Exploring the biophysical and socio-economic barriers to carbon sequestration in viticultural soils

Florian Thomas Payen

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The University of Edinburgh

School of Geosciences

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Declaration of the candidate

I, Florian Thomas Payen, hereby declare that:

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Abbreviations

Abatement potential	AP
Abatement rate	AR
Afforestation and reforestation	A/R
Agri-environment measure	AEM
Agri-environment scheme	AES
Biochar	BC
Bioenergy with carbon capture and storage	BECCS
Carbon	C
Carbon dioxide	CO_2
Common agricultural policy	CAP
Cover crop	CC
Direct air capture	DAC
Enhanced weathering	EW
European Union	EU
Greenhouse gas	GHG
Hedge	HG
High environmental value	HVE
Kaiser-Meyer-Olkin	KMO
Marginal abatement cost curve	MACC
Mean absolute error	MAE
Mean annual air temperature	MAT
Mean annual precipitation	MAP
Mean square error	MSE
Nitrous oxide	N_2O
No-tillage	NT
Normalised root mean square error	NRMSE
Organic amendment	OA
Organic carbon	OC
Organic matter	OM

Out of bag	OOB
Potential evapotranspiration	PET
Principal component analysis	PCA
Pruning residue	PR
Random forest	RF
Root mean square error	RMSE
Soil organic carbon	SOC
Soil organic carbon sequestration	SCS
Soil organic carbon stock response ratio	RR
Soil organic carbon stock rate of change	R
Soil organic matter	SOM
Sustainable development goal	SDG
United Kingdom	UK
Variance inflation factor	VIF

Thesis abstract

To avoid catastrophic changes in the climate system by the end of the 21st century, the world must pursue drastic climate change mitigation strategies. All scenarios for containing the increase in global surface temperatures to below 1.5 or 2 °C by 2100 involve the large-scale deployment of carbon sequestration technologies. If properly managed, agricultural soils may sequester substantial amounts of atmospheric carbon dioxide in the form of soil organic carbon. However, there is a focus on arable land and grassland with regard to soil organic carbon sequestration, and research has overlooked other types of agricultural land, especially vineyards. There is a lack of evidence on the potential of vineyards to sequester carbon and participate in the global efforts to mitigate climate change via soil organic carbon sequestration. This thesis aims to quantify the carbon sink potential of vineyard agroecosystems under different soil management practices and identify the winegrowing regions where it is the highest. It also seeks to investigate the different factors that play a role in the adoption of soil organic carbon sequestration practices by winegrowers. An interdisciplinary approach was used, combining literature review, meta-analysis, machine learning and surveys to investigate the biophysical and socio-economic barriers to soil organic carbon sequestration in vineyards. A meta-analysis was performed to estimate, at the global level, the soil organic carbon sequestration rates associated with the use of different soil management practices in vineyards, based on field experiments. Results show that, under the same management practices, vineyards may sequester similar or larger amounts of organic carbon per hectare compared to other types of agricultural land. The data gathered in the meta-analysis was then used to build a model that predicts, using a random forest regression, changes in soil organic carbon stocks in vineyards under specific management practices, based on soil and climatic characteristics. The model was applied to six winegrowing countries located in Europe (Spain, France, Italy, Portugal, Germany and Austria) for a period of twenty years. The results indicate that the ability of vineyards to sequester carbon in these countries is high, though it varies greatly depending on the winegrowing regions and practices considered. To further understand the decision-making process of implementing soil organic carbon sequestration practices in vineyards, a questionnaire was circulated to winegrowers in France. It enquired about the adoption of different soil management practices, as well as vineyard attributes and winegrowers' socio-economic characteristics, access to information, involvement in policy instruments, resources, confidence and attitudes towards soil organic carbon sequestration practices. The results from a binary logistic regression indicate that many of these factors (*e.g.*, winegrower's and vine's age, farm size, certifications, use of irrigation, etc.) are involved in the adoption process of soil organic carbon sequestration practices. To complement these results, a second questionnaire was circulated to French winegrowers to investigate the motives and barriers to the adoption of soil organic carbon sequestration practices as perceived by winegrowers. Results identify the desire to achieve biophysical outcomes (*e.g.*, returning organic matter to the soil) as a key motivation for the adoption of these practices and biophysical and technical barriers as the main barriers preventing winegrowers from adopting the practices. The findings of this thesis suggest that vineyards have an important role to play in climate change mitigation and should not be overlooked by soil organic carbon sequestration strategies, especially in countries or regions where vineyards represent an important share of the total agricultural land. However, this potential will only be realised if soil organic carbon sequestration practices are adopted by winegrowers. Further policy instruments should be developed at the local, regional, national and European levels to overcome some of the barriers currently hindering the uptake of these practices in the viticulture sector.

