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SPECIAL ISSUE

Barriers and opportunities to increase soil organic carbon in vineyards: A case study of extension personnel in France and in the United States

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ABSTRACT

Increasing soil organic carbon (SOC) in vineyards enhances soil health with associated benefits for climate change resilience and mitigation. However, adoption of SOC-building management practices remains low and hindered by multifaceted barriers. Extension specialists play a crucial role in overcoming adoption challenges by providing tailored advice and training opportunities to growers. This study used semi-structured interviews with extension specialists in warm and cool regions of France and USA to explore context-specific barriers and opportunities for adoption of SOC-building practices. The Multi-Level Perspective framework was implemented to identify SOC-building practices and factors influencing their adoption from niche to mainstream. The practices to increase SOC identified included cover crops, organic fertilisation, and reduced tillage, with regional variations in implementation across climates. Barriers to the adoption of SOC-building practices were centred around costs of implementation, limited knowledge of the long-term impacts of the practices and the complexity of local adaptations of practices to be effective in specific vineyard conditions (*e.g.*, slope, planting density, water availability). Incentives for adoption could include facilitations between grape growers and livestock farmers, targeted research, improved extension programs, and government support through subsidies or restructuring of the supply and value chain both in France and in the USA. A significant gap in extension capacity was identified for cover crop implementation in the USA's warm and cool areas. Research gaps were identified around pruning residue management, the application of arbuscular mycorrhizal fungi, and the integration of grazing animals into winegrape vineyards more in the USA than in France. Expanding applied research and cost-benefit analysis and the long-term impact of these practices is crucial for improving adoption rates of SOC-building practices in the context of climate change.

KEYWORDS: soil organic carbon, sustainability, practices, climate zone, extension perception, vineyard, country, GiESCO 2025

INTRODUCTION

Vineyard systems are located across a range of soils worldwide, many of which are characterised by low soil organic carbon (SOC) levels and substantial soil erosion potential (Muñoz-Rojas *et al.*, 2012). Improving SOC can lead to improved soil health (Liptzin *et al.*, 2022) as well as vineyard productivity and quality (Gonzalez-Maldonado *et al.*, 2024). Additionally, building up SOC can contribute to climate change mitigation while improving the resilience of vines to environmental stressors associated with climate extremes (Brewer *et al.*, 2023; Lazcano *et al.*, 2020).

This is relevant as the world's vineyard surface area is declining (OIV, 2024) and vineyards in major vine-growing regions are removed due to extreme climatic conditions and widespread fungal diseases, culminating in a historically low global wine production in 2023 (OIV, 2024). Faced with the decline in vineyard acreage and the increasing negative impacts of climate change, SOC sequestration in viticultural soils has been identified as an effective mitigation tool for climate change (Sykes *et al.*, 2020). Adoption of SOC-building practices in vineyards could significantly contribute to global efforts to remove carbon from the atmosphere given the high SOC sequestration rates obtained for many practices that can be implemented in vineyards (Payen *et al.*, 2021; Prairie *et al.*, 2023; Visconti *et al.*, 2024), and the large land area still dedicated to viticulture worldwide (~7.45 Mha).

SOC sequestration is considered here as the transfer of carbon dioxide (CO_2) from the atmosphere into the soil via plants, plant residues, or other organic matter where it becomes part of the soil organic matter (SOM) reservoir (Olson *et al.*, 2014); resulting in a net reduction of CO_2 in the atmosphere and increases in SOC stocks over time (Chenu *et al.*, 2019). SOC and more generally SOM are often low in vineyards with bare soil maintained through the intensive use of herbicides (Raclot *et al.*, 2009) and tillage in the inter-row (Eldon & Gershenson, 2015) or under the vines (Karl *et al.*, 2016). The physical action of cultivation can make organic residues vulnerable to degradation by microbes and promote the loss of SOM (Six *et al.*, 1998). In a meta-analysis of soil carbon sequestration practices in vineyards, the most effective SOC sequestration rate was achieved through a combination of organic amendments and no-till (11.06 Mg CO_2-eq. ha^{-1} yr^{-1}) while the lowest was observed with the incorporation of pruning residues (2.82 Mg CO_2-eq. ha^{-1} yr^{-1}) (Payen *et al.*, 2023). The authors did not consider grazing, however long-term, dormant season sheep grazing in California has demonstrated a remarkable 33 % increase in subsoil SOC storage, including higher quantities of physicochemical stabilisation in the mineral-associated organic carbon pool of the deepest measured subsoil layer (30–45 cm) (Brewer *et al.*, 2023)

While the scientific literature can provide data-based recommendations to grape growers on how to improve SOC in vineyards, there is a multitude of potential obstacles to the immediate adoption of scientific recommendations, including lack of dissemination of research results to the industry, low relevance of research results for commercial settings or across vine growing regions, and cost of practice adoption. For instance, a survey of 400 French winegrowers suggested that adoption of practices intended to increase SOC remains limited, except for returning pruning residue to the soil (Payen *et al.*, 2022). A subsequent survey of 506 French winegrowers conducted to identify the adoption rate of SOC-building practices (application of organic amendments including biochar, returning pruning residues to the soil, no-till, cover cropping, and introducing or preserving hedges in the vineyard) showed that a significant proportion of growers (73 %) had adopted incorporation of amendments as well as cover cropping practices, while more than half (57 %) incorporated hedges into their vineyards. Less than half (48 %) adopted no-till and only 2 % of respondents used biochar amendments (Payen *et al.*, 2023). The study identified a wide range of barriers to the adoption of these practices and how some of these barriers could be mitigated. While this question was only answered by ~6 % of respondents, the top action to overcome barriers was better extension and communication of information (Payen *et al.*, 2023).

