important for assessing their GHG emissions mitigation potential (Callesen *et al.*, 2023). As a perennial woody crop, grapevines have good C sequestering potential, with one study estimating that converting land from annual cropping system to a vineyard could increase C sequestration by 59 g C m^{-2} $year^{-1}$ (Kroodsma & Field, 2006). Vineyard management practices play an important role in soil C dynamics, with some practices leading to soil C losses (*e.g.*, cultivation resulting in increased soil respiration, SOM breakdown and soil erosion), while others can help sequester C (*e.g.*, via composts and cover crops which build SOM), although this is context dependent (Figure 3). Given that C sequestration is one of its principal goals, it is for this reason that RV advocates for no-tillage and promotes the use of organic amendments and cover cropping.

A concern regarding the use of soil amendments is their impact on vineyard soil GHG emissions. Studies conducted in Spanish vineyards have reported increases in CO_2 and N_2O emissions following the application of organic amendments at rates ranging from 3.7 to 5 t ha^{-1}, with daily N_2O emissions rising by as much as 400% (Calleja-Cervantes *et al.*, 2015; Marín-Martínez *et al.,* 2021). However, these spikes are temporary and typically last a couple of weeks following application of the amendments, with emissions returning to levels like that of control thereafter. Comparisons of different application rates of organic amendments in vineyards are lacking, and could have strong implications for soil GHG emissions, in addition to soil health and vine performance. Wong *et al.* (2022) compared four different application rates (0, 4.5, 9.0 and 13.5 t ha^{-1} $year^{-1}$) of composted livestock manure and green waste in a Californian vineyard, and found that neither cumulative soil GHG emissions or soil C stocks during the 4 days post-application were significantly different to the control for any of the treatments (Wong *et al.*, 2023). There was also no effect of the compost applications on either grape yield or cover crop biomass. The lack of any significant effects may have been due to the short study duration (2 years), or the compost being broadcast across the entire vineyard floor, rather than being concentrated in the vine rows. The authors also suggested that the lack of yield response may have been due to the soil already having sufficient N for the vines to meet their productive capacity.

5. Future research

Long-term research that increases our understanding of the impact of organic soil amendments on soil nutrient dynamics, GHG emissions, and grape chemical composition is recommended. Whether soil amendments like composts and organic fertilisers could reduce the need for foliar sprays in vineyards remains unclear, as does their potential impact on the total carbohydrate pool (starch and soluble sugars), and the partitioning of soluble sugar and starch in vegetative tissues at winter dormancy. Future studies should also consider the interactions between soil type, rootstock, and scion genotype under different climatic conditions and over multiple years, with a range of diverse application timings and rates to illustrate context specific impacts.

Biological stimulants, control agents and pesticides

As with organic amendments, biostimulants are chosen in RV systems to replace synthetic fertilisers, while BCAs represent an alternative to chemical pesticides and fungicides, although not specific to RV. Biostimulants are formulated from a mixture of natural substances and/or microorganisms selected for their ability to enhance plant nutrition processes by improving their nutrient-efficiency, soil nutrient bioavailability, and/or abiotic stress tolerance, which can benefit both crop yield and quality traits (Jindo *et al.*, 2022; Monteiro *et al.*, 2022). BCAs are organisms that can help to control populations of crop pests and diseases, either through predatory or parasitic behaviour, or by stimulating plant defence responses and the production of antimicrobial compounds, thereby reducing dependence on synthetic fungicides and pesticides, and the risk of their chemical residues being transferred into wine (Rantsiou *et al.*, 2020).

Grapevine pathogens and pests cause substantial production and economic losses to vineyards and this is expected to worsen as climate change drives increases in the frequency and severity of outbreaks (Khangura *et al.*, 2023). Copper (Cu)-based fungicides have been extensively applied to control downy mildew in vineyards for over a century. Since Cu does not easily degrade, biologically or chemically in soil, this results in its accumulation in the topsoil over time. Cu contamination can impair several aspects of plant growth leading to reduced root growth, cell damage, and oxidative stress (Juang *et al.*, 2019). It may also affect fermentation as it impacts yeast activity (Sun *et al.*, 2015). Consequently, viticulturists want to replace these Cu sprays with environmentally sustainable disease control solutions, such as BCAs (Khangura *et al.*, 2023).

1. Soil health

A range of biological alternatives to Cu-based fungicides for controlling downy mildew have been identified, including several species of bacteria and fungi (Dagostin *et al.*, 2011). While this is evidently beneficial in preventing the risk of Cu contamination of vineyard soils, it is possible that applications of microbial BCAs and their subsequent colonisation could alter the composition of soil microbiomes, which may have implications for soil functioning and soil health (Figure 2). Indeed, applications of a BCA comprising a strain of the fungus *Trichoderma atroviride* (which targets the fungus *Armillaria mellea*) to soils has been shown to lead to reductions in the fungal biodiversity within the grapevine rhizosphere in some vineyards, but in others it had no lasting effect on the soil microbiome (Leal *et al.*, 2023). These studies indicate that colonisation and efficacy of BCAs in inducing plant defence responses can vary between soil types. It is likely that these contrasting outcomes were due to differences in environmental conditions, sampling times and soil types. Further research is needed to ascertain the impact of different BCAs on soil health under different vineyard environments, as this will inform vineyard managers as to its compatibility with RV goals.

2. Vine performance, yield, and wine quality

In addition to enhancing plant nutrient status, biostimulants can increase abiotic stress tolerance thereby contributing to the vine's capacity for resilience. This subject was reviewed by Basile *et al.* (2020) including evidence that of seaweed extracts and arbuscular mycorrhizal fungi (AMF) enhanced drought tolerance in grapevines by increasing their leaf water potential and stomatal conductance; in addition to the role of silicon treatments (*e.g.*, K silicate) in improving the tolerance of grapevines to salinity stress which is attributed to the role of silicon in photosynthesis and the protection of photosynthetic machinery (Qin *et al.*, 2016). Meggio *et al.* (2020) also reported that the application of collagen-derived protein hydrolysate biostimulant to grapevine roots enhanced their tolerance to water deficit stress. However, these studies demonstrating the benefits of biostimulants for grapevine abiotic stress tolerance have all used artificial growing conditions (*e.g.*, potted vines in glasshouses or poly tunnels, or micro-propagated grapevine plantlets grown under artificial laboratory conditions). It remains to be seen whether such positive results can occur under field conditions. Further field research is required, particularly since climate and location are known to influence the impact of biostimulants on vine performance (Olavarrieta *et al.*, 2022). If such benefits are demonstrated under field conditions, it would strengthen the case for using biostimulants in RV since it supports the goal to improve the resilience of grapevines to climate change (Figure 1).

Some BCAs can also enhance abiotic stress tolerance *e.g.*, *Bacillus licheniformis* and *Pseudomonas fluorescens* were found to elicit terpenes and stimulate the production of the phytohormone abscisic acid (ABA) in grapevine leaves, thereby helping to reduce water loss (Salomon *et al.*, 2014). Similarly, certain AMF species have been shown to enhance grapevine resistance against pathogens in addition to enhancing plant resistance to water stress and other abiotic stresses (Cruz-Silva *et al.,* 2021; Nerva *et al.*, 2022). Applications of *Bacillus subtilis* strains as a BCA targeting bunch rot (*Botrytis cinerea*) can have secondary benefits by promoting the vegetative development, leaf chlorophyll content and nutrient acquisition of grapevine rootstocks (Sabir *et al.*, 2012). Similarly, species of *Streptomyces* and *Trichoderma* both act as BCAs against downy mildew in grapevine (El-Sharkawy *et al.*, 2018). These additional benefits of BCAs on vine performance further their compatibility with RV goals.