Lay summary

As greenhouse gas emissions continue to increase, the impacts of climate change are becoming more and more perceivable everywhere on the globe. There is a sense of urgency to mitigate how much the climate is changing to avoid dramatic socio-economic and environmental repercussions. In addition to reducing greenhouse gas emissions, carbon dioxide can also be captured from the atmosphere and stored in the soil in the form of organic carbon. Interest in this process, called soil organic carbon sequestration, is growing, and extensive literature on soil organic carbon sequestration has developed, with the aim of quantifying the carbon sink potential of different agricultural systems and identifying the agricultural practices allowing for soil organic carbon sequestration. However, most studies are interested in arable land and grassland, because they represent an important share of the global agricultural land. Less is known about vineyards, and especially whether they could contribute to climate change mitigation through soil organic carbon sequestration. Our understanding of how much carbon could be sequestered in viticultural soils is limited, and there is uncertainty regarding whether winegrowers are adopting practices that increase soil organic carbon sequestration or will in the near future. This thesis investigates how much carbon dioxide could be sequestered in vineyards in the form of soil organic carbon using environmentally-friendly agricultural practices (and whether there are variations between winegrowing regions). It also intends to better understand what informs winegrowers' decisions to adopt these practices; this is important because if these practices are not adopted, vineyards cannot contribute to reducing greenhouse gas concentrations in the atmosphere. Interdisciplinary methods were combined to answer these questions. In Chapter 2, data from published field experiments were gathered and used to calculate how much soil organic carbon can be sequestered in vineyards at the global level under different soil management practices. Results show that large amounts of carbon could be sequestered in vineyards, demonstrating that they have a role to play in helping to attenuate climate change. This dataset was later used in Chapter 3 to build a model, based on machine-learning approaches, that predicts how the stocks of soil organic carbon change over time when specific agricultural practices are used by winegrowers. The model was applied to several countries in Europe. Results from the modelling highlight where areas that are hotspots for storing soil organic carbon are located, which can help to prioritise efforts to increase soil organic carbon sequestration in vineyards at the local and regional levels. The model created is a valuable tool that can be reused by other researchers for vineyards outside of Europe or extended to encompass more permanent crops (such as olive orchards, for instance). The following chapters (Chapters 4 and 5) researched the factors that influence winegrowers when they decide whether to adopt a practice that increases soil organic carbon sequestration. To do so, questionnaires were circulated to French winegrowers, asking questions about their demographics, the characteristics of their viticultural farms, the practices they used in their vineyards, how they felt about using practices that increase soil organic carbon sequestration, etc. The quantitative data collected were used to identify factors that play a role in the adoption of the practices by winegrowers. Several factors (such as the age of the winegrower, the age of the vineyard, the attitudes of the winegrower towards the practices, etc.) played a significant role in the decision to adopt soil organic carbon sequestration practices, but their impact on the decision-making process differed depending on the practice considered. The qualitative data collected provided complementary information about the reasons that motivate winegrowers to adopt practices that increase soil organic carbon sequestration and the barriers that prevent them from doing so. Results indicate that there are plenty of different motives and barriers for each practice, though recurring ones include the desire to improve the biophysical state of the vineyard (for example, returning more organic matter to the soil to improve soil quality) as the main motivations and biophysical and technical barriers as the main obstacles. Overall, this thesis shows that how vineyards are managed is important when it comes to mitigating climate change and strategies aiming at increasing soil organic carbon sequestration in vineyards should be pursued by countries and regions where viticulture is practised. It also suggests that more efforts need to be made in the form of improved or new policies to help winegrowers to overcome the barriers that prevent them from conducting viticulture in a way that increases soil organic carbon sequestration.

Chapter 1

Introduction

1.1. A need for greenhouse gas removal technologies

Despite the concerted efforts of the international community to mitigate climate change, total emissions of GHGs to the atmosphere have increased steadily since 1970 (Olivier and Peters, 2020). More particularly, since 2010, global GHG emissions (including land-use change) have grown by 1.4% per year on average, reaching a record high of 59.1 Gt CO_2-eq. in 2019 (UNEP, 2020). It is estimated that the Earth has already warmed up by approximately 1 °C above pre-industrial levels (IPCC, 2018). Unless the world pursues net negative emissions to reduce GHG concentrations in the atmosphere, human-driven global warming will continue with increasing intensity, leading to catastrophic changes in the climate system (IPCC, 2013). If the radiative forcing induced by high atmospheric GHG concentrations has not peaked by the end of the 21st century, the resulting increase in mean temperature is predicted by various mitigation scenarios to range from 2 to 5.4 °C by the year 2100 in comparison to 1850 (IPCC, 2013).

In 2015, the Paris Agreement was signed by the international community with the aim to keep the overall rise of the global surface temperature at the end of the 21st century below 2 °C – or even below 1.5 °C if possible (UNFCCC, 2015). To reach this target with a likelihood of 66%, no more than 1,200 Gt CO_2-eq. should enter the atmosphere between 2015 and 2100 (Fuss et al., 2014). However, the current mitigation ambitions of countries as pledged to the Paris Agreement are more likely to limit global warming to 2.5-2.8 °C, and only if each country reaches its targets by 2100; otherwise, global warming is more likely to be between 2.8 and 3.2 °C based on the latest GHG mitigation policies (Fig. 1.1). Considering the current atmospheric levels of GHGs, their rates of emission and the under-ambitious pledges to the Paris Agreement, it seems very unlikely that the 2-°C target could be met without extensive GHG removal from the atmosphere in addition to the reduction of GHG emissions (IPCC, 2018). Most models rely on the deployment of GHG removal technologies and negative emission technologies at a large scale to have a greater than 50% chance to reach the Paris Agreement targets by 2100 (Smith et al., 2015).