In both the USA and France, grape growers rely on public and/or private extension specialists/agents to advise them on vineyard management. To be effective, extension specialists collaborate with winegrowers in finding their own solutions since each vineyard requires a specific assessment and practice implementation (Compagnone, 2011; Llewellyn, 2007). Extension specialists provide customised and context-based recommendations and outreach/education programs (including publication of material and demonstration plots) for growers to co-learn, share experiences and observe results first-hand. Extension agents often provide training, and technical support, and produce guidelines through involvement in collaborative research projects. As such, extension agents act as a bridge between researchers and growers; making scientific knowledge accessible and the basis of practical advice while partnering with and informing researchers of grower priorities, obstacles, and opportunities for further research. They are therefore important actors integrating various forms of knowledge with broad expertise in applications of SOC-building practices as well as barriers and opportunities for adoption in their regions.

Multi-Level Perspective (MLP) frameworks can help capture extension agents' knowledge to understand their perception of levers favouring or impeding mainstreaming SOC-building practices (Geels, 2011). This framework considers the broader structural landscape entrenching technological regime (*e.g.*, conventional commercial viticulture) and the pull and push factors that can emerge to disrupt the dominant system through "creative disruption" (Kivimaa & Kern, 2016). Pull levers tend to arise from changes in the landscape, whereas push factors arise through decentralised, grassroots processes. Here, we framed vineyards including SOC-building practices as a niche system, and then identified push and pull factors that would allow for greater adoption and development of these practices. Although France and the USA present drastically different socio-ecological contexts, some push and

pull factors may be common, providing a way to prioritise collaborations and certain SOC-building practices across vineyard growing regions to maximise impacts.

The objective of this study was to explore, through semi-structured interviews of extension specialists, the main SOC-building practices currently implemented in vineyards and their perception of barriers and opportunities for improving SOC in vineyards in France and the USA. We used the MLP framework to better understand the differences between practices in semi-arid and temperate climates and some of the unique or common barriers between these two main wine-growing climates. This information is useful to identify key levers and extension gaps while enhancing the exchange of knowledge to further the adoption of SOC-building practices at a large scale.

MATERIALS AND METHODS

This study included five steps: questionnaire building, country/region/actor sampling, interview of extension specialists, analysis of the survey, and identification of extension gaps relating to the adoption of practices to improve soil SOC (Figure 1).

1. Case study regions

With 792,000 hectares, France accounts for 11 % of the world's wine-growing area (2nd) and 20 % of the global total production of wine (1st). With 392,000 hectares, the US accounts for 5.4 % (6th) of the world's wine-growing area, producing 8.5 % of the global total wine consumed (4th) (OIV, 2024). The two largest warm wine-growing areas were investigated for each country (Table S1): California and Southeast France. California vineyards account for approximately 54 % (212,000/392,000 ha) of the US land area planted to grapevines (Franson, 2016) while the vineyards in Southeast France account for 17 % (135,714/792,000 ha) of the French vineyard area (OIV, 2024). These regions are located in a semi-arid Köppen-type Csa climate characterised by a temperate climate with dry and hot summers.

To enrich the study, two cool climate zones with vineyards were also investigated (Table S1; Figure 2): Northeast USA and 'Grand-Est' of France. Cool climates of the US North-East and French Grand Est are characterised by a temperate-cold Köppen-type Dfa and Cfb climate zone respectively, with continental climate with no dry season and warm summer.

2. Data collection

Data was collected through one-on-one interviews organised as video calls. Responses were transcribed during the interview and validated by the interviewee at the end of the video call. Interviews lasted less than one hour and were conducted from July to October 2022. We did not aim for statistical representativeness, but rather to sample across regions with a wide range of conditions (2 countries and 2 climate conditions) to obtain a diversity of perspectives. We chose to use a qualitative survey approach with semi-structured interviews and questions with open answers so that interviewees could reflect on their ideas and opinions. The questionnaire contained open questions, which first, addressed the perception of extension specialists of SOC-building practices previously identified as having the potential to mitigate climate change in vineyards. Some of these practices mentioned by respondents have already been identified by Payen *et al.* (2023): applying organic amendments, returning pruning residues to the soil, no-tillage, cover cropping, and preserving hedges in the vineyard. Some practices appeared in respondents' answers: agroforestry, mulch and grazing. The first part of the questionnaire allowed us to collect data on seven SOC-building practices. The second part of the questionnaire focused on six practices identified in the literature to be SOC-building practices: returning dormant

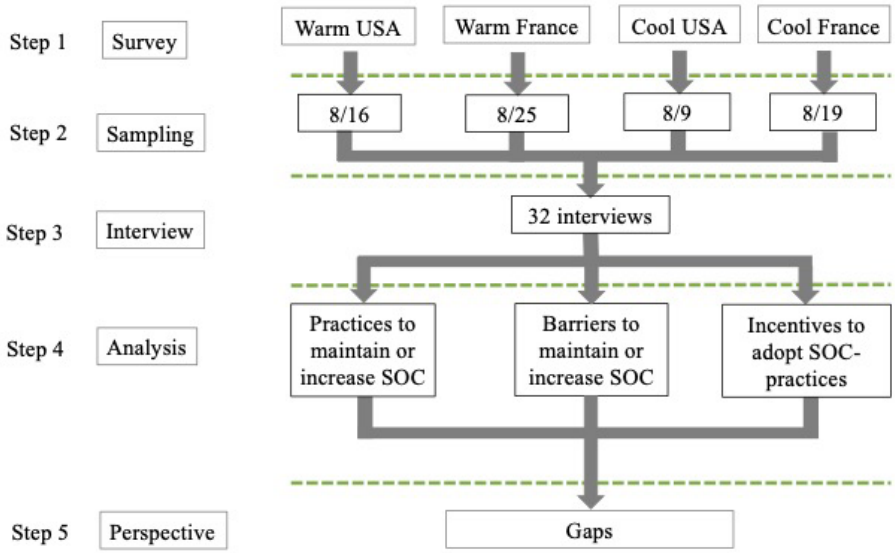


FIGURE 1. Diagram of the study steps and framework to identify SOC-building practices, barriers and incentives to adoption and extension gaps. For step 2, the fraction indicates the number of extension specialists interviewed compared to the total number of individuals contacted.

