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Nature-based solutions to increase sustainability and resilience of vineyard-dominated landscapes

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ABSTRACT

Vineyards are highly intensive systems very often located in biodiversity hotspots at the global scale. These ecosystems are now facing major environmental, agronomical and economic issues that challenge their sustainability. Based on multiple evidence, I illustrate here how biodiversity and several nature-based solutions across scales, from manipulating within-field plant communities to landscape-scale diversification, can provide benefits related to key societal challenges that vineyard socio-ecosystems are facing. These findings support the idea that biodiversity and ecosystem services play a key role in the functioning of these landscapes and that nature-based solutions offer a sustainable pathway for the future of vineyard agroecosystems. This literature review also highlights several gaps of knowledge that define a research agenda for nature-based solutions to strengthen multifunctionality of vineyard landscapes.

Introduction

Vineyard socio-ecosystems evoke ambivalence. On the one hand, they are nowadays very intensive landscapes usually supporting large areas of homogeneous monoculture massively relying on pesticide (Rusch et al., 2021). For instance, the average number of pesticide treatments per year in France is about 20 (Agreste, 2019) and grape is among the most treated crops in Europe (Eurostat, 2007). In addition, many countries planted 70 % to 90 % of their total grape area with the same 12 varieties, illustrating the major crop homogeneity in these landscapes (Wolkovich et al., 2018). Such systems are therefore exerting a high pressure on biodiversity and the environment, especially if we consider that there are presently 7.3 million hectares of vines over the world and that grape is very often cultivated in hot-spots of biodiversity such as the Mediterranean basin, South Africa or South America (OIV, 2020). On the other hand, wine industry, probably more than any other agricultural sectors, is claiming a strong attachment to local environment and biodiversity. In particular, it values biodiversity and ecosystem functions through the "terroir" concept, wine typicity or through specific labeling related to biodiversity or naturality (Bokulich et al., 2014; Mazzocchi, Ruggeri, & Corsi, 2019; Gobbi et al., 2022). This paradox reveals highly unsustainable production systems threatened by loops of negative feedbacks between intensive grape cultivation and degraded agroecosystem processes with huge potential impacts on socio-ecosystem functioning.

In addition to highly unsustainable production systems, the functioning of vineyard socio-ecosystem are threatened by global environmental changes (Hannah et al., 2013; Morales-Castilla et al., 2020). New temperature and precipitation regimes are deeply modifying the climate of most vineyards around the world with major consequences for grape production (Hannah et al., 2013; Rosenzweig et al., 2014). Predictions suggest that climate change will impact production through increased pest pressure, reduction in crop yields, increase in yield variability, and strong mismatch between regional climate and crop phenology leading to major shifts in growing areas (Ollat et al., 2016). In addition, multiple invasive species are directly threatening grape production in different parts of the world. For instance, the invasive plant pathogen, *Xylella fastiodiosa*, or the Japanese beetle, *Popillia japonica*, are presently threatening European vineyards (EFSA, 2018; Poggi et al., 2022). Moreover, modifications of consumers' expectations and the important societal pressure for pesticide reduction impose new challenges for winegrowers that must adapt quickly in a global market context (Santillán et al., 2019; Ubeda et al., 2020). All these concomitant challenges (e.g., limiting pesticide use, halting biodiversity decline, adapting to climate change, mitigating the effects of climate change, limiting the risk of invasive species, adapting to global market) seriously question the future of most vineyards and highlight the urgent need to design resilient and multifunctional vineyards.

In this context, nature-based solutions which are at the heart of the development of a strong agroecology, offers an interesting perspective to

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build multifunctional landscapes providing benefits to multiple stakeholders while facing major socio-economic challenges (Cohen-Shacham et al., 2016). Nature-based solutions refer to the sustainable use and management of ecosystem processes to tackle societal challenges that simultaneously provide environmental, social and economic benefits to society and help building resilience (European Commission, 2015; Seddon et al., 2020). Identifying such solutions requires a multidisciplinary understanding of the relationships between environmental changes across spatio-temporal scales, biodiversity and socio-ecosystem functioning. In this paper, using a literature review (sensu Grant & Booth, 2009), I summarized existing knowledge about how several nature-based solutions can help addressing some of the challenges faced by vineyard socio-ecosystems while providing benefits for biodiversity. I also identify important gaps of knowledge that are presently limiting the adoption and the spread of such solutions. I argue that this body of knowledge provides the basis to design future vineyard landscapes in a global change context and propose a research agenda on nature-based solutions to strengthen multifunctionality of vineyard landscapes.

Nature-based solutions to limit pesticide use

Controlling for pest and disease damages is probably one of the major agronomic challenges in vineyards. Despite large variability across pedoclimatic contexts and years, a very intensive use of pesticide is usually recorded in vineyard due to a large range of pathogens and pests (Pertot et al., 2017). Fungicides generally account for the largest share of pesticide treatments in most vineyards, with an average of 12 to 15 applications per year and up to 25 to 30 applications in the most problematic conditions (Pertot et al., 2017). Insecticide use is usually of lower importance buts still represents 1 to 4 applications per year on average with up to 8 to 10 applications per year for table grape production. The pathogens and pests responsible for pesticide application vary across the pedoclimatic contexts but the main pathogen issues are: the causal agents of downy mildew, *Plasmopara viticola*, the powdery mildew, *Erysiphe necator,* the grey mould, *Botrytis cinerea*, and the black rot, *Phyllosticta ampelicida*, which represent the main diseases affecting grape production that account for the great majority of fungicide applications. Among arthropod pests of grapevines, grapevine moths (e.g. *Lobesia botrana, Eupoecilia ambiguella* or *Sparganothis pilleriana* in Europe), leafhoppers (e.g. *Empoasca* vitis and *Scaphoideus titanus*, vector of the Flavescence Dorée phytoplasma), scales (e.g. *Parthenolecanium corni, Planococus citri*) and spider mites are among the main pest issues (Pertot et al., 2017).