Certain biostimulants can also enhance grape quality through their role as bio-elicitors, triggering the production of secondary metabolites. Several studies have shown that applications of biostimulants (brown seaweed (*Ascophyllum nodosum*) extracts, protein hydrolysates, methyl jasmonate and a commercial yeast extract) result in increased concentrations of anthocyanins and other phenolic compounds (*e.g.*, stilbenes, flavonols, and hydroxycinnamic acids) in grapes (Portu *et al.*, 2018; Boselli *et al.*, 2019; Salvi *et al.*, 2019; Garde-Cerdán *et al.*, 2021).

3. Vineyard biodiversity

Enhancing vineyard biodiversity is a core aspect of RV. The biodiversity of plants within and surrounding a vineyard can affect the efficacy of BCAs. Increased landscape heterogeneity (*i.e.* the presence of semi-natural habitats, such as woodlands, near a vineyard) has been reported to promote the presence and activity of BCAs and natural enemies of grapevine moths, such as birds and parasitic wasps (Begum *et al.*, 2006; Thomson & Hoffmann, 2009; Rusch *et al.*, 2017). The role of landscapes in the functional biodiversity of vineyards is discussed further in Functional biodiversity in vineyards, section 1.

4. Future research

The lack of field-based studies demonstrating the effects of biostimulants and BCAs in vineyards was highlighted in reviews by Jindo *et al.* (2022) and Monteiro *et al.* (2022). Future studies should focus on the stability of the product, its lifespan after spraying, effects of dose rate, application timing, environmental conditions, and mode of application under field conditions, in addition to determining the mechanisms underpinning them. There is a lack of long-term experiments testing for interactions between combinations of biostimulant/BCA products and cultural practices (*e.g.*, leaf removal). Further assessments of the long-term impacts of these products on soil health and biodiversity, particularly in relation to soil microbial communities, are necessary. Pertot *et al.* (2017) suggested that the combined use of agronomic practices, disease resistant grape varieties, biopesticides and mating disruption in combination with optimal use of chemical active substances can help to strongly reduce pesticide applications in vineyards. However, studies and solutions are needed for the control of parasitic nematodes, pathogenic bacteria, phytoplasma and viruses, in addition to research into the impact of biostimulants and BCAs on the wider vineyard ecosystem and its ecological processes.

Cover crops

As with other perennial cropping systems, grapevine rows are separated by alleyways maintained either as bare soil (through herbicide or tillage) or covered to varying degrees with vegetation (sown or a natural sward). The under-vine area is typically kept free of vegetation using chemical (herbicide) and/or mechanical (cultivation) means. RV systems advocate for the inclusion of cover crops (occasionally referred to as service crops) in alleyways since they have been shown to improve several aspects of soil health, functional biodiversity, and vine performance.

1. Soil health

Cover cropping can promote soil health through its effect on soil physical, chemical, and biological properties. Certain cover crop species, such as forage radish, can improve soil structure and alleviate compaction (Hudek *et al.*, 2022), while legumes such as vetch and faba beans can increase soil fertility via biological N fixation (Ball *et al.*, 2020). Over time, cover crops can increase SOM primarily via root turnover and the production of root exudates, which are also beneficial to soil microbial communities and soil structure (Gattullo *et al.*, 2020). The improvements in aggregate formation, pore connectivity and SOM content associated with cover crops can lead to increased soil water infiltration and retention (water holding capacity), which helps mitigate against flood and drought risks, as well as reducing N leaching (run-off) rates (Celette *et al.*, 2008). The reduction in leaching can result in cover cropped alleyways having higher nutrient retention, which is thought to be the main explanation (excluding N-fixing cover crops) for the higher soil N levels recorded in cover cropped alleyways (Gattullo *et al.*, 2020). In arid regions, such as the Mediterranean, where vineyard alleyways have traditionally been kept bare as a strategy to maximise vine-water availability, cover crops have been shown to help prevent soil erosion and concomitant organic C losses, particularly on steep sloped vineyards (Novara *et al.*, 2019). However, soil moisture content needs to be monitored and managed carefully in these regions with limited rainfall, as competition with the cover crops may lead to water stress in the vines.

In addition to directly competing with the vine for water and nutrients, cover crops in the vine row (under-vine) can lead to increased humidity in the canopy which may in turn increase disease pressure. Notwithstanding these apparent risks, research indicates that, in comparison to rows kept bare either by tillage or herbicide sprays, under-vine cover crops can have several positive effects on soil health, such as reduced soil bulk density, increased soil porosity, improved aggregation, and increased soil organic carbon (SOC) (Abad *et al.*, 2023; Bernaschina *et al.*, 2023). The shade from under-vine cover crops can cool soils, which could alleviate heat stress (Abad *et al.*, 2023). Under-vine cover crops are associated with increased active C, soil protein content and soil respiration rates, indicating they are more microbially active than the bare weed-free strips (Bernaschina *et al.*, 2023). This influence on the soil microbiome could potentially be exploited to benefit the vines by inoculating the under-vine cover crops with AMF, so that they can function as AMF donor plants. This may be beneficial since vineyards often have depleted AMF populations due to the detrimental impact of soil management practices (*e.g.*, cultivation) over time (Nogales *et al.*, 2021).

1.1. Impact of cover crop termination on soil health

Whilst cover crop termination is not necessarily a desirable activity in RV systems, it is commonly employed in vineyards to facilitate beneficial outcomes and to avoid detrimental impacts that tall cover crops may have on vines due to their effect on air flow and humidity. Cover crop termination is carried out using either mechanical (*e.g.*, cultivation, roller-crimping, mowing), chemical (*e.g.*, herbicide) or herbivory (*e.g.*, grazing animals) means. The method of termination can have a strong role in determining the extent of weed suppression achieved by a cover crop, as well as its impact on soil health parameters. Research on the effects of cover crop termination on soil health primarily comes from arable studies, and there is a lack of available data that is specific to vineyards.

Cultivation (tillage) of cover crops results in soil turnover, which can generate a temporary spike in CO_2 emissions, and can damage mycorrhizal networks, thus counteracting some benefits associated with cover cropping. The disruption of soil aggregates by cultivation can result in microbial degradation of previously occluded soil particulate organic matter (POM), as well as SOC losses due to soil erosion, particularly in the case of heavy tillage (Moukanni *et al.*, 2022). A comparison of three termination methods (conventional disk tillage, flail mowing and roller-crimping) identified that, in the absence of a cover crop (bare control treatment), tillage resulted in significantly smaller soil aggregate sizes in comparison to the flail mowing treatment. However, in the two legumes cover crop treatments (hairy vetch and crimson clover) tillage had no effect on soil aggregate size, which suggests that cover crops can ameliorate the damage to soil structure caused by tillage (Bloszies *et al.*, 2022). Additionally, tillage resulted in temporary increases in microbial biomass N and potentially mineralisable N relative to other termination methods irrespective of cover crop presence (Bloszies *et al.*, 2022).