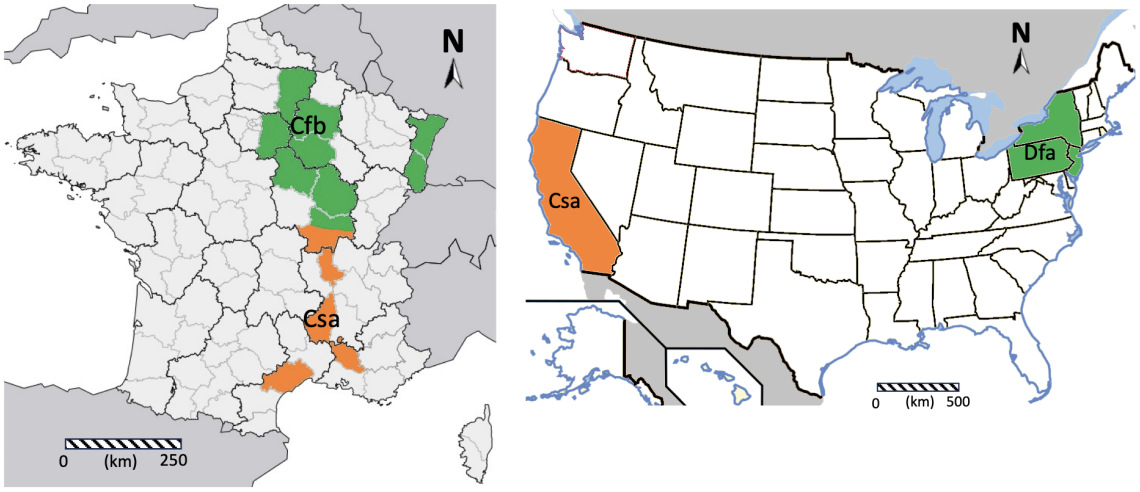


FIGURE 2. Vineyard regions studied. Coloured areas are the department (France) or state (USA) where there are vines and extension specialists and where the research was conducted. Green regions in temperate-cold climate: (France-cool) Alsace, Burgundy, Champagne vineyards (Köppen-type Cfb) and (USA-cool) New York, New Jersey, Pennsylvania vineyards (Köppen-type Dfa). Orange regions in semi-arid climate: (France-warm) Ardèche, Beaujolais, Hérault, Vaucluse (Köppen-type Csa) and (USA-warm) California (Köppen-type Csa).

vine pruning wood to the soil, reducing tillage, increasing the use of cover cop or resident vegetation, reducing the use of herbicide, inoculating vines with arbuscular mycorrhizal fungi, and introducing animals for grazing.

The questionnaire included questions about (i) which SOC-building practices they think already exist and could maintain or increase SOC in their region, (ii) the barriers to SOC–building practice adoption and (iii) levers to encourage the use of practices which maintain or increase SOC (Figure S1).

Interviewees were extension specialists located in the four regions described above. Interviewees were first identified through the researcher's networks (Cornell University, UC Davis, and Institut Français de la Vigne et du Vin (IFV) for France. In France and California, we used the snowball method to identify more interviewees (Chantre & Cardona, 2014) to reach a balanced design across regions. We did not need this method in the USA-cool since the initial contacts were sufficient (Figure 1). Indeed, a small number of extension specialists represent a much greater proportion of the cultivated vine area than what would have been possible to cover by interviewing the same number of growers. Each region had eight extension specialists (n = 8), ensuring a range of perspectives from various vineyard management conditions. Our sample of 32 interviewees represented actors working with a significant number of winegrowers in the two countries (214,000 hectares of 792,000 hectares in total in France; 229,000 hectares of 392,000 hectares in total in the US). Our method was inspired by previous studies using surveys of farmers with a similar size sample (14 farmers in Ryschawy *et al.*, 2021; 35 farmers in Bohnert & Martin, 2023; 33 farmers in Revoyron *et al.*; 2022). We extrapolated this method to survey extension specialists. We focused on extension specialists instead of winegrowers because extension specialists represent aggregated knowledge since they are each in contact with several winegrowers. This survey of 32 extension specialists therefore gives access to more knowledge of practices than 32 winegrowers could have given us.

3. Data analysis

Data were collected, quantified and coded into key themes. We used inductive content analysis (Ryschawy *et al.*, 2021) by open-coding our interviews into key themes emerging from the interviews (Elo & Kyngäs, 2008). Relevant sentence fragments were identified (Beudou *et al.,* 2017) and organised into pre-defined sub-categories based on the general framework of adoption (advantages, barriers and levers) (Prokopy *et al.,* 2008). We grouped sub-categories into these main categories through an iterative coding approach, re-listening to the interviews and grouping emerging themes according to our pre-existing mental models of how structural and individual contexts influence farmer perceptions (Cortner *et al.,* 2019; Niles *et al.,* 2018). We carefully limited redundancies while prioritising one category only for each fragment, when it may be classified into two different categories.

We examined each interview through the lens of practices favourable to SOC and illustrated them using selected interviewee quotes (mentioned by a letter + number exponent and reported in supplementary data). Once finalised, a detailed analysis was then conducted on each theme and cross-referenced with the literature, which formed the basis of the qualitative results and parts of the discussion (Ludlow *et al.*, 2021).

RESULTS AND DISCUSSION

1. Current practices to increase SOC

Respondents from warm climates listed fewer current practices in their regions to improve SOC (USA-warm listed 3 current practices, France-warm listed 4 current practices) compared to the cooler regions, where 5 (USA-cool) and 6 (France-cool) were listed; perhaps reflecting the reduced spatial and temporal niches to grow vegetation in and around the vineyard in warm climates. However, the responses relating to current practices to increase SOC were generally similar across regions–for example, only 1/32 interviewees mentioned reducing herbicide as a current practice, but most extension specialists, regardless of region, emphasised increased use of cover cropping and increased organic fertilisation.