Several nature-based solutions operating at different spatio-temporal scales can limit pest infestations and pesticide use in vineyards. They act either directly through impacts on pests or pathogen populations (i.e., the resource concentration hypothesis) or indirectly through natural enemy communities and biological control services (i.e., the natural enemy hypothesis) (Root, 1973; Rusch et al., 2017a). First of all, developing and cultivating resistant or tolerant varieties of *Vitis* to pests and pathogens represents a historical way to limit pesticide use. These cultivars are based on exploiting the natural genetic diversity within the *Vitis* genus. Such cultivars can be obtained by crossing naturally resistant varieties, such as American *Vitis*, with traditional *Vitis vinifera*. Several breeding programs based on monogenetic and then on polygenetic resistance have contributed to produce resistant varieties with direct effects on pesticide use reduction. Recent assessment of the effect of such cultivar deployment revealed a reduction of up to 90 % of the treatment frequency index (Miclot et al., 2022). Exploiting genetic diversity to design resistant or tolerant varieties to multiple pests holds a great potential for pesticide reduction especially if they are combined with other management options.

Secondly, field-scale solutions such as increasing within-field plant diversity in the interrow by extensive management of spontaneous vegetation or sowing cover crops has been found to enhance natural pest control services and reduce pest populations (Beaumelle et al., 2021; Berndt et al., 2002; Begum et al., 2006; Rusch et al., 2017b; Winter et al., 2018). Rusch et al. (2017b) demonstrated that maintaining full grass cover in vineyards reduces grape moth density below a pesticide intervention threshold compared to partial grass cover (Fig. 1). This positive effect of grass cover or higher within-field plant diversity results from lower probability of pests finding their host plants due to physical or chemical disturbance, and/or more abundant and diverse communities of natural enemies due to the provision of key resources (e.g., pollen, nectar or alternative hosts) or refuges (e.g., overwintering sites) in these environments. The effect of within-field plant diversity appears to be mediated by positive effects across multiple trophic levels. For instance, in a manipulative experiment in real farmers' fields, Beaumelle et al. (2021) found that increasing within-field plant diversity from 2 to 20 plant species enhanced the abundance of natural enemies by 140 %. Similarly, Barbaro et al. (2017) found that insectivorous birds were 15 % more abundant in vineyards with full grass cover compared to vineyards with partial grass cover. In addition of manipulating within-field plant communities, other management options such as reducing soil tillage, mulching, or planting flower strips can also contribute to limit pest populations and hence pesticide use (Letourneau et al., 2011; Rusch et al., 2010).

In addition to field-scale solutions several landscape-scale solutions can also contribute to limit pesticide use. Observational studies have demonstrated that increasing landscape heterogeneity through higher amount of permanent grasslands or forests can enhance pest control services, reduce the level of pest or pathogen infestations, and limit pesticide use (Muneret et al., 2019a; Paredes et al., 2021; Etienne et al., 2023). Here again, the beneficial effects of increasing the amount of semi-natural habitats in the landscape on pesticide use come from direct effects on pests or pathogen dispersal (e.g., barrier effect), or indirect effects mediated by natural enemy communities. Etienne et al. (2023) for instance, quantified that increasing the amount of woodlands in the landscape from 5 % to 50 % (in a 2000 m radius buffer) decreased the probability of spraying insecticide in vineyards from 0.84 to 0.22 in a French national-scale study (Fig. 1). Similarly, Paredes et al. (2021) demonstrated that insecticide use doubled in vineyard-dominated landscapes but declined in vineyards surrounded by shrublands in Spain. Similar results were also found in Italy (Geppert et al., 2024). Moreover, increasing the amount of semi-natural habitats in the landscape has been found to enhance the abundance and the diversity of natural enemy communities including vertebrates and invertebrates, suggesting beneficial effects of semi-natural habitats on pest populations mediated by natural enemies and top-down control (Rösch et al., 2023; Muneret et al., 2019b; Kolb et al., 2020). For instance, increasing landscape heterogeneity through native vegetation remnants has been found to enhance bat activity and pest control services in vineyard landscapes (Rodriguez-San Pedro et al., 2019; Rodríguez-San Pedro et al., 2020; Tortosa et al., 2023; Charbonnier et al., 2021).