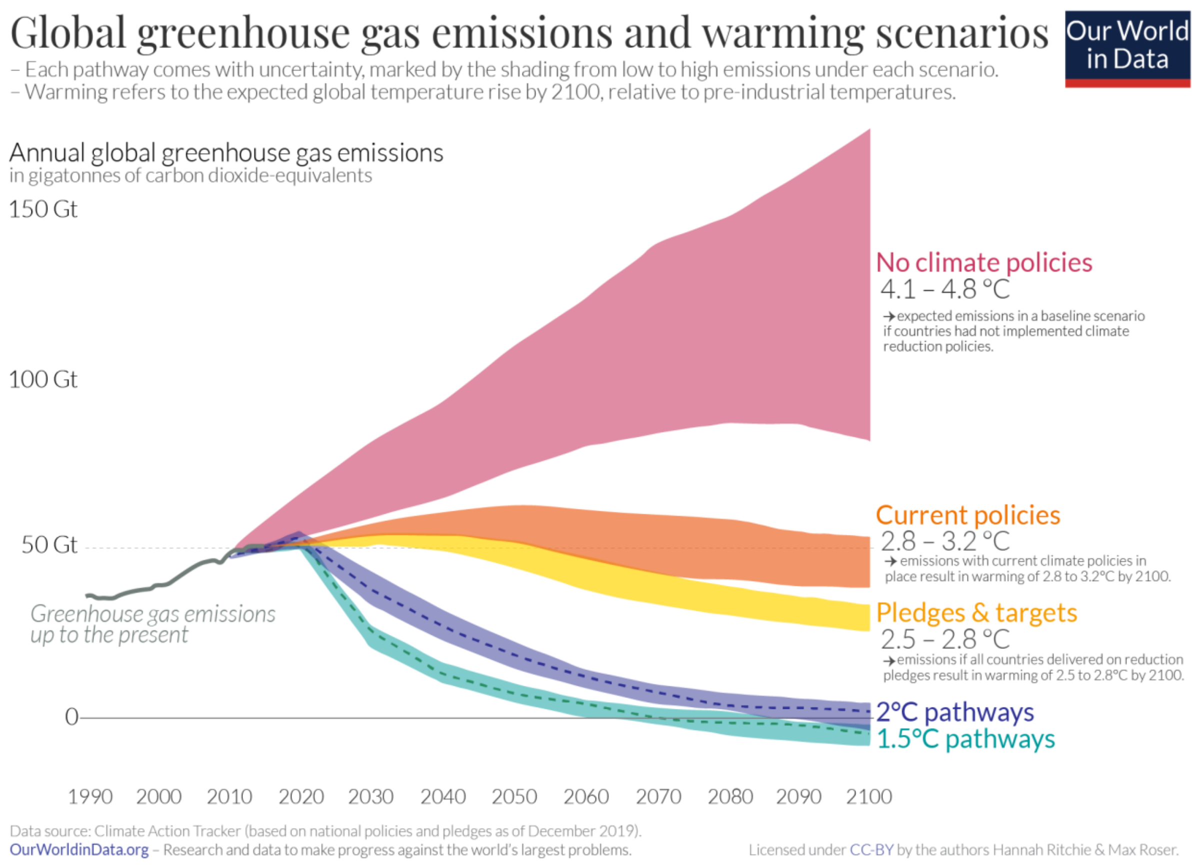

Fig. 1.1. Temperature rise at the end of the 21st century according to different GHG emission scenarios (Ritchie and Roser, 2020).

1.2. Which greenhouse gas removal technologies are of interest?

GHG removal technologies are land- or ocean-based strategies using biological, chemical or physical approaches to remove CO_2 from the atmosphere and store it (Zhang et al., 2015). The most frequently proposed ones are land-based strategies and include bioenergy with carbon capture and storage (BECCS), direct air capture of CO_2 (DAC), enhanced mineral weathering (EW), afforestation and reforestation (A/R), soil organic carbon sequestration (SCS) and biochar (BC) (Smith et al., 2015; Fuss et al., 2018). Table 1.1 summarises the effects of these technologies on atmospheric CO_2. Each of these GHG removal technologies has a different mitigation potential, which could be reached with varying costs, energy uses, and land, water and nutrient requirements (Smith et al., 2015; Smith, 2016). These global impacts and requirements need to be assessed cross-comparatively between all GHG removal technologies to ensure that they are optimally developed and implemented. Ocean-based approaches (*e.g.*, ocean iron fertilisation) are not considered viable options due to the large risks and uncertainties associated with their deployment (Smith et al., 2015; Zhang et al., 2015).

Table 1.1. Summary of the different processes through which GHG removal technologies reduce atmospheric CO_2 concentrations.

GHG removal technology	**Process**	**References**
Bioenergy with carbon capture and storage (BECCS)	Extracting bioenergy from biomass while capturing and storing C via geologic sequestration[1].	Creutzig et al. (2015) Hanssen et al. (2020)
Direct air capture (DAC)	Capturing CO_2 directly from the ambient air by engineered chemical reactions and generating a concentrated stream of CO_2 for sequestration or utilisation.	Keith (2009) Beuttler et al. (2019)
Enhanced weathering (EW)	Accelerating the natural weathering of minerals, which absorb CO_2 and transform it into other substances through chemical reactions, and storing the products in soils, or burying them inland or in the deep ocean.	Strefler et al. (2018) Beerling et al. (2020)
Afforestation and reforestation (A/R)	Planting trees to fix atmospheric CO_2 in biomass and soils.	Canadell and Raupach (2008) Doelman et al. (2020)
Soil organic carbon sequestration (SCS)	Modifying agricultural practices to increase C storage in soils.	Smith (2016) Sykes et al. (2020)
Biochar (BC)	Converting biomass to biochar, rich in C content, and using it as a soil amendment to increase C storage in soils.	Smith (2016) Majumder et al. (2019)

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[1] CO_2 is extracted from the atmosphere by the biomass as it grows. The C is then captured from the biomass during the energy extraction process (*e.g.*, pyrolysis, fermentation, combustion or other conversion methods) and can be stored by geologic sequestration.

1.3. Rationale for using soil organic carbon sequestration

1.3.1. What is soil organic carbon sequestration?

SOC sequestration corresponds to the process of transferring CO_2 from the atmosphere into the soil through plants, plant residues and other organic solids that are stored or retained in the soil as part of the SOM (Olson et al., 2014). The retention time of sequestered C in the soil can range from short-term storage (not immediately released back into the atmosphere) to long-term storage (millennia) (Olson et al., 2014). SOC sequestration assumes a net removal of CO_2 from the atmosphere (Chenu et al., 2019), which means that concentrations of CO_2 in the atmosphere have decreased overall.

SOC sequestration is not to be confused with soil C storage, also sometimes called soil C accumulation, which is a broader term. It is defined as an increase in SOC stocks over time in the soils of a given land unit, but it is not necessarily associated with a net removal of CO_2 from the atmosphere (Chenu et al., 2019). For example, deciding to redirect manure from an area where it is traditionally spread to a new area will lead to soil C storage in the new area but not to a net CO_2 removal from the atmosphere at the landscape scale (Chenu et al., 2019).

1.3.2. How does soil organic carbon sequestration work?

The process of SOC sequestration is illustrated in Fig. 1.2. Via the process of photosynthesis, plants convert CO_2 into glucose and other compounds rich in C, which they use to build their biomass. Some C is also simultaneously released back into the atmosphere as CO_2 through respiration. As plants grow, so does the amount of C they contain. Some of this C is located in plants' aboveground biomass (stem, leaves, flowers, seeds) and some in their root structure (Garnett et al., 2017). Throughout a plant's life, plant C can be added to the soil by deposition of leaf litter onto the soil surface, by incorporation of plant biomass into the soil and by direct belowground transfer via the root structure (Rees et al., 2005). During decomposition processes, some of the plant C transferred into the soil may be converted into stable C compounds that stay in the soil, while the rest is lost and emitted back into the atmosphere as CO_2. The total amount of C sequestered in the soil as SOC depends on the long-term balance between C uptake and release mechanisms (Abdullahi et al., 2018). The presence of favourable soil and climatic conditions along with the soil management practices used are critical to the formation of soil C and the maintenance of its stability over time (Garnett et al., 2017).