The use of cover crops was cited by all but one of the extension respondents (31/32) as a current practice (Figure 3). There were differences among the four study regions on how cover crops were implemented in the vineyard, in particular, which cover crop species were used, whether cover crops were tilled into the soil, planted year-round or seasonally and whether they were between rows only (warm regions) or also under vines (cool regions). In warm regions, cover crops grow winter long and are terminated early to avoid potential competition for precipitation and irrigation water. In cool climates, cover crops can be maintained for longer periods of time, further enhancing C fixation and SOC storage potential.

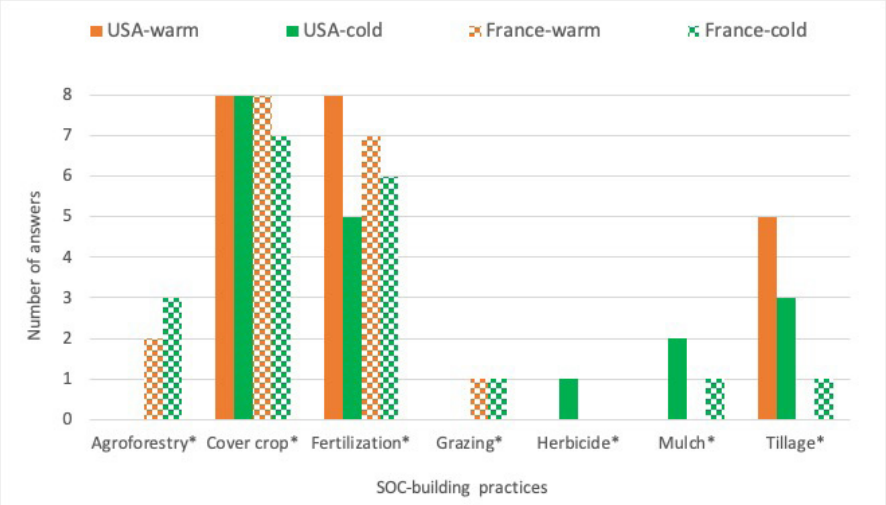


FIGURE 3. Seven SOC-building practices identified as currently implemented by extension specialists in four regions (*n* = 8 respondent/region). *: Increase hedges or agroforestry; increase/maintain/diversify/till cover crop; use compost/organic fertilisation/return pruning residue; increase grazing; reduce herbicide; straw mulch inter-row; reduce/eliminate/change tillage.

Organic fertilisation was mentioned by 26 of the 32 extension specialists as a current practice in their region (Figure 3), either using organic fertilisation in general, or by specifying the use of compost-based fertilisation, application of pomace, or returning dormant pruning to the soil. The lowest number of positive respondents to this query was in USA-cool, perhaps because the organic matter content of the soil is already quite high, often in the range of 3–5 %, and returning pruning to the soil is a common practice (Wolf, 2008).

Emphasis on reducing tillage was noted only in the USA, and 9 out of the 32 extension specialists mentioned reduction, elimination, or change of soil tillage (Figure 3) as a current practice. Tillage is recognised as an unsustainable practice and a key factor in increasing soil and nutrient losses in vineyards (Telak & Bogunovic, 2020). The greatest number of extension specialists acknowledging the need to reduce tillage were in USA-warm (5/8) and USA-cool (3/8) where conservation tillage remains a common practice. In USA-cool, inter-rows are managed with a permanent cover crop (Wolf, 2008) and under-vine is usually managed with herbicide rather than tilled, so tillage is less likely to be mentioned as a factor. Only one respondent from France-cool suggested it as a current practice and none from France-warm.

Other practices previously identified to increase SOC-building were rarely cited as being implemented. For example, only one of 32 respondents cited herbicide reduction, even though the use of under-vine vegetation is increasing as a practice in that region (USA-cold, T. Martinson, personal communication). Similarly, increasing hedges/agroforestry, grazing, and straw mulch in the interrow were rarely mentioned, regardless of region. In total, 6 of the 32 respondents cited increasing hedges/agroforestry. Interestingly, increased hedges/agroforestry was not listed by respondents as a current practice in the US-cool, maybe due to the substantial forested areas that surround many vineyards in the region. Three respondents cited the application of straw mulch to the interrow (Figure 3). Only two respondents cited grazing as a current practice to increase SOC-building, although this practice is being increasingly adopted in semi-arid regions of the US and France, mainly as a wildfire suppression strategy.

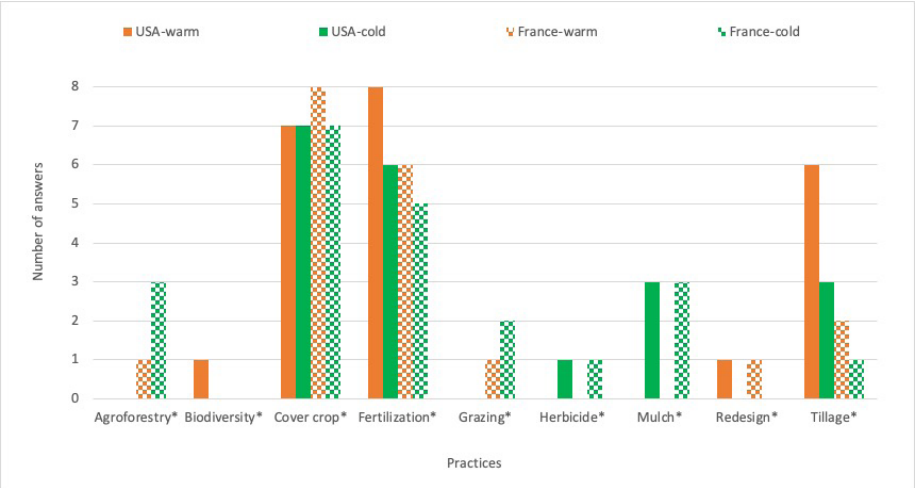


FIGURE 4. Practices identified by extension personnel that could be adopted in their region to increase or maintain SOC. *: Increase hedges or agroforestry; increase biodiversity; increase /maintain/diversify/till cover crop; use compost/organic fertilisation/return pruning residue; increase grazing; reduce herbicide; add straw/green waste mulch; adapt whole vineyard system; reduce/eliminate/change tillage.