This association between the termination of cover crops by tillage and increased soil N is supported in other studies (Garcia *et al.*, 2024). A three-year study conducted in a vineyard in the south of France found that although there was no significant effect of termination method on soil microbial biomass or SOM, termination of a cover crop mix comprising species of *Fabaceae*, *Poaceae* and *Brassicaceae* by tillage resulted in soil inorganic N concentration reaching 61 kg ha^{-1}, which was almost four times greater than termination by rolling or mowing (Garcia *et al.*, 2024). Conversely, a study conducted in southern Italy found that roller-crimping vetch resulted in significantly higher soil total N in comparison to termination by cutting and ploughing (Tarricone *et al.,* 2020). Enhanced soil nutrient content following tillage of cover crops is due to the acceleration of the mineralisation of organic matter when plant residues are incorporated into the soil, in contrast to other methods where the residues are left on the surface (Coppens *et al.*, 2006). Consequently, cover crops can reduce or even negate the need for fertiliser applications in vineyards when they are incorporated into the soil.

Tillage-mediated cover crop termination has also been associated with significantly higher soil water content than termination using a roller, which may be attributed to tillage being more effective in killing the cover crop and thereby stopping transpiration (Garcia *et al.*, 2024). Evidence demonstrates it is important to consider that the impact of cover crop incorporation on soil health will be dependent on soil type and climate, as well as cover crop species. The impacts of cultivation on soil health are discussed further in Weed management, section 4.

The herbicide glyphosate may be suitable for terminating cover crops in difficult circumstances (*e.g.*, heavy clay soils). The implications of using glyphosate are widely debated in the literature, with some claiming that it is detrimental to human and soil health, while others state that its impact is minimal (Meftaul *et al.*, 2020). The impacts of glyphosate on soil health are further discussed in Weed management section 1.

Mowing, particularly using a flail mower, is one of the least intensive methods of cover crop termination with regards to soil disturbance and can also result in increased nutrient availability. In comparison to herbicide and mechanical (disking) methods, flail mowing cover crops has resulted in higher soil microbial biomass C, nitrification potential and N and C mineralisation rates (Liang *et al.*, 2014). Flail mowing of cover crops was reported to result in significantly higher potentially mineralisable N in comparison to roller-crimping, and significantly higher available P and active C in comparison to a no cover crop control treatment (Eivazi *et al.*, 2024).

Roller-crimpers can be used to create cover crop mulches, which can benefit various aspects of vineyard soil health (Tarricone *et al.*, 2020). Over time the mulch will degrade, returning nutrients back into the soil. The formation of mulches by roller-crimping cover crops can help to cool surface soil temperatures, thereby reducing evaporation rates and conserving soil moisture (Kornecki & Kichler, 2023). Mulches can also improve water infiltration, reduce soil erosion, and suppress weed germination and growth by blocking sunlight (Kornecki & Kichler, 2023).

The timing of termination can impact the effect of a cover crop on soil health. A study conducted in a vineyard in a Mediterranean region in the south of France found that termination of a cover crop mix comprising species of *Fabaceae*, *Poaceae* and *Brassicaceae* at budburst rather than earlier termination in February resulted in significantly higher soil microbial biomass (Garcia *et al.*, 2024). This is likely due to the larger amount of cover crop biomass and root exudates being accumulated in the soil when the crop was left to grow until budburst, in addition to the longer period of root exudate inputs.

2. Vine performance, yield, and wine quality

Several studies indicate that, if managed effectively, cover crops have no detrimental impact on the vine or the wine quality characteristics (Pérez-Álvarez *et al.*, 2015a; Jordan *et al.*, 2016). Cover crops help to limit vine growth, a useful tool in vineyards with fertile soils and/or high rainfall, where excessive vigour reduces yield and grape quality due to over-shading of the canopy and developing bunches (Abad *et al.*, 2021). In regions with high precipitation, cover crops can also help reduce the risk of diseases such as *B. cinerea* since the prevention of excessive vegetative vine growth results in better air flow in the canopy and reduces cluster compactness, thereby alleviating disease pressure (Vanden Heuvel & Centinari, 2021).

However, an Italian split-plot study conducted over two years using three-year old vines, demonstrated that vine canopy water use efficiency (WUE) (calculated as the ratio between net C exchange rate and transpiration) decreased with increasing competition with cover crops (Poni *et al.*, 2024). These results highlight the potential risk of installing cover crops in Mediterranean or arid climates that encounter water shortages. Under these conditions, vineyard managers are challenged to find a balance between achieving the benefits associated with cover crops while avoiding major competition for water and nutrients with the grapevines that could result in diminished grape yield and quality (Poni *et al.*, 2024).

In terms of yield, cover crops have been reported to have a positive effect in some cases (e.g., Messiga *et al.*, 2016), while others have reportedly had no effect (*e.g*., Cabrera-Pérez *et al.*, 2023). Some cover crops have been associated with decreased YAN in grapes (Griesser *et al.,* 2022), but this may be avoided through the use of leguminous cover crops, such as clover (*Trifolium resupinatum L.*) (Pérez-Álvarez *et al.*, 2015b). Research conducted in Uruguay demonstrated that a permanent under-vine cover of *Festuca arundinaceae* had no detrimental effect on either grape yield or grape chemical composition (Bernaschina *et al.*, 2023), while another study found that under-vine cover of *Festuca rubra* helped to control vine vigour and resulted in grapes with higher TSS and anthocyanin content (Coniberti *et al.*, 2018). However, in both studies supplementary irrigation was used in the under-vine cover crop treatments to mitigate water-stress. When additional irrigation is not supplied, under-vine cover crops have resulted in lower pruning and berry weights, but TSS and TA were unaffected. It is important that water demand and availability are considered when selecting cover crops for a vineyard. Water stress, to a certain degree, can increase some grape quality characteristics including berry anthocyanin and phenolic compounds (e.g., flavonols), and in some instances, TSS (Bálint & Reynolds, 2014; Buesa *et al.*, 2021; Caruso *et al.*, 2023). However, water stress typically incurs a yield penalty, as well as a reduction in berry size and weight (Santesteban *et al.*, 2011; Bálint & Reynolds, 2014).

Vineyard cover crop studies often use bare, tilled alleyways for the control treatment, rather than spontaneous (natural) vegetation. This point was illustrated by a study conducted in a Mediterranean organic vineyard, which found that while a pigeon bean cover crop and a mulched spontaneous vegetation cover did not differ in their effect on grape yields, they were both significantly higher than the tilled alleyway control (Warren Raffa *et al.*, 2022). This highlights the importance of including appropriate controls in studies.

3. Vineyard functional biodiversity

Cover crops can enhance aspects of vineyard functional biodiversity. The inclusion of flowering cover crops, such as phacelia and clover, can increase the abundance and diversity of insect pollinator populations in vineyards (Griffiths-Lee *et al.*, 2023). Although this may not directly benefit self-pollinated vines, the pollination of wildflowers or other crops in the surrounding area contributes to wider biodiversity and ecosystem stability. The inclusion of cover crops or spontaneous ground cover was identified as a strong promoter of biodiversity in vineyards in a review conducted by Paiola *et al.* (2020), resulting in increased arthropod species richness and habitat provision for ground-foraging insectivorous birds.