Gaps of knowledge: despite the significant body of knowledge previously explained about how several nature-based solutions across scales contribute to limit pesticide use in vineyard landscapes, we still lack important information about factors limiting their adoption. First, the large majority of studies on this topic focus on the effect of a single nature-based measure on pest pressure and pesticide use (e.g., Muneret et al., 2019a; Beaumelle et al., 2021; Etienne et al., 2023), and we lack information about combined effects across spatiotemporal scales. This issue is of particular importance if we consider that pesticide-free agriculture will only be possible if we combine partial effects solutions across the entire agrifood systems (Jacquet et al., 2022). Second, studies quantifying the efficiency of nature-based solutions to limit pest pressure are generally dedicated to one or few pests and we lack an integrative assessment of their effects on multiple pests and pathogens as well as on yield losses and farmers' incomes (Rusch et al., 2017b). Third, efficiency of nature-based solutions to limit pest infestation levels and pesticide use is generally assessed at small spatiotemporal scales and we need a more robust assessment if we are to anticipate the effect of

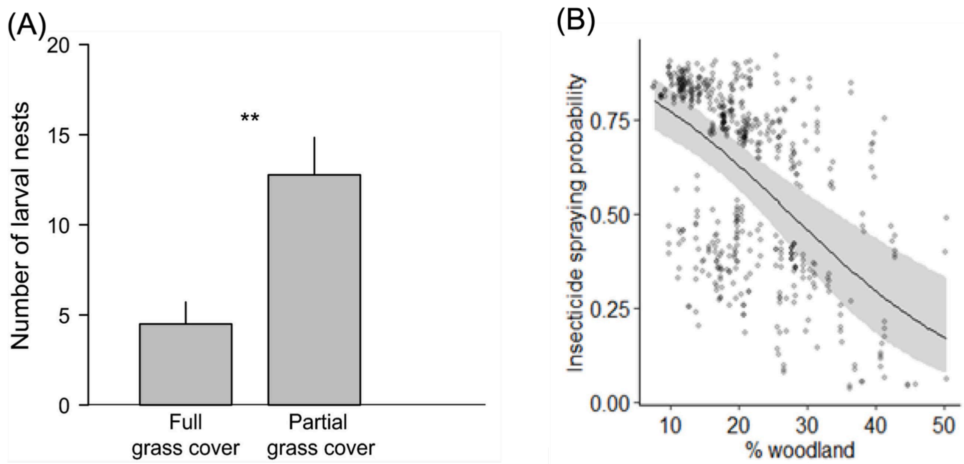

Fig. 1. Illustration of how two nature-based solutions in vineyard-dominated landscapes operating at two scales contribute to limit pest pressure and pesticide use: A) maintaining full grass cover in the interrow contribute to limit density of grape moth larval nests and B) increasing the amount of woodland in the landscape decreased the probability of spraying insecticide. These two figures are from Rusch et al. (2017b) and Etienne et al. (2023); permissions obtained from the publishers.

nature-based solutions deployment over large spatiotemporal scales on pest pressure, yield losses and farmers' incomes (Rusch et al., 2017b). Finally, we lack predictive models relating environmental changes and nature-based solutions to guide practitioners designing pest suppressive vineyard landscapes and explore optimal scenarios of nature-based solutions deployment in a global change context.

Nature-based solutions to enhance soil health

Soil health is fundamental for wine production and the functioning of vineyard socio-ecosystems (Giffard et al., 2022). As in many other ecosystems, soil biodiversity, which encompasses different communities belonging to soil microbes, mesofauna and macrofauna, provides multiple ecosystem functions that support grape production. These communities are involved in many key ecological processes such as organic matter decomposition, provision of nutrients to vine, control of pests and diseases, modification of the soil structure, limitation of soil erosion and impacting biogeochemical cycles (Brussaard et al., 2007). Several components of agricultural intensification, such as large monocultures, intensive soil tillage, inorganic fertilizers and pesticides have strongly affected soil functioning and soil health (Tsiafouli et al., 2015; de Graaff et al., 2019).

To date several nature-based management options support vineyard soil health with positive effects on soil fertility, soil biodiversity or climate change mitigation. First, using sown cover crops or extensive management of spontaneous vegetation in interrows improved soil conditions compared to intensive soil tillage (Winter et al., 2018). It limits soil erosion through improved soil structure and higher water infiltration capacity. It also contributes to increased soil organic matter, soil ability to recycle nutrients through increased abundance and diversity of microorganisms and decomposers with potential beneficial effects on carbon sequestration and soil water holding capacity (see also below the nature-based measures to combat climate change section) (Whitelaw-Weckert et al., 2007; Vukicevich et al., 2016). Second, the use of biostimulants, which could be mineral or biological substances (such as microorganisms or protein hydrolysates), has recently emerged as a way to boost or regenerate soil functioning (Ochoa-Hueso et al., 2023). Certain strains from the *Bacillus* or *Pseudomonas* genera, as well as mycorrhizal fungi or whole-communities of miroorganisms have been found to benefit soil-plant functioning with positive impacts on nutrition use efficiency, plant defense or abiotic stress tolerance (Jindo et al., 2022; Ochoa-Hueso et al., 2023). Other farming practices such as integration of animal husbandry, adding wood pruned into the soil or mulching have beneficial effects on soil biodiversity, soil erosion limitation, soil water retention and carbon storage and thus offer complementary practices to enhance soil functioning in vineyard (Giffard et al., 2022).

Gaps of knowledge: while a large body of knowledge presently exists about management options that can benefit soil activity and soil health, we still lack information about the potential consequences of such practices on some communities (e.g., microbial communities) and on important agroecological functions such as pests or pathogen damage, biomass production or farmers' income. In addition, direct and indirect impacts of landscape-scale solutions on soil health remain poorly explored in vineyard landscapes although solid evidence exists about the importance of land-use intensity over large scales for belowground communities and functioning (Le Provost et al., 2021).