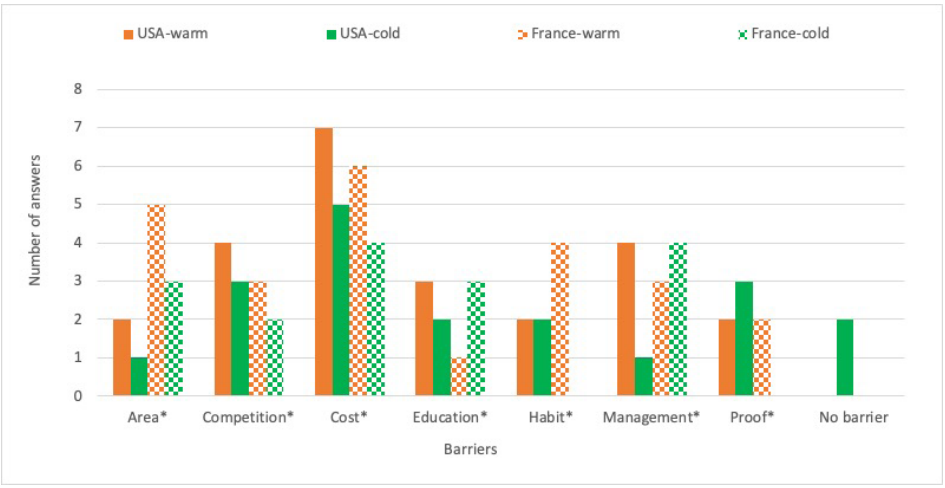


FIGURE 5. Barriers to maintaining or increasing SOC identified by extension personnel as applicable in their region. * Vineyard or climate characteristics; competition for vine/Yield/Water/Cover crop/small animals; cost of equipment/labour/time/alternative/seeds/organic fertiliser; education, knowledge, information, advice-grower, industry, consumer; habit of management history; practice management of reducing herbicide, increasing cover crop, reducing tillage, manage organic fertilisation or agroforestry; No challenge; proof of benefit of the practice/alternative.

2. Potential practices that could be adopted to increase SOC

Extension specialists from the four regions perceived that several practices could move from niche to mainstream in their regions to increase SOC. Respondents from the four zones identified roughly the same number of practices that could be enhanced or adopted to increase SOC-building (5, 5, 6, and 7, respectively, in USA-cool, USA-warm, France-warm, and France-cool, respectively). A total of 29 of the 32 respondents cited increasing/maintaining/diversifying cover crops as a practice that could be adopted or expanded in their region (Figure 4). Thirty-one respondents cited it as a current practice (Figure 3), suggesting that cover cropping could be one practice that could be increased across all regions. The impact of increasing/maintaining/diversifying cover crops on SOC will likely be variable depending on the region and specific practice.

Use of compost/organic fertilisation/return of pruning to the vineyard was cited by 25/32 respondents as a practice that could be further adopted to increase SOC-building (Figure 4), with 8/8 respondents in USA-warm indicating it as a potential practice for this region and perhaps reflecting current government incentives around these practices (*i.e.*, healthy soil program in California). Long-term studies (Giagnoni *et al.*, 2019; Morlat & Chaussod, 2008) show that the addition of exogenous organic matter increased SOM content and therefore SOC (García & Hernández, 1996; Liebhard *et al.*, 2024; Lützow *et al.*, 2006). The corresponding values of SOC increase depend on the origin and chemical composition of the added organic matter and the application rate. This has a strong impact on fertilisation and nutrient

management needs. For instance, while biochar has the potential to achieve carbon sequestration in soil, it shifts the soil microbial activity, and the impacts of such a change on the soil's biological fertility should be carefully considered (Novara *et al.*, 2013; Wang *et al.*, 2017; Zehetner *et al.*, 2015).

While only 9 respondents reported a reduction of tillage as an adopted practice in their region (Figure 3), 12 extension respondents reported it as a practice that could be adopted (Figure 4)–especially in the USA (9/12 respondents). Only two respondents cited a change in herbicide practices as potentially being adopted to increase SOC, and only four cited increasing hedges/agroforestry. Again, the responses for USA-cool are likely impacted by the significant forests that surround many vineyard blocks in portions of the region. Only three respondents cited grazing as a potential practice to be adopted that could increase SOC (Figure 4), despite the significant increase in SOC that occurs with long-term grazing (Brewer *et al.*, 2023).

3. Barriers and incentives to increase soil organic carbon

Extension specialists identified a wide range of barriers to the widespread adoption of SOC-building practices. These barriers can be categorised into different types: socio-economic, policy, eco-environmental conditions of the vineyard/field, production/practices, and socio-cultural factors.

Barriers to practice adoption were mostly similar among regions, although respondents from cool regions specified fewer total barriers than respondents from warm regions, as evidenced by total responses (24 responses for barriers in France-warm and USA-warm, 16 in France-cool, and 17 in USA-cool). Extension specialists may perceive more barriers to the adoption of practices in warm climates due to the interactions of soil management practices with irrigation water needs, water being increasingly scarce and costly as drought episodes become more frequent in these regions (Lazcano *et al.*, 2020).

The cost of adoption of new practices was cited by the greatest number of respondents (22/32) as a barrier to practice adoption (Figure 5), with the cost of both equipment and labour cited as main drivers, as well as costs of inputs such as seeds and delivery of organic amendments. The cost of adoption of new practices was the most common barrier to adoption cited by interviewees in France-warm, USA-warm, and USA-cool (Figure 4), and it tied for the top barrier with practice management in France-cool.