A common concern regarding the inclusion of cover crops in vineyards is their potential to harbour or attract vine pests and pathogens. Whilst increased pest and pathogen incidence in association with cover crops have been observed in some studies (León *et al.*, 2021), others have reported that cover crops are responsible for a reduced incidence of certain diseases such as *B. cinerea* (Bernaschina *et al.,* 2023; Coniberti *et al.,* 2018). Furthermore, cover crops may serve as refuges for natural enemies of vine pests, thus potentially reducing the need for chemical pest control methods (Abad *et al.*, 2021). Natural enemies, including species of *Hymenoptera*, *Anthocoridae* and *Aeolotrhipidae*, are reported to be more abundant in cover cropped vineyards (as reviewed by Abad *et al.*, 2021). The inclusion of summer flowering cover crops (sunflower and buckwheat) substantially reduced populations of thrips and leafhoppers in a Californian vineyard (Altieri *et al.*, 2005). Similarly, data obtained from pitfall traps in an Italian vineyard planted with five different cover crop species (in addition to a control that was periodically tilled) found that predatory ground beetles (*Carabidae* species) were more abundant in buckwheat and faba bean cover crop treatments compared to the control, while predatory rove beetles (*Staphylinidae* species) were more abundant in the faba bean and the vetch and oat mixture (Sommaggio *et al.*, 2018). A study conducted in a Spanish vineyard reported that, in comparison to a tilled control treatment, both spontaneous groundcover and a cover crop treatment comprising a flowering species mix had a significantly more diverse population of insect natural enemies captured at ground level, with the flowering cover having double the abundance of insect parasitoids of the bare tillage treatment (Sáenz-Romo *et al.*, 2019).

Cover cropped vineyards have also been found to have higher AMF biodiversity than more intensively managed tilled vineyards (Lumini *et al.*, 2010). This could impact vine performance since AMF enhanced the uptake of certain nutrients (*e.g*., K, boron (B), Mn, and zinc (Zn) by grapevines (Moukarzel *et al.*, 2023).

4. Cover crop management and GHG emissions

Cover crops can help offset vineyard GHG emissions through C sequestration both below and above ground. In a seven year field experiment, Wolff *et al.* (2018) concluded that the SOC accumulated in vineyard alleyways that were planted with a barley cover crop in combination with minimum tillage (disked at a 2-3 cm depth once every other year) resulted in the vineyard having a negative net global warming potential

(GWP), as the CO_2-equivalent GHG emissions from soil N_2O and CH_4 fluxes and fossil fuel consumption were offset by the C sequestered in the soil and through biomass accumulation. However, in comparison to treatments which used conventional tillage (disked three times a year at 10 cm depth) with or without the barley cover crop, the min-till cover crop treatment did result in significant yield reductions. Conversely, cover crops also have the potential to contribute to vineyard GHG emissions. In comparison to bare tilled soils, alleyway cover crops were associated with a 4-fold increase in denitrification rates, a process which can result in increased emissions of N_2O (Steenwerth & Belina, 2008a). These emissions may be exacerbated if legumes are included in the cover crop mix, particularly if fertiliser inputs are not reduced in response to this additional N input (Garland *et al.*, 2011; Steenwerth *et al.*, 2015). However, when interpreting such results, it is important to consider that these vineyard emissions are very low in comparison to other agricultural GHG sources such as synthetic N fertilisers, the production and use of which results in an estimated 1.31 Gt of CO_2-equivalent emissions annually (Gao & Cabrera Serrenho, 2023). Furthermore, in the case of legume cover crops, the nitrogen they release upon decomposition originates from the nitrogen that the crops take up from the atmosphere via N fixation. Indeed, the amount of N accumulated in the biomass of a leguminous cover crop mix in alleyways of a vineyard in California has been estimated to be 47 kg N ha^{-1}, while the rate of N_2O–N emissions from the cover cropped alleyways was approximately 0.19 kg ha^{-1} per growing season (Garland *et al.*, 2011).

Weed management

If not managed effectively, weeds can diminish grape yield and quality as they compete with vines for nutrients and water, potentially resulting in a loss of income (Sanguankeo *et al.*, 2009). To counter these risks, it is widespread practice to keep the under-vine strip bare or with minimal vegetation. Conventional viticulture has traditionally relied on either chemical (predominantly glyphosate) or mechanical (cultivation) methods of weed control, or a combination of the two. RV encourages the minimal use of chemicals, but also aims to promote soil health through minimal soil disturbance. There has been a growing shift towards an overall reduction in herbicide use in recent years due to a combination of factors including a rise in herbicide-resistance among weeds; concerns regarding herbicide persistence and toxicity in water, soils, and grapevines; and growing pressure from consumers and regulators driven by concerns for human and ecosystem health in addition to the C footprint associated with their manufacture, distribution and application (Annett *et al.*, 2014). Consequently, there has been an increase in the uptake of cultivation-based weed control methods in vineyards, especially in organic viticulture where glyphosate is banned (USDA, 2023). However, soil disturbance caused by cultivation has negative effects on soil health, including vineyard functional biodiversity, drought resistance, nutrient run-off and soil structure (Biddoccu *et al.*, 2016; Novara *et al.*, 2019).

Alternative weed control strategies that align well with RV principles include novel technologies (*e.g.*, electric weeding), cover crops and mulches. Non-living mulches can comprise either organic or inorganic materials applied to the surface of the soil, providing a physical barrier to light interception on the soil surface suppressing weed emergence. Organic mulches include straw, vine cuttings, almond shells, and wood chips (Stenger and Hatterman-Valenti, 2016; Cabrera-Pérez *et al.*, 2023; Mairata *et al.*, 2023). Examples of materials used as inorganic mulches include geotextiles and plastic.

1. Soil health

As discussed in Cover crops, section 1.1, tillage can result in increased soil N due to the stimulation of N mineralisation caused by cultivation. This was reported in a study conducted in the Catalonia region of Spain, where mechanical cultivation with an under-vine cultivator/in-row tiller resulted in soil nitrate concentrations over five times greater than in either the mowing or mulching treatments after three years of application (Cabrera-Pérez *et al.*, 2023). However, this may be a short-term effect since a thirty-year study conducted in Germany by Pingel *et al.* (2019) reported that in comparison to permanently covered alleys, tillage resulted in decreased soil C and N levels as well as some other plant-available nutrients.

There remains much debate regarding the impact of glyphosate on soil microbial communities. Some studies have reported shifts in soil bacterial community composition with potential implications for the provision of soil functions such as nutrient cycling, while other studies have reported no effect (*e.g*. Newman *et al.*, 2016; Chávez-Ortiz *et al.*, 2022). Tilling has also been reported to affect the soil bacterial and fungal communities of a vineyard, possibly due to elevated soil pH and plant-available P concentration associated with this method in comparison to undisturbed alleys (Pingel *et al.*, 2019). The study found that tilled alleyways had fewer fungal operational taxonomic units (OTUs), which concurred with existing reports in the literature of tillage having a negative effect on fungal community richness (Wang *et al.*, 2021). Tillage has been also been associated with reductions in vineyard soil bacterial diversity (Burns *et al.*, 2016). The relationships between tillage-induced changes in the soil microbial community and soil functioning, and/or the quality and characteristics of wines is an area for further research.