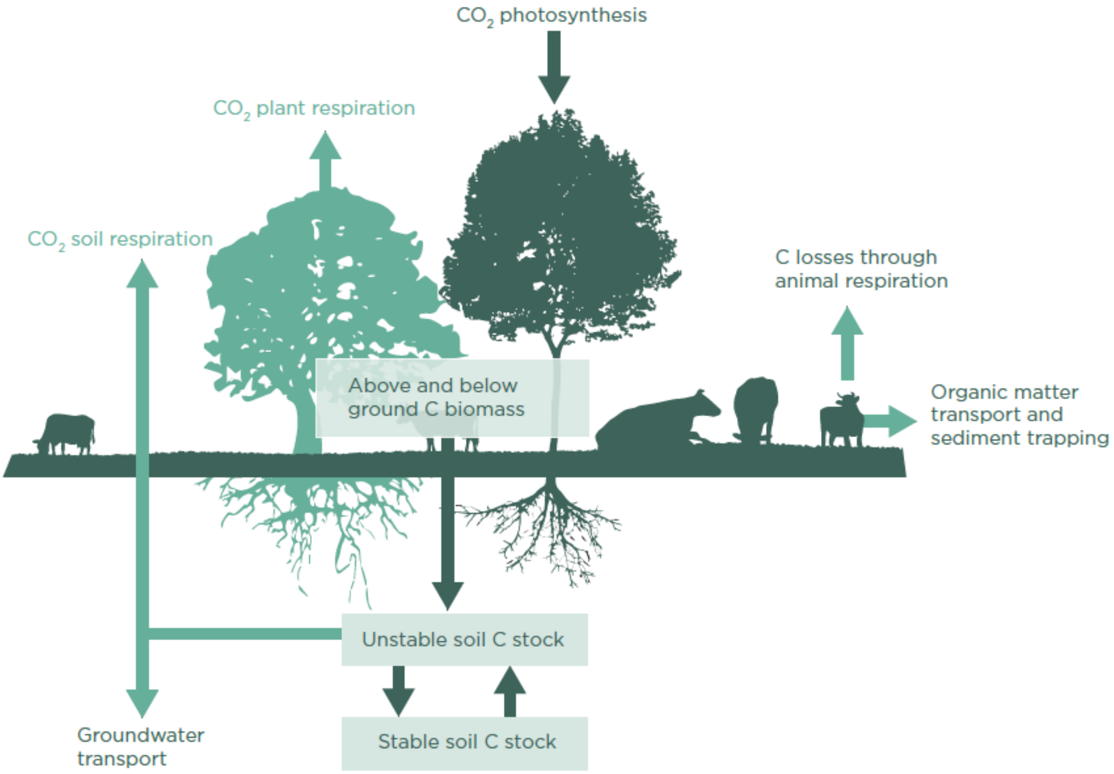

Fig. 1.2. Key C cycling dynamics in terrestrial ecosystems involved in the process of SOC sequestration (Garnett et al., 2017).

SOC sequestration can, therefore, be seen as a transfer of C: it corresponds to the difference between the uptake and the release of CO_2 from a particular environment (Rees et al., 2005). It is considered to have happened only when the C is transferred to pools that have a relatively long lifetime, such as SOM or soil humus. The SOC sequestration potential of a given soil represents the maximum gain in SOC allowing a net removal of CO_2 from the atmosphere under a given climate and for a specified timeline (Chenu et al., 2019).

1.3.3. Soil organic carbon sequestration on agricultural land

Though SOC sequestration may happen on a variety of different land uses (*e.g.*, wetlands, woodlands, croplands, grasslands, etc.), this thesis focuses on SOC sequestration in the context of agricultural land, *i.e.* understanding which changes in agricultural practices may lead to an increase in SOC sequestration. A lot of different soil management practices can increase SOC sequestration on agricultural land (MacLeod et al., 2015). In a comprehensive review of the literature, Sykes et al. (2020) established a shortlist of SCS measures that have been identified as having the potential to lead to a substantial increase in SOC stocks (Fig. 1.3). These measures were selected based on expert confidence in their mitigation potential and a high likelihood that a significant uptake in the agriculture sector could be achieved using policy instruments. Fig. 1.3 illustrates the five different pathways through which SCS measures can increase SOC sequestration on agricultural land. Three of these pathways aim at increasing C inputs to the soil, while the other two aim at reducing C losses from the soil (Fig. 1.3). The effect of SCS measures on SOC sequestration can happen via several pathways simultaneously depending on the measure (Sykes et al., 2020). SOC sequestration and the use of biochar are often considered separately in the literature; in this thesis, however, when referring to SOC sequestration or SCS practices, all practices leading to SOC sequestration are considered, including biochar. This is because the mechanism through which biochar amendments increase SOC sequestration is similar to that of other SCS measures aiming at maximising organic resource management.