Vineyard/climate characteristics were cited by 11/32 as a barrier to new practice adoption, particularly in the French regions which accounted for eight of those citations, perhaps due to the concept of terroir and the AOC system. Proof of the benefit of the practice was noted by 7/32, suggesting that there was ample knowledge existing already relating to the benefits of many of these practices. Practice management was cited by 14/32, habit management history by 9/32, education/information by 9/32, and competition for resources by 12/32 (Figure 5). Competition included a range of concerns including competition of cover crops under vines (particularly relating to yield maintenance), competition for water resources (USA-warm), and voles chewing on trunks. However, there are appropriate cover crops for at least a portion of the year for most climatic conditions (Kesser *et al.*, 2023; Vanden Heuvel & Centinari, 2021).

Interestingly, only two respondents cited 'no challenge' to maintaining or increasing SOC. These responses were both in USA-cool, where high organic matter soils predominate and there is ample precipitation in most growing seasons.

Figure 6 categorises factors identified by extension personnel that may prevent grape growers from adopting SOC-building practices. For some practices the regional differences were minor. For increasing the use of cover crops, extension personnel in the USA-cool identified socio-economic factors (cost of equipment, cost of labour, opportunity cost of vine growth and yield) as the greatest barrier (6 respondents), while eco-environmental and production practices were listed by other regions as barriers. Eco-environmental constraints were listed by only 1/8 respondents in USA-cool, likely due to the high OM soils and ample precipitation in the Northeastern U.S. Interestingly, the most numerous opportunities listed by respondents for encouraging the use of cover crops in vineyards were in the category of production practices (Table 1), with responses from warm regions focusing on the need for more knowledge about cover crops that use less water. Opportunities for extension programming in this area may include information on appropriate species, seeding techniques, and maintenance/termination (Steenwerth & Belina, 2008). Significant academic literature exists in this research area for both cool climates (Vanden Heuvel & Centinari, 2021) and warm climates (Lines *et al.*, 2024), the results of which need to be better communicated to extension specialists and grape growers.

A range of factors were listed by respondents regarding production practices and socio-cultural constraints to increasing the use of grazing in vineyards (Figure 6). Respondents expressed concern about the expense of grazing, the lack of information about its effectiveness, and the interactions between pesticides and grazing animals. Understandably, microbial contamination was listed by interviewees as a constraint to adoption in table grape production. However, there was again a disconnect between barriers and opportunities, as most respondents mentioned socio-economic incentives to encourage grazing (Table 1; Table S2), rather than addressing barriers in production practices or socio-cultural barriers. The main socio-economic factor mentioned by respondents related to grazing and the need for collaborations between growers and livestock farmers in this area, a point also noted by growers in a California survey (Ryschawy *et al.*, 2021). Little published research exists to guide extension specialists and growers on optimal grazing practices, although innovative grape growers are adopting grazing under a range of different vineyards and climatic conditions (Niles *et al.*, 2018; Brewer *et al.*, 2023). Adopters of dormant season vineyard grazing in California (classified as USA-warm in this study) reported labour