Mulches can confer many benefits on vineyard soil health. The application of both vine pruning waste and straw mulches have been demonstrated to be effective weed control treatments in Rioja, Spain, while also resulting in higher soil water content and lower soil temperatures in comparison to herbicide-treated rows (Mairata *et al.*, 2023). Similarly, soils amended with mulches composed of chopped pine wood and almond shells exhibited greater soil water potential and cooler temperatures when compared to mechanical cultivation and mowing (Cabrera-Pérez *et al.*, 2023). Therefore, in addition to controlling weeds, mulches could help to protect grapevines from heat and drought stress, thus representing a valuable tool to mitigate against the impacts of climate change on vineyards, further demonstrating the compatibility of mulches with RV goals. However, some studies report that when combined with no-tillage, the application of mulches can result in reduced infiltration rates due to increased bulk density and compaction (Cheng *et al.*, 2014; Buesa *et al.*, 2021; Caruso *et al.*, 2023). This highlights the interactive effects of different RV practices, which in some cases can be detrimental to achieving RV goals and should be closely considered and monitored.

2. Vine performance, yield, and wine quality

The efficacy of weed control measures can impact vine performance and grape quality. A study conducted in a vineyard in Catalonia, Spain reported that a permanent under-vine cover of spontaneous vegetation mown regularly, can result in reduced vine nutrition in comparison to weed management by tillage or mulching (Cabrera-Pérez *et al.*, 2023). This is likely to be due to competition between the vine and spontaneous vegetation. A study comparing two different herbicide treatments (flumioxazin and simazine), cultivation, cover crops (mainly California brome) and an untreated control in a Californian vineyard found that the two herbicide treatments resulted in the vines with higher canopy light interception, cane weight, number of clusters and yield in comparison to the other treatments (Sanguankeo *et al.*, 2009). This greater productivity in the herbicide-treated vines could be attributed to these being the most effective weed control treatments. The cover crop treatment was associated with lower values for some the yield parameters in comparison to the other treatments, whereas the cultivation treatment resulted in lower °Brix in grape juice, but this latter result was only observed in the first year of the two-year experiment.

The enhanced soil water content resulting from the application of mulches has been shown to correspond with improvements in vine water status, as indicated by increases in mid-day stem water potential, and vegetative growth, as evidenced by the increased shoot length, canopy area and pruning weight (Cabrera-Pérez *et al.*, 2023). Grape yield has also been shown to be significantly higher in vines treated with organic mulches as opposed to mechanical weed control (Cabrera-Pérez *et al.*, 2023). These effects could be due to the higher level of weed control achieved by mulches, as well as their beneficial effects on soil temperature and water content. While increases in yield may be desirable, greater vegetative growth is not since it can increase disease risk and affect grape quality, therefore this may need to be monitored and managed in vineyards where mulches are applied. On the other hand, mulches may help to reduce irrigation demand in vineyards in arid climates, potentially reducing both the environmental impact and economic costs of a vineyard.

Geotextile mulches have also been shown to promote vine growth, resulting in significantly higher pruning weights in comparison to a control treatment consisting of mowed grass alleyways with a herbicide-treated under-vine strip (Hostetler *et al.*, 2007). This was attributed to the reflective mulches achieving more prolonged weed suppression than the herbicide treatment which exhibited faster regrowth. The black geotextile mulch also had a significant effect on grape berry characteristics at one of the sites, resulting in significantly higher TA and lower anthocyanin content at harvest in comparison to the control, in addition to their musts having lower phenolic contents and antioxidant activity (Hostetler *et al.*, 2007).

3. Vineyard biodiversity

Weed management strategies can drive compositional shifts in vineyard plant communities. Pingel *et al.* (2019) found that alleyways that were tilled at least twice a year exhibited more diverse plant communities (when assessed at least 8 weeks after tilling) compared to alleyways with permanent plant cover in a vineyard in Germany, however they were predominantly colonised by less competitive weed species such as hairy bittercress (*Cardamine hirsuta*) and chickweed (*Stellaria media*). Conversely, the increased use of herbicides (paraquat and glyphosate) in combination with tillage has been shown to result in an overall reduction in plant species richness in South Australian vineyards, but an increased abundance of broadleaf ruderal plant species that are fast-growing, produce large seed volumes and are well adapted to disturbance (Kesser, Joubert, *et al.*, 2023). Less intensive weed management (*e.g.,* by mowing or grazing animals), on the other hand, favoured slow-growing perennials, including members of the *Poaceae* and *Fabaceae* families, which are less competitive. The increased presence of the family of legumes, *Fabaceae*, was proposed to be a possible explanation for the increased soil ammonium-N and total N content that Kesser *et al.* (2023) observed in the under-vine areas of low management intensity vineyard soils, in addition to the role of the increased plant coverage in reducing leaching rates. The impact of different weed treatments on soil health, biodiversity and vine performance are summarised in Table 2.

4. Future research

Substantial evidence from the current literature indicates that mulches can serve as a viable alternative to conventional weed management strategies, namely herbicide and tillage (Table 2). Furthermore, mulches can also benefit several aspects of soil health and improve grapevine resilience to heat and water stress, thus making them compatible with RV goals. Additional alternative weed control options that could be compatible with RV systems include flame weeding (Mainardis *et al.*, 2020), the application of a woody biomass with biochar residue (Morselli *et al.*, 2022a), hot foam (Antonopoulos *et al.*, 2023), hot air (Morselli *et al.*, 2022b) and electrical weed control (Slaven *et al.*, 2023). Several of these are emerging technologies that have not been included in vineyard-based studies, and further research is required to determine how well these treatments align with RV goals.

Functional biodiversity in vineyards

While there is a wealth of research relating to vineyard biodiversity at a taxonomic level (*i.e.* the total number of different species within a system), a growing number

TABLE 2. A summary of select research into the effects of herbicide, tillage, and mulches on weed control in vineyards.