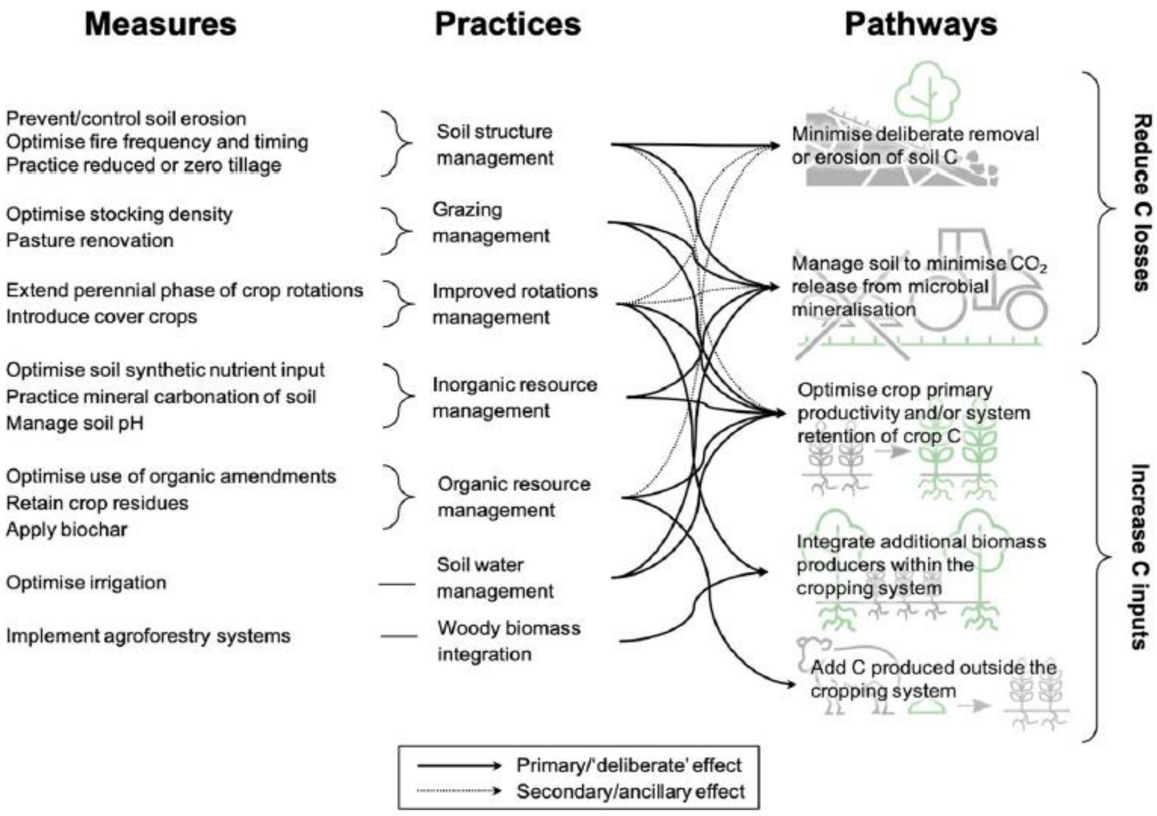

Fig. 1.3. List of SCS measures and pathways to SOC sequestration identified by Sykes et al. (2020).

1.3.4. Mitigation potential of soil organic carbon sequestration

Quantifying the mitigation potential of SOC sequestration is crucial to assess the effectiveness of SCS practices compared to other GHG removal technologies (Table 1.1) and inform policy decisions in the field of climate change mitigation. Several estimates have been proposed. Smith (2016) estimated that the mitigation potential of SOC sequestration (including biochar) ranged from 4 to 6 Gt CO_2-eq. yr^{-1} at the global level. Paustian et al. (2016) suggested that this potential could even be as high as 8 Gt CO_2-eq. yr^{-1}, though in a more recent study Fuss et al. (2018) indicated that it is more likely to have a maximum of 7 Gt CO_2-eq. yr^{-1}. Considering that total anthropogenic GHG emissions reached 59.1 Gt CO_2-eq. in 2019 (UNEP, 2020), SOC sequestration in agricultural soils could offset 7 to 10% of global GHG emissions annually based on the estimate by Smith (2016), and even up to 12% based on the estimate by Fuss et al. (2018). Although the potential of SOC sequestration is lower than that of BECCS and DAC, it is comparable to that of A/R and greater than that of EW (Table 1.2).

Table 1.2. A comparison of the mitigation potential and global impacts between different GHG removal technologies (Smith et al., 2015; Smith, 2016; Fuss et al., 2018).

GHG removal technology	**Mitigation potential (Gt CO_2-eq. yr^{-1})**	**Additional land requirement (Mha)**	**Additional water requirement (km^3 yr^{-1})**	**Energy requirement (EJ yr^{-1})**	**Costs (US\$ t CO_2-eq.$^{-1}$)**
SCS	3.8	0	0	0	-45–10
BC	2.6	40–260	0	-14 to -35	30–120
A/R	4	320	370	Very low	5–50
BECCS	12.1	380–700	720	-170	100–200
DAC	12.1	Very low	10–300	156	100–300
EW	0.7	2	0.3	46	50–200

1.3.5. Advantages of soil organic carbon sequestration

SOC sequestration could reach its mitigation potential with fewer disadvantages than other GHG removal technologies (Smith et al., 2015; Smith, 2016; Fuss et al., 2018). SCS practices require no additional land or water, while BC requires less land than A/R and BECCS, and no additional water (Table 1.2). SCS practices also have lower energy requirements than DAC and EW (Table 1.2): energy use is considered to be neutral for SOC sequestration since it does not differ substantially from baseline practices; BC can even produce energy during its production by pyrolysis. SCS practices are highly cost-effective when compared to BECCS, DAC and EW (Table 1.2): 20% of the mitigation from SOC sequestration could be delivered at negative costs (between -US$45 and US$0 t CO_2-eq.$^{-1}$) and 80% at low costs (< US$10 t CO_2-eq.$^{-1}$), potentially leading to an overall saving of US$7.7 billion yr^{-1} at the global level (Smith, 2016). BC is less cost-effective than SOC sequestration and A/R, with global costs estimated between US$30 and US$120 t CO_2-eq.$^{-1}$, though associated costs are still lower than that of BECCS, DAC and EW.

In addition to helping to mitigate climate change, SOC sequestration provides other benefits in terms of soil quality, even if its mitigation potential is not realised. SCS practices can improve soil fertility, enhance soil water-retention capacities, reduce risks of soil erosion and counteract soil acidification (Honegger et al., 2021). These co-benefits are expected to improve global agricultural productivity and food production (Lal, 2004), and reduce the vulnerability of managed soils to climate change (Smith and Olesen, 2010). However, trade-offs among these effects may also exist, especially if SCS practices are not adapted to local soil compositions (Smith et al., 2013). SCS practices could, therefore, contribute to the delivery of SDGs, especially no poverty, zero hunger, climate action and life on land, if their implementation is in accord with local soil characteristics (Honegger et al., 2021). For these reasons, SOC sequestration is often considered to be a ‘win–win’ option.