Nature-based solutions to combat climate change

Multiple impacts of climate change on vineyard systems have been highlighted. We expect an increase in biomass production with higher CO_2 concentration, a change in crop phenology with an advancement of three to four days per decade of the vegetative and reproductive cycle due to higher temperatures, an increase of water stress with consequences on crop quantity and quality, a higher risk of pest or pathogen introduction with potential consequences for grapevine production, or an increase in the probability of extreme climatic events such as drought, flood or hail with major impacts on production (Bindi et al., 1996; Caffarra & Eccel, 2011; Naulleau et al., 2021). Several management options can help vineyard systems to adapt to climate change and can contribute to mitigate the consequences of climate change on vineyard functioning.

First of all, manipulating intra-specific diversity of the cultivated plant is probably one of the main and efficient solutions to adapt to climate change and to increase the resilience of vineyard systems without changing the identity of crops or geographic distributions of crops. *Vitis vinifera*, the wine grape, supports a huge genotypic and phenotypic diversity which is a major adaptation potential to ongoing environmental changes. There are 6000 to 10,000 varieties of *V. vinifera* estimated at the global scale and about 1100 commercial varieties (Wolkovich et al., 2018). The high variability of crop traits provides a major adaptation potential with varieties that differ in their cold or heat tolerance, in their ability to cope with drought and water stress, and in their phenology (Duchêne et al., 2012; Wolkovich et al., 2018). For instance, phenological stages can vary between six to ten weeks across varieties under the same climate (Boursiquot et al., 1995; Wolkovich et al., 2018). A modelling study at the global scale even estimated that exploiting cultivar diversity limits the consequences of climate change on grape production and represents therefore a major mitigation strategy (Morales-Castilla, 2020). According to this study, exploiting cultivar diversity halved projected losses of current winegrowing areas under *a* + 2 °C scenario, decreasing areas lost from 56 % (without changing varieties) to 24 % (when growers shift to more suitable varieties). Such findings are clearly demonstrating that using cultivar diversity is a major solution to adapt vineyard socio-ecosystem to climate change. However, intraspecific diversity as an adaptation strategy to climate change remains unexploited as the same 12 varieties make about 35 % of the total wine grape area at the global scale. In addition, these solutions raised major issues relative to the socio-economic consequences of such solutions on territories, wine sectors and the consumers' expectations.

Secondly, other management options based on plant diversification such as intercropping, cover crops or agroforestry can contribute to mitigate the effects of climate change. These management options have potential beneficial effects on water use efficiency, on water cycle as well as on carbon sequestration (Winter et al., 2018; Moléna et al., 2023). In intercropping or agroforestry systems, better water-use efficiency is generally attributed to a better water uptake in the soil due to complementarity in root systems between crops or between trees and crops, even though roots of old grapes go very deep. Trees, by exploiting water resources deeper than the crop, can even lift water from deep soil layers up to the upper layers through hydraulic lift (Bayala & Prieto, 2020). In addition, soil water content is increased in intercropping systems or cover crops through limited soil evaporation, transpiration or runoff (Brooker et al., 2015). In agroforestry systems, trees contribute to the regulation of the local microclimate, and thereby limiting evapotranspiration and water loss through soil evaporation. Moreover, all farming practices that improve soil organic matter content and soil aggregation also contribute to enhance water infiltration and increase water storage capacity in the soil (Ruiz-Colmenero et al., 2013; Marques et al., 2020). These diversification practices that imply long-term vegetal diversification and lower soil perturbation have also beneficial effects on carbon sequestration. A recent meta-analysis quantified the gain in carbon sequestration in vineyards under various soil management options compared to conventional systems with tillage and synthetic fertilizers (Payen et al., 2021). This study shows that all options including reduced soil tillage, organic amendments, incorporation of pruning residues in the soil, or cover crop increase soil carbon sequestration. For instance, organic amendments increase by 44 % soil organic carbon stock, while no-tillage systems or cover crop increased soil organic carbon stock by 20 % and 22 % respectively. This meta-analysis also indicated that the highest effect size was obtained when combining organic amendments and no-tillage systems which was associated with a soil organic carbon sequestration rate of 11.06 Mg CO2-eq. ha−1 yr−1 (Payen et al., 2021).

In addition to these field-scale nature-based solutions, there are several landscape-scale solutions that can contribute to mitigate the impact of climate change on vineyard functioning. Diversifying crops, adapting farming practices using permanent soil cover and avoiding bare soils at the landscape scale can contribute to better water use efficiency and limited soil runoff with positive effects on water cycle, water soil content and soil organic matter content (Moléna et al., 2023). In addition, several habitats such as hedgerows, forests or stone barriers can play a role here by facilitating water infiltration of runoff water and slow down the water cycle (Moléna et al., 2023).

Gaps of knowledge: despite an emerging body of knowledge on how nature-based solutions can mitigate climate change and offer adaptation options to climate change, we lack an integrative assessment of how nature-based solutions contribute to increasing resilience of vineyard landscapes to climate change. In addition, a majority of the available studies on the topic tend to focus on how nature-based solutions mitigate very specific aspects of climate change (e.g., water stress or carbon sequestration) (e.g., Stanchi et al., 2021), while other such as how nature-based solutions can mitigate extreme climatic events, remain poorly studied. Moreover, most of the studies on the topic have considered local-scale management options and, here again, landscape-scale nature-based solutions remains poorly explored. Finally, we lack predictive models to anticipate the consequences of climate change on vineyard functioning and assess optimal scenarios of adaptation through various management options.