Research focus	Key findings	References
Challenges with conventional herbicide and tillage practices	High soil erosion rates due to bare soil under-vine.	Novara *et al.* (2011); Biddoccu *et al.* (2016)
	Bare soil favoured rapidly growing weed species. Increased noxious weed species, especially ruderal species.	Kazakou *et al.* (2016)
	Reduced plant biodiversity. Detrimental to ecosystem stability.	Kazakou *et al.* (2016); Hall *et al.* (2020); Guerra *et al.* (2022a)
Benefits of a diverse herbaceous community	Stable weed community reduced soil erosion.	Novara *et al.* (2011)
	Stable weed community improved water infiltration.	Celette and Gary (2013)
	Diverse weed communities provided essential ecosystem services. Less competition with vines.	Kazakou *et al.* (2016)
	Weed community comprised of fewer noxious weed species. Increased therophyte grassland species.	Guerra *et al.* (2022b)
Effect of mulches on weeds	Mulches reduced noxious weed species.	Mairata *et al.* (2023)
	Straw, vine pruning cuttings, chopped pine wood, woodchip and textile mulches controlled excessive weed growth.	Stenger and Hatterman-Valenti (2016); Cabrera-Pérez *et al.* (2023); Mairata *et al.* (2023)
	Spent mushroom compost resulted in high weed growth due to improved soil nutrition.	Mairata *et al.* (2023)
	Straw, textile and woodchip mulches had no effect on vine growth.	Stenger and Hatterman-Valenti (2016)
Mulches for climate change adaptation	Improved water holding capacity and retained soil moisture in upper soil layers. Reduced need for irrigation.	Pou *et al.* (2021); Mairata *et al.* (2023)
	Reduced extreme soil temperature fluctuations.	Pou *et al.* (2021); Mairata *et al.* (2023)
	Summer dormant perennial grasses could be selected for low competition.	Volaire and Lelièvre (2010)
Effect of mulches on soil microbiome	Increased soil fungi.	Mundy and Agnew (2002)
	Some combinations of mulch type and soil type increased native entomopathogenic nematodes.	Blanco-Pérez *et al.* (2022)

of studies are focussing on the functional biodiversity of vineyards. Functional biodiversity can be regarded as a more valuable metric since it accounts for the fact than many species overlap in terms of the services, or functions, they provide, while also accounting for the importance of having diversity within each functional group to act as a buffer during periods of stress. Functional biodiversity can be defined as grouping together components (ranging anywhere from the gene level to whole habitats) contained within the total biodiversity of a system (in this case, vineyards) that provide the same (agro)ecosystem service (Moonen and Bàrberi, 2008). These services include many aspects of soil health (*e.g.,* water management, soil fertility, SOM formation, soil aggregate stability, and nutrient cycling), as well as pest and disease control, pollination, buffering of climate change effects, and enhanced resource use efficiency (Figures 2 and 3). As this review demonstrates, many RV practices are integral to and can promote functional biodiversity in vineyards. Functional biodiversity can also be enhanced by the integration of ecological infrastructures (*e.g.*, hedgerows, woodlands and dry-stone walls) in the vineyard and improving their management to both increase the quality of production, while simultaneously maintaining the quality of the landscape (OIV, 2018).

1. Enhancing functional biodiversity in vineyards

1.1. Plants and insects

The functional biodiversity of a vineyard can be assessed by monitoring key indicator species that possess certain traits (effect traits) known to contribute to the provision of ecosystem services. In the case of plants, for example, effect traits include root mean diameter which is known to influence soil aggregate stability; N fixation which contributes towards nutrient cycling; and range of flowering which will impact the provision of nectar for pollinators (Garcia *et al.*, 2019). This knowledge should be used to identify suitable species to establish as cover crops in a vineyard.

Intensive agricultural practices are believed to be the primary cause for the loss of insect biodiversity and abundance in farming systems, including viticulture. The effects of vineyard alleyway management practices on both pests and beneficial arthropods were investigated by Zanettin *et al.* (2021) in north-eastern Italy, through field experiments that studied the effects of different green manure mixtures, frequency and timing of mowing, and the effect of non-mown alleyway spontaneous grasses on the populations of arthropods in conventional and organic vineyards. The non-mown spontaneous grassed alleyway favoured the abundance of natural enemies such as predatory mites on grapevine leaves, which the authors attributed to the increased pollen availability from the flowering plants. However, the non-mown alleyways were also found to have increased presence of American grapevine leafhoppers (*Scaphoideus titanus*) which are a grapevine pest as they are vectors of the phytoplasma-borne disease *Flavescence dorée* (Chuche and Thiéry, 2014).

1.2. Bats and birds

Bats can provide biocontrol services in vineyards, particularly in terms of their ability to reduce populations of *Lobesia botrana* (Baroja *et al.*, 2019; Baroja *et al.*, 2021;

TABLE 3. The roles of fauna in regenerative viticulture systems and the impact of management practices on their abundance.

Animal	Viticultural practices to manage and encourage animal presence	Impacts	References
Sheep	Integration of sheep in well-established vineyards during the winter dormancy period with consideration for animal care and health. Training system adaptations and/or use of specific breeds can enable growing season grazing. High density short duration rotational grazing.	Weed control between and under the vines, wild animal deterrent, sucker shoot removal, leaf removal, stimulation of soil ecosystem carbon flux, increased subsoil carbon storage.	Schoof *et al.* (2021); Conrad *et al.* (2022); Brewer *et al.* (2023).
Geese	Rearing geese in the vineyard during growing season.	Weed control, fertiliser provision, contribution to soil biomass, copper removal from soil.	Massaccesi *et al.* (2019)
Birds of prey	Introduction or encouragement of raptors as biocontrol agents. Installation of nest boxes to attract species such as *Falco sparverius* (American kestrel) and *Tyto furcate* (American barn owl). Introduction of F. novaseelandiae (New Zealand Falcon).	Reduction in damage to grapes by birds including *Turdus migratorius* (American robin), *T. merula* (blackbird), *T. philomelos* (song thrush), *Sturnus vulgaris* (starling) and *Zosterops lateralis* (silvereye), reduction in economic loss inflicted by rodents on vine roots, stalks, irrigation lines and farm machinery due to burrowing.	Whisson and Guisti (1998); Kross *et al.* (2012); Jasinski *et al.* (2021); St George and Johnson, (2021); Monteagudo *et al.* (2023).
Insectivorous birds	Installation of nest boxes to increase insectivorous birds, including cavity-nesting birds; increased uncropped areas; cover cropping; establishment of hedges, trees, woodland patches, traditional orchards, grassland areas tailored to local context/species increases breeding.	Biocontrol of insect pest species.	Rollan *et al.* (2019); Herrera *et al.* (2022); Olmos-Moya *et al.* (2022); Rosch *et al.* (2023).
Bats	The preservation or provision of native vegetation bordering the vineyard, along rivers and hedgerows to provide foraging habitat for bats through presence of prey insects; preservation of remnant oak trees to increase number or species and activity compared to open treeless areas.	Biocontrol of insect pest species *Lobesia botrana* (grapevine moth) and *Sparanothis pilleriana* (leaf rolling tortrix) by multiple species including *Rhinolophus hipposideros* (lesser horseshoe bat), reduction in insect damage.	Baroja *et al.* (2019); Froidevaux *et al.* (2017); Polyakov *et al.* (2019); Charbonnier *et al.* (2021); Rodriguez-San Pedro *et al.* (2020); Chaperon *et al.* (2022).

Charbonnier *et al.*, 2021). This can have significant implications for grape yield, as demonstrated by a study conducted in Chile in which bats were found to reduce insect damage to leaves and grape clusters, resulting in 7 % higher grape yield which represented an estimated average economic benefit of US \$188-\$248 ha^{-1} $year^{-1}$ (Rodríguez-San Pedro *et al.*, 2020).