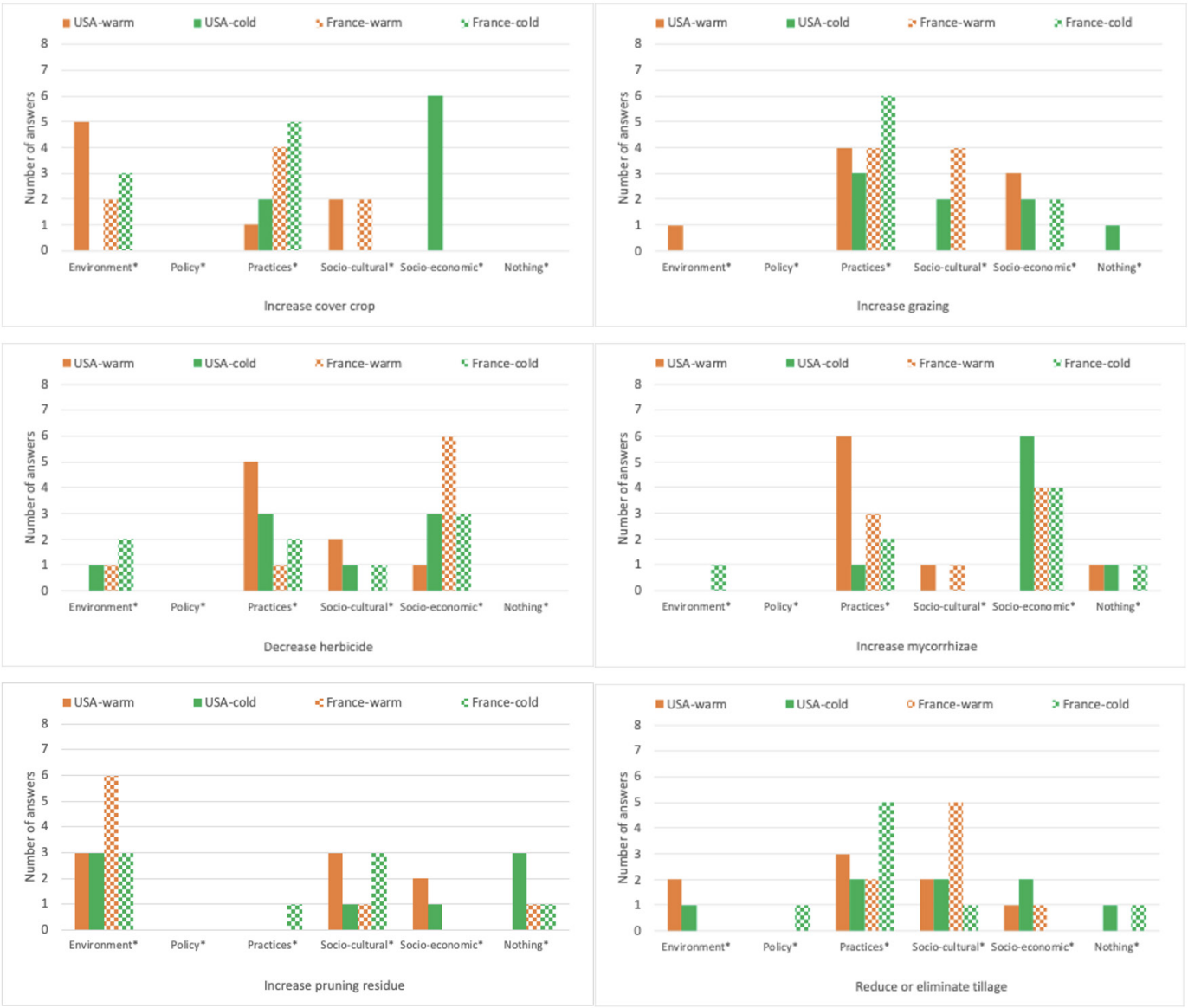


FIGURE 6. Factors identified by extension personnel that may prevent grape growers from adopting the top 6 practices to maintain or increase SOC in their region. * Ecological or environmental factors; Public policy factors; Practices in production management factors; Socio-cultural factors; Socio-economic factors; No idea/no need of something.

and fuel savings, soil quality improvement, and marketing advantages (Ryschawy *et al.*, 2021). In that same region, dormant season sheep grazing for 10+ years in vineyards has been demonstrated to increase SOC storage in the subsoil by 33 % (Brewer *et al.*, 2023). A preliminary experiment in New York (USA-cool) indicates the potential for sheep to conduct ecosystem services during the growing season such as mowing and suckering of the vine, additionally allowing for easy adoption of under-vine vegetation in place of herbicides or tillage (Jackson, 2021).

Constraints to decreasing the use of herbicides differed by region (Figure 6). More respondents in both warm regions–particularly France-warm (5/8)–cited current practices (training system, peak work periods) as limiting adoption. Socio-economic constraints (required investment in new equipment) were cited by most respondents in France-warm, but fewer in the other regions. For practices to encourage decreased use of herbicides, respondents mostly cited barriers relating to production practices (Table 1). The limitations on decreasing herbicide use cited by French respondents related to redesigning the vineyard system to accommodate decreased herbicide use including the need to switch from goblet trained to cordon trained; use technical innovation as mulching; or restructure the vineyard to use less herbicide by adapting all the practices to climatic conditions and societal expectations. USA responses were more focused on a perceived lack of effective alternative options to herbicides.

Adoption of increasing the use of mycorrhizae or bioinoculants was cited as being constrained by socio-economic factors, particularly in USA-cool, and by production practices in USA-warm (Figure 6). Responses focused on the cost-benefit proposition and lack of knowledge about soil ecology and the products. One respondent indicated considerable concern about "fake products" on the market

	Extension	Research	Regulatory	Incentives	No idea/no need/ nothing/I don't know
Increase cover cropping	●●	●●	●●	●●	●
Increase integration of grazing animals	●●	●●	●	●●●	●
Reduce herbicide use	●●	●●	●●●	●●	●
Increase mycorrhizal associations	●●	●●	●	●	●●
Increase return of pruning residues	●	●●	●●	●●	●●
Reduce/eliminate tillage	●●	●●	●●	●●	●●

TABLE 1. The total number of responses relating to encouraging the adoption of SOC-building practices that fall within each category. One dot < 10 % of respondents identified this area, two dots 11–40 % of respondents, three dots 41–100 % of respondents. Data details are in Table S2.

that have no impact. The greatest responses for encouraging mycorrhizal colonisation were in the socio-economic category (Figure 6), likely because these products can be expensive (Vanden Heuvel *et al.*, 2020) and uncertainties regarding how long the impact of commercial bioinoculants lasts (Fors *et al.*, 2023). It was noted that research needs to determine the cost:benefit (ex. soil health, reduced labour needs and cost) compared to product price.

Increasing return of pruning was cited as having eco-environmental constraints (Figure 6), although four respondents said there was no need for this practice. For example, respondents listed that grape growers are concerned about winter inoculum for the next season and that the field accessibility (slope or size) is difficult for the mechanisation of pruning residue management. Respondents suggested socio-economic incentives for encouraging the use of this practice (Table 1), particularly to address the cost of equipment for adopting this practice, particularly in sloped vineyards.

Few USA respondents cited factors that limited the adoption of reduced tillage (Figure 6), however, 5 respondents in France-cool cited production/practices as a constraint (for example, the effectiveness of tillage), while 5 respondents in France-warm cited socio-cultural issues (habit, cultural norms of seeing grass in the vineyard) as a constraint to adoption. Respondents in France-cool suggested production/practices (competition with the vine) as constraints to reducing the use of tillage. Respondents suggested that there are no satisfactory alternative practices currently and cover crop termination remains a main goal, especially in warm regions. Respondents in France-warm suggested socio-cultural issues as constraints to adopting no-tillage, particularly cultural habits and psychological effects, such as the transition from a "clean" field to one perceived as "unclean". Growers' traditional views on soil management and cultural norms include "bare land," contributing to resistance against vegetation-based practices. A USA-cool respondent expressed the need to 'hill up' over the graft union as a requirement, which is a common practice in the Northeastern U.S. to enhance vine recovery after winter frost (Wolf, 2008).