Nature-based solutions to limit biodiversity erosion

Vineyards are very often cultivated in biodiversity hotspots (Geldenhuys et al., 2022). Because vineyards are perennial, they hold great potential for biodiversity conservation through temporal continuity in resources provided for multiple taxa. However, because they are often very intensive agricultural systems with frequent soil tillage and pesticide applications, they are most often seen as negative for biodiversity conservation (Bruggisser et al., 2010; Pailoa et al., 2020) and could even be considered ecological traps.

Nature-based solutions to limit biodiversity erosion at local and regional scales are now well known and mainly consist of combining extensive farming practices with landscape-scale diversification to increase spatio-temporal continuity of resources and limit anthropogenic pressures (Grass et al., 2021). At the local scale, specific farming practices such as limiting the use of pesticide (organic or not) and their accumulation in the soil, limiting soil perturbation through reduced or no soil-tillage, as well as conserving diversified and permanent vegetation cover in the interrows are key practices with major beneficial effects on above- and belowground biodiversity (L. Muneret et al., 2019; Paiola et al., 2020; Ostandie et al., 2021; Kratschmer et al., 2021) (Fig. 2). Increasing the functional richness of plant species in vineyard interrows, for instance, has been found to enhance wild bee diversity in vineyard landscapes while intensive tillage frequency or insecticide use was found to limit abundance or diversity of wild pollinators (Ostandie et al., 2021; Kratschmer et al., 2021). Although organic farming has been found to have variable effects on vineyard biodiversity, a recent assessment of the effect of organic farming on multitrophic diversity indicates an overall positive effect on diversity and abundance of most taxa (Beaumelle et al., 2023). Spiders, beetles and birds were among the taxa that benefitted the most from organic farming in terms of taxonomic diversity, while ground beetles and earthworms tended to be reduced by organic farming practices (Beaumelle et al., 2023). At the landscape scale, increasing heterogeneity is a key element to enhance abundance and diversity of multiple taxa. Increasing heterogeneity includes both crop and non-crop diversification (i.e., manipulating compositional heterogeneity) as well as reducing average field size and increasing habitats interface (i.e., increasing configurational heterogeneity) (Martin et al., 2019; Rodriguez-San Pedro et al., 2019; Barbaro et al., 2021). For instance, increasing the amount of non-crop habitats, such as forests, grasslands or hedgerows, enhanced the abundance and diversity of many taxa, including wild pollinators, birds and bats, while increasing the connectivity of natural habitats enhanced the occurrence of mammalian predators such as gray fox, coyote, or bobcat (Hilty et al., 2006; Kratschmer et al., 2018; Ostandie et al., 2021; Barbaro et al., 2021; Tortosa et al., 2023; Rösch et al., 2024).

Among the several management options, ground vegetation management by cover cropping, conservation of native ground cover as well as increasing habitat heterogeneity are considered the most effective ones to promote biodiversity in vineyard landscapes, while organic farming is expected to have weaker effects on biodiversity (Paiola et al., 2020). However, effect sizes of management options across scales on biodiversity depend on the taxa considered and are mainly determined by their functional traits (Martin et al., 2019; Ostandie et al., 2021). Taxonomic groups with poor dispersal abilities, like several arthropod species, are most affected by local farming practices and much less by landscape-scale management options while taxonomic groups with large dispersal abilities, such as bats, are more affected by landscape-scale management. For instance, Ostandie et al. (2021) compared the