Birds of prey, such as the New Zealand falcon (*Falco novaeseelandiae*) and American kestrel (*Falco sparverius*), are also encouraged in RV systems as they can be effective deterrents to vineyard pest birds that cause damage to grapes (Kross *et al.*, 2012; Jasinski *et al.*, 2021). Their abundance and activity in vineyards can be enhanced through the installation of nesting boxes (Jasinski *et al.*, 2021), while cover cropping in alleyways has been demonstrated to enhance the abundance of insectivorous birds in vineyards in comparison to bare alleyways (Rollan *et al.*, 2019). Nest boxes have also been used to attract American barn owls (*Tyto furcata*) to vineyards in Napa Valley, California, in an effort to mitigate the economic and environmental costs of rodent pest removal from vineyards (St. George & Johnson, 2021). Over the two-year study, the authors estimated that one pair of nesting barn owls removed 1001 rodents from the area surrounding a nest box in a single nesting cycle. With a diet consisting almost exclusively of voles, mice, and gophers, the barn owls helped protect the vineyard from economic losses that these vertebrate pests can inflict by feeding on the vine roots and stalks (potentially leading to reduced yields), chewing irrigation lines and burrowing. The installation of nest boxes in vineyards can also help to increase the abundance of insectivorous birds that serve as BCAs for vineyard insect pests, particularly during wetter years (Olmos-Moya *et al.*, 2022).

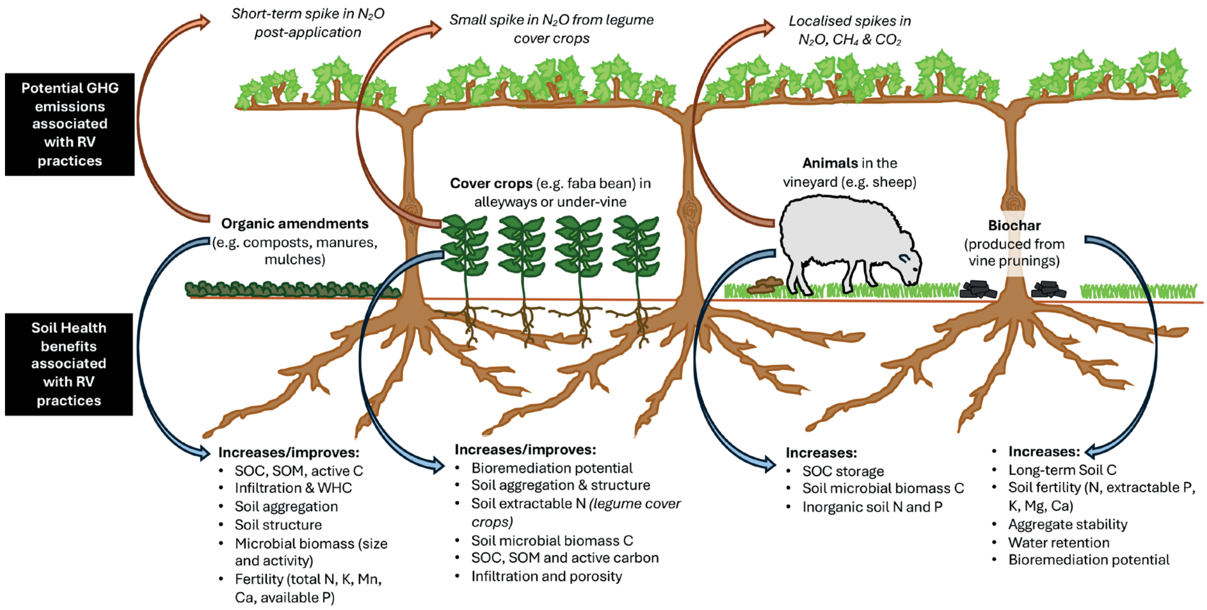

FIGURE 4. Schematic representation of the potential impacts of selected RV practices on aspects of vineyard soil health and GHG emissions.

This diagram has been produced using information from Abad *et al.* (2023); Ball *et al.* (2020); Bernaschina *et al.* (2023); Brewer *et al.* (2023); Calleja-Cervantes *et al.* (2015); Cárdenas-Aguiar *et al.* (2023); Chen and Weil (2010); Gaiotti *et al.* (2017); Gattullo *et al.* (2020); Hamzenejad Taghlidabad and Sepehr (2018); Hudek *et al.* (2022); Laird *et al.* (2010); Lazcano *et al.* (2022); Mackie *et al.* (2014); Mondini *et al.* (2018); Peregrina *et al.* (2012); Pérez-Álvarez *et al.* (2015a); Ramos (2017); Steenwerth and Belina (2008b); Steenwerth *et al.* (2015); Wilson *et al.* (2021).

At the landscape scale, the presence of natural or semi-natural habitats nearby to a vineyard is often reported to enhance the abundance and activity of these beneficial fauna in vineyards. The number of bat species and their activity was found to be greater in areas of Californian vineyards with large remnant oak trees compared to those with open, treeless areas (Polyakov *et al.*, 2019). A study in the south of France also reported that landscape features were more influential on bat populations than vineyard management practices, with higher bat activity occurring in vineyards near rivers and hedgerows (Froidevaux *et al.*, 2017). Similarly, populations of beneficial farmland bird species in vineyards could be encouraged by the establishment of hedges, trees, woodland patches, traditional orchards, and grasslands in the surrounding areas, provided that they are tailored to the specific features of their location and species (Rösch *et al.*, 2023). Such actions require careful consideration however, since planting green infrastructures along the edges and in vineyards could introduce or attract previously unobserved vineyard pests.

1.3. Integrated livestock-vineyard systems

The integration of animals in crop production, referred to as integrated crop–livestock systems, has extended to vineyards due to their ability to increase functional biodiversity. Within RV, the integration of livestock in vineyards is advocated for both their contribution to vineyard management practices, such as weed control and leaf stripping, and for their potential to improve aspects of soil health, including nutrient cycling, organic inputs, and soil microbial biomass (Table 3) (Massaccesi *et al.*, 2019). Sheep are currently the animal most commonly featured in vineyards because they can support or partially replace some labour- and fuel-intensive duties that are usually carried out mechanically, chemically, or manually (Ryschawy *et al.*, 2021; Conrad *et al.*, 2022). The effect of animals on vineyard soil health depends on the breed, size, and number of livestock that are introduced, their management (*e.g.*, the timing and duration of grazing period, and their movement through the vineyard), as well as the physical characteristics of the vineyard soil (*e.g.*, texture and bulk density). The key practices and impacts relating to different livestock in vineyards are summarised in Table 3.

The impact of livestock on GHG emissions has been widely publicised. However, a two-year study conducted by Lazcano *et al.* (2022) in a biodynamic commercial vineyard in California, found that while plots exposed to sheep grazing exhibited sporadic and localised peaks in daily N_2O, methane (CH_4) and CO_2 emissions, there was no significant effect on the cumulative emissions of any of these GHGs (Lazcano *et al.*, 2022). Furthermore, the increased soil N_2O emissions associated with grazing occurred mainly during the wet season of the study period, which the authors ascribed to increased nitrification rates associated with a higher proportion of water-filled pore space and sheep urine patches creating hotspots. This suggests that the impact of sheep grazing on soil GHG emissions is negligible in comparison to other factors, such as rainfall (Lazcano *et al.*, 2022). They also found that sheep grazing had no significant effect on available soil N or C.