1.4. Limitations to soil organic carbon sequestration as a climate change mitigation strategy

Despite the high mitigation potential and numerous advantages of SOC sequestration, there are constraints inherent to SCS practices that may limit their implementation. The main limitations to SOC sequestration include (i) finite capacity and time-limitedness, (ii) non-permanence, and (iii) risks of displacement. Other limitations involve verification issues; because changes in SOC are small in comparison to the large stock of C present in the soil, they can be difficult to measure, leading to problems for monitoring, reporting and verification (Smith, 2004b).

(i) SOC sequestration is a finite and time-limited process (Smith, 2012; Sykes et al., 2020): directly after the implementation of a SCS practice, SOC stocks increase rapidly, but this rate of increase then diminishes progressively over time as the soil tends to reach a new equilibrium (Fig. 1.4). After equilibrium is found, the net removal of CO_2 from the atmosphere approaches zero (Smith, 2014). This phenomenon, called sink saturation, occurs after 10 to 100 years, depending on the SCS practice, climatic zone and soil type (Fuss et al., 2018). As a result, the mitigation potential of a SCS practice is time-limited. IPCC (2006) guidelines use a default saturation time of 20 years, after which the increase in SOC stocks is deemed negligible. Because of this finite capacity and time-limitedness, SOC sequestration will be most useful for meeting short- and medium-term mitigation targets, especially if the targets are large (Smith, 2012). SOC sequestration is often referred to in the literature as a stop-gap measure, whose aim is to reduce GHG concentrations in the short term and hence buy time while longer-term mitigation options with a higher technical potential are developed across all economic sectors. Despite this rationale, SOC sequestration should not be regarded as a way to compensate for GHG emissions and, thus, allow continuing business as usual; instead, it should be seen as an additional lever in the portfolio of options that countries can consider to reduce their agricultural GHG emissions (Wollenberg et al., 2016).

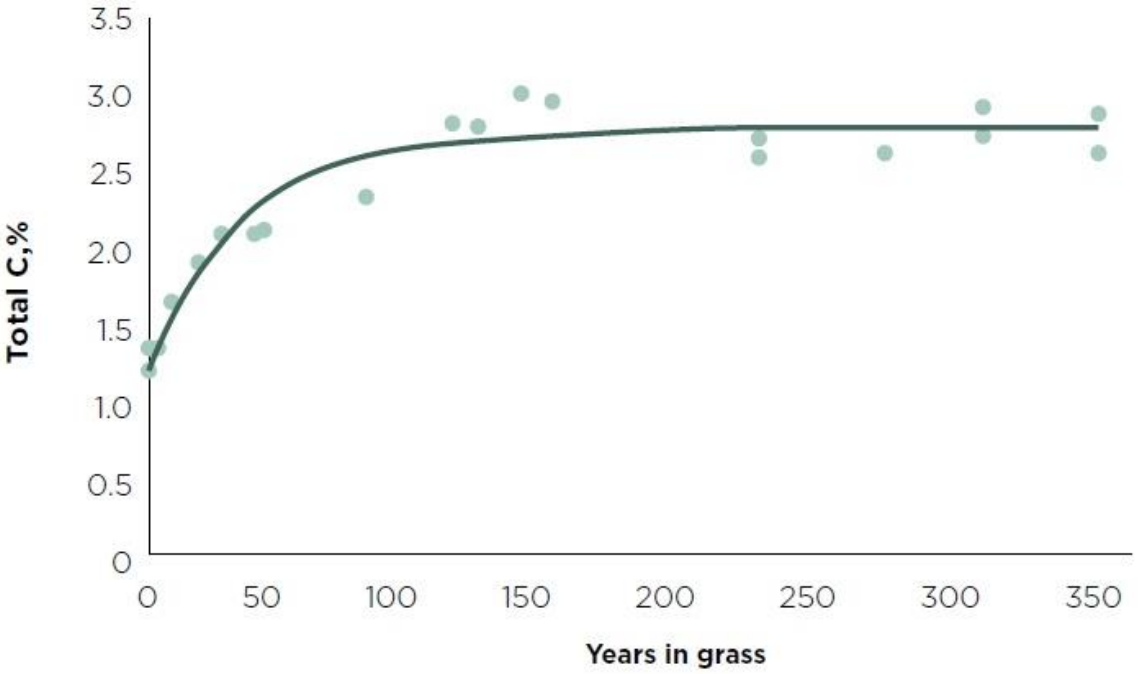

Fig. 1.4. Change in SOC stocks over time following the implementation of a SCS practice (Smith, 2014).

(ii) Since SOC stocks are reversible, SCS practices need to be maintained indefinitely (without any additional increase in SOC stocks), even when the sink is saturated (Fuss et al., 2018). Due to this reversible nature, C sequestered in soils is non-permanent in the long term, which means that there is a risk of future release in the form of atmospheric CO_2 if SCS practices are not maintained (Smith, 2005). This risk is due to frequent changes in farm ownership and the high number of variables (*e.g.*, social, economic, behavioural, cultural, etc.) influencing whether a specific SCS practice continues over time.

(iii) Displacement occurs when high amounts of OM are applied in one area to enhance SOC stocks when they would otherwise have been applied to another area (Powlson et al., 2011). This leads to a transfer of where SOC stocks are increased from one area to another, but there is no net CO_2 removal from the atmosphere overall (Smith, 2012). This is the most common form of displacement, but it can also happen via indirect land-use change when a change in land use in one area to store more C leads to subsequent land-use changes elsewhere causing C to be released (Searchinger et al., 2008). It is particularly the case when the change in land use reduces food production (*e.g.*, a switch from cropland to pasture); this can trigger the conversion of pasture or even forests into croplands somewhere else, leading to C losses and negative environmental impacts.