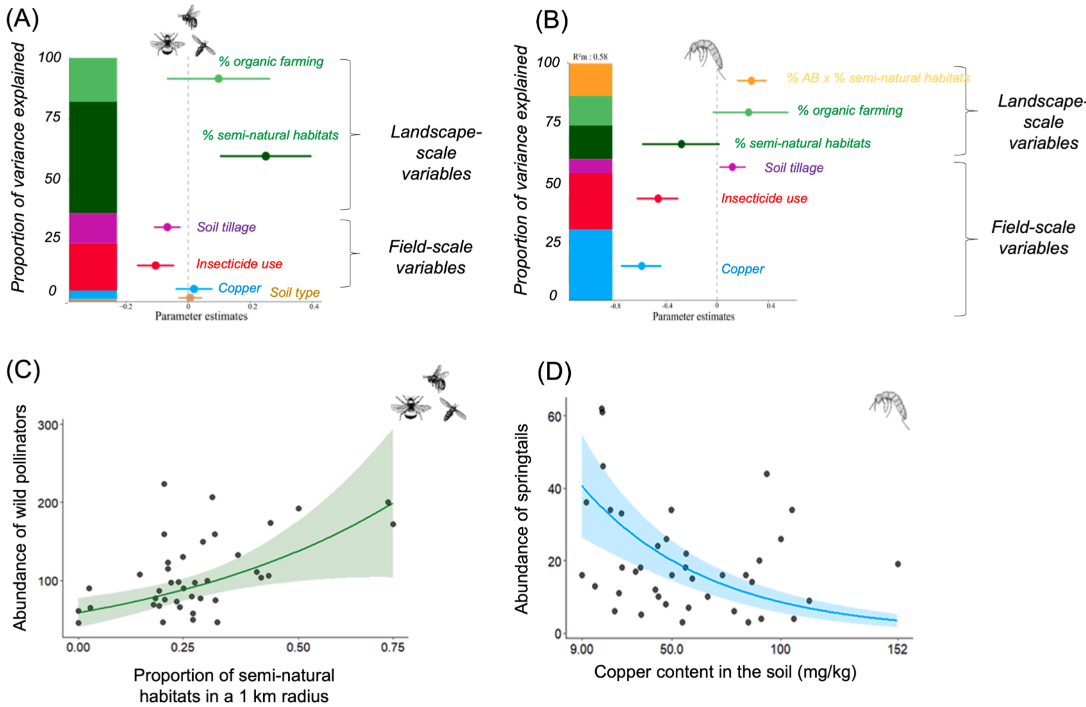

Fig. 2. Illustration of how management options across scales, from the field (A-B) to the landscape (C-D), affect differently multiple components of biodiversity in vineyard-dominated landscapes. (A) and (B) show direction of effects of multiple management options related to field and landscape scales and their relative importance (proportion of variance explained) in explaining abundance of wild pollinators (A) and springtails (B); (C) illustration of the effect of the amount of semi-natural habitats in a 1 km radius on abundance of wild pollinators; (D) illustration of the effect of soil copper content on abundance of springtails. These figures are from Ostandie et al. (2021); permission obtained from the publisher.

relative importance of local farming practices and landscape scale parameters on abundance and diversity of very different groups and found that groups such as springtails or microbes were very much determined by soil tillage frequency, local insecticide use and soil copper content while wild pollinators or ground beetles were much more affected by landscape context (Fig. 2).

Gaps of knowledge: while key solutions for designing biodiversity-friendly vineyard landscapes exist, we lack a good understanding of the multitrophic impacts of implementing nature-based solutions management in such landscapes. We particularly need quantitative assessments of direct and indirect effects (i.e., mediated by trophic or non-trophic interactions) of nature-based solutions on multiple communities to better forecast the multitrophic consequences of large-scale deployment of such solutions. In addition, we still lack operational tools and practical guidelines that help practitioners in assessing the effects of management on biodiversity and farm functioning.

Nature-based solutions to improve vineyard multifunctionality

A very limited number of studies have explicitly considered how nature-based solutions impact bundles of ecosystem services as well as multifunctionality of vineyard systems, considering agronomic, ecological and socioeconomic dimensions (Ostandie et al., 2022; Beaumelle et al., 2023). Existing studies have been mainly performed at the field scale and, to my knowledge, no empirical studies assessed landscape multifunctionality in vineyard-dominated areas using a large panel of ecosystem services and over large spatial scales (Ostandie et al., 2022; Beaumelle et al., 2023).

Using a meta-analysis, Winter et al. (2018) showed that extensive vegetation management at the field scale increased above- and below-ground biodiversity and ecosystem service provision by 20 % in comparison to intensive management. These authors found significant positive effects of such practices for biodiversity conservation, soil fertility, carbon sequestration and pest control services, while other aspects were not affected (eg, quantity or quality of grape yield or soil water budget). Although this study did not explicitly measure and assess multifunctionality of vineyard systems, it suggests predominance of synergistic effects of extensive vegetation management on bundles of ecosystem services with no major disservices. At the local scale, organic farming has no or weak effect on agroecosystem multifunctionality as it was found to promote some ecosystem services while limiting others (Ostandie et al., 2021; Beaumelle et al., 2023). For instance, organic farming promotes biodiversity and pest control services but reduced wine production leading to no differences in overall multifunctionality and very similar economic margins between organic and non-organic systems (Ostandie et al., 2021; Beaumelle et al., 2023). In addition, Beaumelle et al. (2023) exploring synergies and trade-offs between multiple performances of vineyard systems, revealed that there is no systematic trade-off between biodiversity conservation and grape productivity across a large range of situations on vineyard landscapes. They found that some farming systems promoted synergies between biodiversity conservation and productivity, while other favoured biodiversity conservation at the expense of grape yield or the inverse. Qualitative analysis suggests that farmers that combine local and landscape-scale management options had a higher probability of reaching a synergistic effect between biodiversity conservation and productivity (Beaumelle et al., 2023).

Gaps of knowledge: very few studies investigated how management options affect multiple ecosystem services in vineyard landscapes and they are mainly oriented towards organic / non-organic systems (Ostandie et al., 2022; Beaumelle et al., 2023). In addition, there is presently a crucial lack of studies explicitly measuring multiple ecosystem functions and services in vineyard landscapes. A recent systematic review of the literature revealed that of 76 papers linking ecosystem conditions to ecosystem services in vineyard systems, 62 % considered one ecosystem service, 19 % considered two ecosystem services and less than 20 % considered three services or more (Candiago et al., 2023). Moreover, a large majority of these studies considered ecosystem services assessment at the field scale. We therefore miss the ecosystem services delivered by other habitats and the spatial dynamics of ecosystem services at the landscape-scale. It is however of utmost importance to assess multifunctionality of vineyard landscapes by explicitly integrating multiple services in several habitats and across scales if we are to understand how deployment of nature-based solutions can meet societal challenges. In addition, we lack quantitative assessments of the socio-economic consequences for the farmers and other stakeholders of promoting nature-based solutions.