2. Future research

There is a considerable body of research that demonstrates the interconnections between management practices, landscape variables, species richness, functional traits, functional diversity, vegetation cover and grapevines (Figure 4). From plants and insects, to bats and birds, these species can perform a range of valuable ecological services that can benefit vineyards. They can act as biological controls for various vineyard pests and diseases, help buffer the vineyard against extreme weather conditions, and support soil health and vine productivity (Winkler *et al.*, 2017). These services can represent a significant economic and environmental saving to vineyards (Rodríguez-San Pedro *et al.*, 2020). The functional biodiversity of a vineyard is intrinsically linked to the management practices employed, and more research is needed to support vineyard managers in identifying practices that promote and support functional biodiversity and ecosystem service provision. In particular, there is a need for more holistic research on functional biodiversity that assesses the synergies between different vineyard management practices and potential ecosystem service trade-offs, as highlighted in a review by Giffard *et al.* (2022).

CONCLUSION

RV focusses on the regeneration and utilisation of ecological processes to enhance both production and environmental outcomes. This goes beyond simply substituting conventional inputs with organic ones and requires a holistic ecosystem-based management approach. This review found limited literature on whole vineyard ecosystems or the use of RV within them. To achieve this, and in agreement with Candiago *et al.* (2023), RV related research could adopt a comprehensive holistic approach, both regarding the variables that are studied, (*e.g*., the impact of cover crops on the vineyard ecosystem, GHG emissions, vine physiology, grape quality and the resultant wine), and how these multiple aspects of RV are investigated collectively (*e.g*., long-term, multiple vineyard ecosystem locations). For growers seeking to incorporate aspects of RV based on empirical, robust science-based evidence, the nature of scientific research has meant that the focus of studies conducted to date have tended to be restricted to one or two practices and their impact on a limited range of variables, failing to capture the effects on the vineyard as a whole ecosystem or its ability to mitigate or adapt to climate change challenges. The co-creation of knowledge through future studies could be undertaken across multiple locations in collaboration with practitioners and scientists. Research at local and regional scales should reflect differences in climate soil types; ecology; and present/potential pest and pathogen risks. A multidisciplinary approach is recommended to evaluate the impact of RV on vineyard productivity, soil health, biodiversity, climate change resilience and GHG mitigation, because with further research, context specific ecosystem risk and rewards associated with RV practices could be more fully elucidated.

In terms of soil health, the impact of RV related practices such as the use of cover crops and limited or no-tillage has been shown to be beneficial, however it is an area that would benefit from broader research in different contexts. This research should include the impact of practices on vine performance and wine characteristics because the review identified that vineyard practices which alter the soil microbiome, could have an indirect but significant effect on vine performance, juice chemistry and the characteristics of wine (Reynard *et al.,* 2011; Hendgen *et al.*, 2018).

Cover crops have been demonstrated to assist with the control of excessive vine growth and are sources of functional biodiversity, nutrient cycling, shade and refuge for wildlife and pest predators. However, a greater body of context specific research would be of benefit to decision makers, enabling them to optimise cover crop species selection and management in order to maximise the value that they provide in RV systems.

Evidence from the literature also indicates that cover crops and mulches can serve as alternatives to conventional weed management strategies, namely herbicide and tillage. While the literature is inconclusive regarding the balance of ecosystem risks and rewards associated with either of these conventional weed control methods, there is considerable evidence demonstrating that the application of mulches aligns with RV goals due to their positive impact on soil health and their contribution towards enhanced grapevine resilience to heat and water stress. However, there are many new and emerging methods of weed control that could be compatible with RV but require further research to confirm this.

This review highlighted a lack of field-based studies demonstrating the effects of biostimulants and BCAs in vineyard settings. Specifically, more research is needed to assess the efficacy of commercially available microbial BCAs in targeting soil-borne diseases and their potential impact on grape microbiomes, in addition to the interactions between biostimulant and BCA products and other RV practices. Further research into these potentially valuable tools would support growers looking for alternatives to synthetic plant protection products. Additionally, molecular tools could be used to study interactions between the rootstock microbiome and scion phenotype in relation to these products. These studies would need to be performed at a variety of locations to account for different soil types and climates.

Enhancing the functional biodiversity of vineyards through actions that encourage the presence and activity of beneficial fauna such as bats and birds of prey, or through livestock integration, have been shown through this review to provide a range of beneficial ecological services. However, the limited research available does not reveal the full potential or consider the risks associated with them under different contexts and, therefore, cannot fully support decision making.

Research reviewed herein provides evidence that regenerative practices can contribute to climate change mitigation (*e.g.,* by tillage reduction or elimination and enhanced C sequestration via the use of vineyard resources, cover crops and organic mulches). Several studies reported that vineyard applications of composts, manures and other organic amendments including biochar can result in significant increases in soil nutrients (N, P, K), SOM content and microbial biomass, as well as aggregate stability and soil structure, which in turn promotes soil water infiltration and water holding capacity (Laird *et al.*, 2010; Calleja-Cervantes *et al.*, 2015; Gaiotti *et al.*, 2017; Mondini *et al.,* 2018), although not all studies found equally positive results (Tangolar *et al.*, 2020). In the context of climate change, for viticulture to thrive and in some areas survive, it is the potential for adaptation and increased vineyard resilience that regenerative approaches are more immediately of interest. Research has shown that minimal or no tilling and permanent cover crops in vineyards reduces soil erosion, improves soil water management, reduces soil temperatures, and increases soil health. These are all critical when extreme rainfall events threaten soil stability, heat and drought stress place pressure on water resources, changing climate conditions alter pest and disease presence, and increasing climate variability has the potential to disrupt both vine phenology and the ecosystem status-quo within winegrowing regions.

There are many reviews concerning agroecology and RA, but this review is the first to examine the literature regarding RV and related practices and assess their potential to achieve the goals of RV. Several topics were beyond the scope of this review including the management of vineyard wastewater, agroforestry, and the socio-economic benefits, specifically labour, farmer well-being, and the economics of RV management. Nevertheless, this review provides an assessment of the potential benefits of RV to both the grower and the wider environment and could serve as a valuable resource for growers. It could also inform policymakers, enabling them to broaden the scope and relevance of future policies relating to regenerative farming to include vineyards, particularly regarding their potential contribution towards climate change mitigation and adaptation.

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CONFLICT OF INTEREST STATEMENT

Two of the authors, Rebecca Sykes and Dr Alistair Nesbitt declare a conflict of interest. Rebecca Sykes is an employee of the Regenerative Viticulture Foundation (RVF), and Dr Alistair Nesbitt is a Trustee. The RVF is a U.K. registered charity that advocates for Regenerative Viticulture. Flora O'Brien and Belinda Kemp have no conflicts of interest to declare.

CONTRIBUTION OF AUTHORS

Flora O'Brien contributed to all sections of the review, leading the sections on vineyard soil health and cover crops, and edited all sections. Alistair Nesbitt contributed to all sections of the review. Rebecca Sykes contributed to the mulches, biostimulants, biocontrol agents, biopesticides and functional biodiversity sections (birds and bats). Belinda Kemp conceived the idea, contributed the text for the introduction, integration of animals in the vineyard, abstract and conclusion, and managed and edited the manuscript.

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