1.5. What prospects for soil organic carbon sequestration in vineyards?

1.5.1. Why focus on soil organic carbon sequestration in vineyards?

Relatively little research has been conducted on the influence of soil management practices on SOC in woody perennial cropping systems, especially in vineyards. This is because most research in the field of SOC sequestration focuses on arable and pasture-based systems since they cover the highest proportion of managed land at the global level (Longbottom and Petrie, 2015), and less consideration has been given to vineyard agroecosystems regarding the influence they exert on SOC sequestration (Brunori et al., 2016). Attributing the function of C sink to vineyards (and other fruit tree orchards) is still a rather new concept (Holmes et al., 2015). So far, numerous studies have assessed the C balance in vines; however, the majority of them have been conducted to quantify the C allocation among plant organs (to optimise agricultural techniques and product quality) rather than to assess the SOC sequestration potential of these cropping systems (Brunori et al., 2016).

Yet, evaluating the potential of vineyards to store OC has received increasing attention over the past decade across the globe, and more particularly within Europe in the context of the CAP's agri-environment schemes (AESs) and in the framework of the EU's decision 529/2013 regarding C accounting for the Kyoto Protocol (Brunori et al., 2016). Among all woody perennial crops, vineyards are usually associated with the lowest SOC content (Eldon and Gershenson, 2015). In France, vineyards also contain some of the lowest SOC content out of all agricultural systems (Angers et al., 2011). There is, thus, a need to quantify the potential increase in SOC stocks in vineyards under SCS practices to assess the extent to which these cropping systems could participate in global climate change mitigation efforts via SOC sequestration.

In Europe, the Mediterranean region is an important area with regard to possible increases in SOC sequestration on viticultural land. Grapevines are native to the Mediterranean basin and more than 70% of European vineyards are cultivated in a Mediterranean climate (OIV, 2019). Vineyards, along with other fruit tree orchards (*e.g.*, olive orchards), usually dominate the landscape and the economy in the producing areas of rural Mediterranean regions (Aguilera et al., 2015). Traditionally, vines in Mediterranean regions are cultivated on soils characterised by low OM content and limited water availability and are frequently located on medium to steep slopes (Vicente-Vicente et al., 2016). When cultivated with conventional agricultural practices, the soils of Mediterranean vineyards act as net sources of CO_2, contributing to climate change (Vicente-Vicente et al., 2016). The implementation of SCS practices in European vineyards could, therefore, play an important role in reducing the GHG emission intensities of viticultural activities in the EU, estimated to be close to 12 Mt CO_2-eq. yr^{-1} (Litskas et al., 2017), through the process of SOC sequestration.

1.5.2. Which soil organic carbon sequestration practices can be adopted on viticultural land?

An array of SCS practices exists for agricultural soils, grasslands and wetlands (Fig. 1.3); however, they are not universally applicable to all crop systems and, therefore, require system-level evaluation to identify the practices that could be implemented in vineyard agroecosystems. SCS practices that could be applied to vineyards are presented in Table 1.3.

This shortlist of practices was created based on a literature review and discussions with experts from the National Research Institute for Agriculture, Food and Environment (*Institut national de recherche pour l'agriculture, l'alimentation et l'environnement*) and the French Institute of Vine and Wine (*Institut français de la vigne et du vin*): it includes SCS practices already in use in vineyards (*e.g.*, CC, NT, etc.) and practices suitable for vineyard agroecosystems but not yet implemented (*e.g.*, BC, agroforestry, etc.). In this thesis, however, not all SCS practices that could be applied to vineyard agroecosystems will be taken into account. Only OA, BC, PR, NT, CC and HG will be considered in this work, due to the lack of data on the effect of the other SCS practices on SOC stocks in vineyards. This lack of data makes it impossible to quantify the SOC sequestration potential of these practices in vineyards.

Table 1.3. List of SCS practices suitable for vineyard agroecosystems.

Category	**SCS practice**
Soil cover management	Cover cropping (CC)
Woody biomass	Agroforestry (with low tree density)
	Planting or maintaining hedges (HG)
Water management	Optimising irrigation[2]
Organic resource management	Using organic amendments (OA)
	Returning pruning residues to the soil (PR)
	Adding biochar amendments (BC)
Tillage management	Implementing no-tillage (NT)
Erosion control	Preventing soil erosion
Nutrient management	Optimising nutrient input to the soil
pH management	Keeping pH at an optimum for plant growth (*e.g.*, through liming)

1.5.2.1. Using organic amendments

The application of organic amendments on agricultural land to improve soil quality and fertility is a traditional soil management practice dating back thousands of years (Scotti et al., 2015). There exist many different types of organic amendments, which can be grouped into

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[2] Optimal irrigation can improve SOC sequestration in water-scarce viticultural systems by increasing primary productivity and OM input to the soil (Sykes et al., 2020), while over-irrigating vineyards may decrease SOC stocks by halting the development of complex vine root systems and by accelerating microbial mineralisation from repeated wetting-drying cycles (Mudge et al., 2017).

six broad categories: animal manure, municipal biosolids and septage[3], green manure, waste from manufacturing processes, food residues and waste, and compost (Goss et al., 2013).

OA has the potential to contribute to SOC sequestration in croplands and grasslands (Brar et al., 2013; Zhu et al., 2018), including in viticultural land (Vicente-Vicente et al., 2016). The adoption of OA leads to increased OC inputs to the cropping system by both increasing the primary productivity of the crop and adding OC produced outside the cropping system to the soil (Sykes et al., 2020). OA also has positive environmental externalities, such as improving soil structure and soil water retention, and reducing soil erodibility (Shehzadi et al., 2017).

1.5.2.2. Adding biochar amendments

Biochar is pyrogenic OM produced by a high-temperature, low-oxygen conversion of biomass and can be used as a soil amendment on agricultural land. Biochar has a high OC content; when applied to the soil, it contributes to substantially increasing OC inputs to the soil (Lehmann, 2007). In principle, this offers an unlimited sink for OC in the soil. Biochar also allows for more permanent changes in other soil properties, such as reduced soil acidity or increased nutrient and moisture availability (Jeffery et al., 2017).