Evidence-informed policies to support the development of nature-based solutions

Several policies or institutional frameworks operating at various scales could be used to support the deployment of nature-based solutions in vineyard-dominated landscapes, as in many other socio-ecosystems. Based on selected examples, I illustrate here the type of policy instruments that could be useful to support the deployment of nature-based solutions and to address major societal and environmental challenges.

Since 2019, the European Green Deal and its underlying strategies, such as the Farm to Fork strategy and the Biodiversity strategy, aim at tackling the negative climate, environmental and public health impacts of the European agrifood system. The Common Agricultural Policy (CAP) is a key instrument at the crossroads of these strategies that shape European agriculture (EC, 2021). CAP is representing more than 30 % of the annual European Budget with major influence on land-use decisions (Pe'er et al., 2022). CAP now includes three instruments devoted to climate mitigation and environmental protection, namely conditionality requirements, agri-environment and climate measures (AECM) and eco-schemes (see Pe'er et al., 2022). Eco-schemes provide incentives for farmers implementing specific practices such as diversifying crops or maintaining vegetation in the interrows, using specific environmental certification such as organic farming, or maintaining specific habitats such as permanent grasslands. Some of these practices are close to nature-based solutions mentioned in this paper. These policy instruments therefore hold the potential to support the development of nature-based solutions in agriculture in general and in viticulture in particular. However, despite "greener" ambitions and new policy instruments, severe science-based critiques questioned the low-target ambitions and challenged the efficiency of this policy to reach sustainable development and climate neutrality (Pe'er et al., 2022; Cuadros-Casanova et al., 2023; Guyomard et al., 2023). Several key actions based on scientific evidence have been identified to strengthen the efficiency of the CAP regarding sustainable development goals: maintaining 10 % to 20 % of semi-natural habitats per km^2 to sustain key ecosystem services contributing to agricultural production, supporting and rewarding multifunctional farms and landscapes providing a range of services to society, or designing spatial planning and coordination of measures at territorial scales to significantly enhance their efficiencies (Pe'er et al., 2022; Mohamed et al., 2024). Overall, a large majority of actions that could increase the efficiency of the CAP instruments are based on nature-based solutions (Pe'er et al., 2022). A better alignment and integration of scientific evidence to identify clear and ambitious targets for farmers and territories could significantly increase the transformative effect of this key European policy.

The Geographical Indications schemes (either protected designation of origin, PDO, or protected geographical indication, PGI) are major mechanisms to strengthen rural development in the European Union. These schemes have been very powerful in delivering higher added value and safeguarding the identity and heritage of the product through the notion of terroir. Geographic indications provide benefits for producers by securing fair returns for their product qualities but also provides robust information on the quality and authenticity of the products for consumers. No current studies about the role of Geographical Indications in supporting the implementations of nature-based solutions in vineyard landscapes currently exist while interesting examples exist in other agricultural sectors (see Lamarque & Lambin, 2015). Such instruments could potentially play a major role in supporting nature-based solutions if clear targets and actions are identified and integrated in the specification documents defining each Geographical Indication (Owen et al., 2020; Martinez-Arnais et al., 2022; Ruggieri et al., 2023; Tscholl et al., 2024). This integration could benefit both producers and consumers and would be an ideal instrument to design tailored local policies promoting nature-based solutions adapted to each terroir. Scientific evidence about the multifunctional impacts of nature-based solutions in vineyard-dominated landscapes should serve as guidelines to inform actions that could be included in specifications of Geographic Indications with the aim of enhancing efficient nature-based solutions.

Gaps of knowledge: Scientific evidence suggests that in addition to general rules that could be applied in several regions, policies need to allow the development of tailored solutions adapted to local context. Vineyard-dominated landscapes are at the crossroads of multiple policies operating at various scales (e.g., CAP, Geographic Indications) and could serve as interesting case-studies to develop contextualized collective actions, to enhance territorial multifunctionality. Such collective actions bringing scientists and local stakeholders together could be promoted by the living labs approach (Gamache et al., 2020). Better alignment between existing policy instruments and the nature-based solutions agenda may provide major socioeconomic opportunities for vineyard-dominated territories.

Conclusions and research agenda for nature-based solutions in vineyard socio-ecosystems

This literature review revealed that several nature-based solutions can contribute to address major societal challenges that vineyard socio-ecosystems are now facing (Fig. 3). These challenges include limiting pesticide use, regenerating soil health, mitigating and adapting to climate change, limiting biodiversity erosion or increasing farming system multifunctionality. The solutions identified for these challenges converge to a set of key management options across scales that include: using cover crops and maintaining plant communities within-field, reducing soil perturbation and soil tillage, developing biological control strategies, increasing intra-specific diversity in *Vitis vinifera* species, using resistant cultivars, applying biostimulants or microbial consortia, enhancing the amount of semi-natural habitats such as grasslands or hedgerows in the surrounding landscape, and increasing overall landscape heterogeneity and connectivity (Fig. 3).