4. Opportunities for changing practices

4.1. Extension gaps

An original aspect of our study lies in the detailed analysis of the perceptions of a stakeholder group in the viticulture sector that has been little studied: extension specialists. The literature provides numerous studies on the perceptions of vineyard managers, but few on those of extension specialists. This study identified a notable extension gap relating to the adoption of cover crops (both between row and under-vine) in vineyards. While 29/32 respondents suggested cover cropping could be increased in their region (Figure 5), a range of barriers to adoption were provided by respondents (Table 1). Significant academic literature exists in this research area for both cool climates (Vanden Heuvel & Centinari, 2021) and warm climates (Lines *et al.*, 2024) which can guide extension specialists, although the research is focused on wine grapes and may not be appropriate for table, juice, or dry grape production. Opportunities for extension programming in cover crops for wine grapes may include information on appropriate species, seeding techniques, and maintenance/termination (Steenwerth & Belina, 2008), all with a focus on the potential competitiveness of the cover crop for water and nutrients with the vine. Strengthening interactions between extension specialists and farmers/vineyard managers can foster the adoption of new practices (Llewellyn, 2007), and promote a shift toward more agroecological practices (Payen *et al.*, 2023). Extension specialists and vineyard managers interact through

both formal and informal networks for knowledge sharing and experiential feedback, which encourages the adoption of new practices in the vineyard (Payen *et al.*, 2023). Closing this extension gap is therefore critical to realise the potential of cover crops for SOC accrual in vineyard systems.

4.2. Research gaps

While we did not specifically ask about research gaps, the extension specialists interviewed clearly delineated several research gaps impacting the ability and willingness of grape growers to adopt practices that improve SOC. These gaps were identified when the respondents provided an answer relating to a lack of knowledge about a particular practice as a barrier to adoption or more knowledge as a factor that could encourage the adoption of a practice (Table 1). The knowledge identified by respondents is linked to production or practices (impact of the practice, benefit of the practice for vine or the soil) and the cost of the practice. The details of the knowledge required to adopt SOC-friendly practices include socio-economic factors, such as understanding the costs and benefits of these practices, as well as production and practice-related factors. Specific factors mentioned were adaptation to pedoclimatic conditions, selection of cover crops, the impact on soil microbiome health, access to knowledge for growers, and the sharing of knowledge among growers. Particular research gaps identified included 1) the benefit of incorporation of pruning residues compared to the risk of inoculum spread with the practice, 2) the appropriate use of commercial bioinoculants to increase root length colonisation of arbuscular mycorrhizal fungi as well as the economic benefits of adoption, and 3) a cost:benefit analysis of incorporating grazing animals into vineyard systems.

4.3. Regulations and Incentives

While there was a range of responses regarding factors that could encourage grape growers to adopt practices to increase SOC, many of the factors identified could be grouped under regulations or incentives (Table 1).

Regulations around agricultural practices are generally more numerous in France than in the USA, as France is included in the European Union's Common Agricultural Policy. France generally has more stringent environmental laws and stronger domestic policies on food production, sustainability, and environmental protection. Additionally, French AOCs standardise practices while American AVAs have little commonality in comparison. As a result, responses from French regions may not apply in the USA. In France, respondents mentioned that there are some incentives through subsidies to support agroecological transitions, specifically for equipment purchases. Respondents also mentioned that better pricing of the wines to offset production costs would encourage growers to invest in SOC-building practices. If herbicides are replaced, one respondent in France mentioned a second potential approach that could involve limiting fuel subsidies.

Additional incentives for the adoption of SOC-building practices may be available through marketing channels. For example, in both France and the USA, environmental certifications such as organic, biodynamic, and regenerative labels also exist. Finally, a potential strategy suggested that could be applicable in both countries could involve a payment mechanism for carbon sequestration in vineyard soils.

Respondents mentioned incentives for increasing the integration of grazing animals (13/32) independent from legislation. Incentives for increasing grazing are facilitating contact and then building partnerships between grape growers and livestock farmers, and the availability of animals in the area. For other practices, incentive policies, market support harmonisation, tax incentives, technological advancements, and coherence between local, national, and transnational legislation are crucial for driving the economic feasibility and sustainability of Circular Nutrient Technologies and Practices (CNTP) (Teleshkan *et al.*, 2024) suggesting that for SOC-promoting practices, the situation is more complex than simply implementing financial incentive policies.

CONCLUSION

In conclusion, our results show that current practices aimed at improving the adoption of SOC-building practices in vineyards, such as the use of cover crops, organic fertilisation, and reduced tillage, show regional and climate-specific variations, with cover cropping being the most widely adopted. Despite this, adoption of many of these practices remains low, primarily due to high costs, limited knowledge, and specific vineyard conditions. Key barriers to wider adoption include socio-economic challenges, management limitations, and ecological factors such as water stress in warmer climates. To enhance the adoption of SOC-building practices, targeted research, improved extension programs, and government support are needed. Expanding research on various practices, including the integration of grazing animals, incorporation of pruning residue, and the use of bioinoculants to improve mycorrhizal associations - including cost-benefit analyses of all of these practices - will be essential to overcoming these barriers. These efforts are critical in the context of climate change, where understanding the long-term impacts of these practices is crucial for sustainable vineyard management.

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2. Ethics

The survey has been carried out according to the Code of Good Research Practices of INRAE and the French legal regulations. A staff member at the Institutional Review Board (IRB) at Cornell University reviewed the questionnaire and proposed data collection in Summer 2022 and determined that neither IRB approval nor an exemption was needed. The captured data did not include personal information. The information published corresponds to aggregated data.

3. Consent to participate

Informed consent was obtained from all participants included in the study.

4. Consent for publication

Participants provided informed consent for publication of the data they reported for this study.

5. Availability of data and material

The data for this study is not available, as the questions asked were sensitive and the participants were guaranteed that their data would not be shared and remain confidential.

Code availability (software application or custom code) 'Not applicable'

6. 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 article.

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8. Credit authorship contribution statement

MTS: Conceptualisation, methodology, investigation, formal analysis, writing—original draft, review & editing, funding acquisition. AG: Methodology, writing—review and editing. JVH: Conceptualisation, methodology, writing—original draft, review and editing.

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