Despite the fact that some information already exists, this literature review also highlights major gaps of knowledge that limit the adoption and the spread of nature-based solutions in vineyard landscapes. These gaps are of major importance and define several key topics for a multidisciplinary research agenda about nature-based solutions in vineyard landscapes. Future research should particularly address the following topics:

- **Combining nature-based solutions across scales.** A majority of studies on nature-based solutions consider solutions independently and we lack a quantitative assessment about the expected outcomes of combinations of nature-based solutions across scales (e.g., Beaumelle et al., 2021). However, we know that developing agroecological landscapes will require territorial combined actions along the agri-food value chain Gamache et al. (2020). We need more studies investigating how combined options across scales affect vineyard socio-ecosystems.
- **Assessing the contribution of nature-based solutions to landscape multifunctionality.** A majority of studies investigate the supply of one or very few ecosystem services in vineyard habitats at small spatiotemporal scales (e.g., field scale for one or two years). We therefore miss important information about the effects of nature-based solutions on landscape multifunctionality (*sensu* Manning

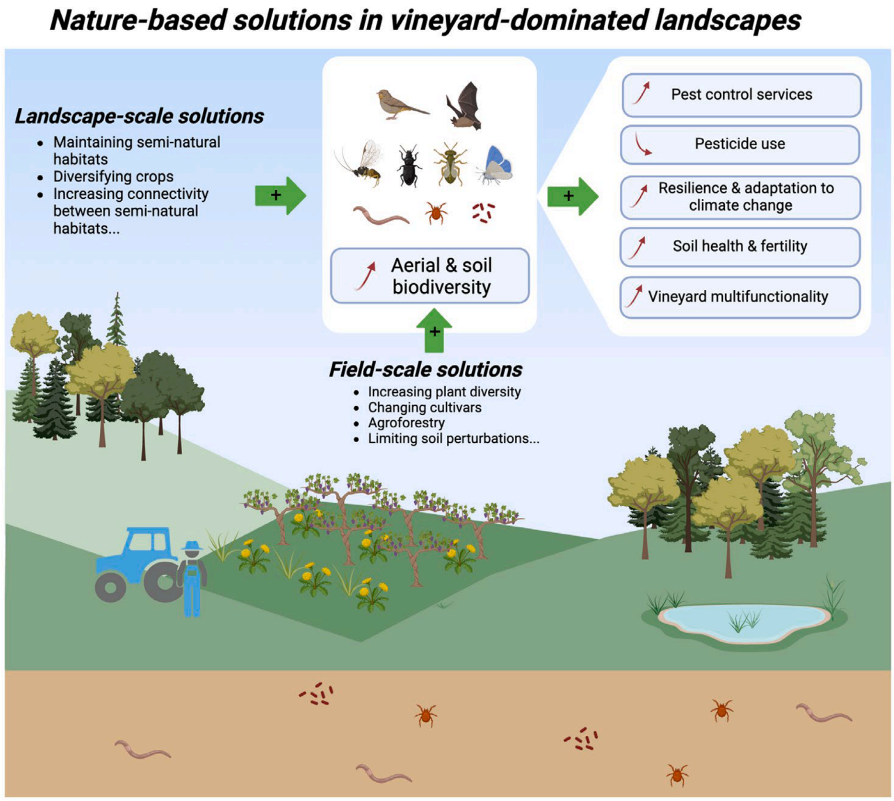

Fig. 3. Figure illustrating the demonstrated impacts of nature-based solutions on the functioning of vineyard socio-ecosystems. See the text for gaps of knowledge and research agenda about nature-based solutions.

et al., 2018), limiting our ability to upscale the expected effects. We need more integrative assessments of how nature-based solutions support multiple ecosystem services in various habitats at the landscape scale in order to provide a more holistic view of the effect of nature-based solutions on the functioning of vineyard-dominated landscapes.

- **Integrating stakeholders' perspectives to impulse change.** A large majority of the studies about nature-based solutions in vineyard landscapes assess how management options affect the supply of ecosystem services but not how they match stakeholder's demand or their adaptation to local socio-ecological context. We need dedicated long-term research infrastructures, such as living labs, bringing together researchers and stakeholders that can co-design and assess solutions tailored to local contexts using participatory approaches. Such research infrastructure makes it possible to ensure adoption and efficiency of nature-based solutions and could contribute to impulse transformative changes toward sustainable trajectories (Palomo et al., 2021). This approach is currently largely missing and should be supported.
- **Evidence-based policies to efficiently support the deployment of nature-based solutions.** Existing policies could be adapted to better support nature-based solutions in agriculture and viticulture in particular (eg, CAP, Geographic Indications). In vineyard-dominated landscapes, Geographical Indications policies could play a major role in designing tailored local policies promoting nature-based solutions adapted to each terroir through contextualized collective actions. However, better alignment between scientific evidence and ambitions of these policies are needed and could provide major opportunities for transformative changes in vineyard-dominated landscapes.
- **Modelling and upscaling the effects of nature-based solutions.** The body of existing knowledge mainly comes from empirical studies in a given context that a posteriori assesses nature-based solutions to understand their effects and the mechanisms driving them. We strongly need to develop models (statistical and mechanistic models) to forecast the impacts of nature-based solutions and to upscale the consequences of large-scale expansion of these solutions in real landscapes. Modelling supply and demand of multiple services at the landscape scale (e.g., carbon sequestration, food and wine production, aesthetic values of the landscape, or water quality) would make it possible to assess the consequences of several land-use scenarios and should help decision makers.

CRediT authorship contribution statement

Adrien Rusch: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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