Several studies (*e.g.*, Liu et al., 2016; Bai et al., 2019) have shown that the long-term impact of BC on SOC stocks is positive in agricultural soils; nevertheless, other studies (*e.g.*, Majumder et al., 2019) have also observed neutral or negative effects. The impacts of BC on SOC stocks are biochar-, climate- and soil-specific; the application of this practice in agricultural soils at the global level is, therefore, context-dependent. The effects of biochar amendments on GHG emissions also vary based on biochar inputs, crop systems, climates and soil types. However, many studies (*e.g.*, Han et al., 2022; Shen et al., 2017) report lower GHG budgets in agricultural systems using BC than in systems under conventional management. In viticultural soils, the use of biochar is still new and experimental; as a result, there is high uncertainty regarding the effects of BC on viticultural SOC stocks and grape quality.

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[3] Septage refers to the waste material (*e.g.*, excrement) and sewage removed from a septic tank.

1.5.2.3. Returning pruning residues to the soil

Every year, winegrowers conduct pruning activities in their vineyards to optimise grape development. In certain winegrowing regions, the removal of pruning residues is common (for use as animal feed, bedding, fuel, industrial feedstock or building material), resulting in SOC losses from the vineyard agroecosystem. Retaining pruning residues in the vineyard leads to SOC sequestration by minimising the deliberate removal of OC from the agroecosystem (Wang et al., 2015; Sykes et al., 2020).

1.5.2.4. Implementing no-tillage

In vineyards, tillage can be used in the vines' inter-rows or under-rows as a weed control measure. Implementing no-tillage on viticultural land consists of putting an end to mechanically ploughing the soil. NT intends to reduce OC losses from the cropping system by reducing soil disturbance, which lessens the atmospheric release of CO_2 from microbial mineralisation (Merante et al., 2017). NT may also have benefits for sustainable soil management, including improving soil structure, enhancing soil moisture and reducing soil erosion (Derpsch et al., 2010).

However, the adoption of NT is not a universally applicable SCS practice, since its effects on SOC stocks vary based on climatic and soil characteristics (Ogle et al., 2019). Depending on the context, adopting NT could lead to SOC sequestration, losses in SOC stocks or have no effect on SOC stocks. The introduction of NT may also lead to a vertical redistribution of SOC stocks, with increases in the top 0-10 cm of soil but decreases in the 10-40-cm layer of soil (Luo et al., 2010).

1.5.2.5. Cover cropping

CC consists of growing an additional crop primarily to maintain soil cover in the agroecosystem. In arable land, cover crops are mainly used during winter fallow periods to avoid leaving the soil bare; in viticultural land, cover crops are implemented in the inter-rows or under the rows of vines; they can be permanent or temporary. Implementing CC increases OC inputs to the cropping system through the integration of additional biomass produced by the cover crop within the system (Sykes et al., 2020). Additionally, CC may reduce OC losses by minimising the lateral transport of SOC via erosion processes (Poeplau and Don, 2015).

1.5.2.6. Planting or maintaining hedges

HG refers to the practice of incorporating hedges in vineyards or preserving already existing hedges in vineyards. Hedges can be implemented within the vineyard, resulting in an intercropped system with, for instance, alleys of hedges, or at the edge of the vineyard, forming wind belts, shelterbelts or buffer zones. The introduction of hedges in vineyards increases OC inputs to the cropping system through the integration of additional biomass producers within the system (Sykes et al., 2020). Hedge roots also improve the quality and quantity of belowground OC inputs (Lorenz and Lal, 2014).

1.6. Aims, objectives and research questions

Realising the mitigation potential of SCS practices on viticultural land will mostly depend on the extent to which these practices are adopted in vineyards by winegrowers and maintained in the long term. It is, thus, crucial that the barriers preventing adoption are understood and available solutions to alleviate these barriers are identified and used to incentivise uptake. This research seeks to further our understanding of the different barriers that may impede the adoption of SCS practices in vineyards. It assesses both natural and social science elements that may be at play in the implementation process of SCS practices on viticultural land. The objectives of the thesis are to:

- Quantify the SOC sequestration potential of SCS practices in vineyard agroecosystems and identify the winegrowing regions where it is the highest.
- Understand the drivers of and barriers to the adoption of SCS practices by winegrowers to promote further adoption and improve policymaking.

To meet these objectives, this thesis addresses the following research questions:

- Are certain vineyards hotspots for SOC sequestration and, if so, where are they located?
- What is the SOC sequestration potential of the SCS practices suitable for viticultural soils and how does it compare with other cropping systems?
- Which biophysical elements may hinder the realisation of the SOC sequestration potential of these SCS practices in vineyards?

- Which socio-economic factors underlie the adoption of these SCS practices by winegrowers?
- What is preventing winegrowers from implementing some of these SCS practices in vineyards?
- Are existing policy instruments in the viticulture sector adequate for promoting the adoption of these SCS practices?

1.7. Research approach and thesis structure

The thesis takes an interdisciplinary approach, spanning natural and social science methodologies, and uses mixed methods[4]. It is divided into six chapters, starting with an introduction (Chapter 1) and ending with a discussion/conclusion chapter (Chapter 6). Chapters 2 to 5 constitute the body of the thesis. While Chapters 2 and 3 draw from the field of natural science, the approach taken in Chapters 4 and 5 is from the domain of social science. Chapter 2 undertakes a meta-analysis of the SOC sequestration rates of SCS practices in vineyard agroecosystems at the global level. In Chapter 3, the data collected in Chapter 2 is used to develop a random forest regression model that quantifies SOC stock changes over time under SCS practices in vineyards. This tool is employed to predict and map the abatement rate of SCS practices in vineyards at the regional and national levels of several European countries. Chapter 4 uses a binary logistic regression to identify the factors playing a significant role in the adoption process of SCS practices by winegrowers in France. The regression is built from quantitative data collected via a questionnaire circulated to French winegrowers. Chapter 5 presents the main motives and barriers to the adoption of SCS practices by winegrowers in France, using qualitative data.

Chapters 2 to 5 are written as individual papers and can be read independently, though each chapter builds on those previous to form an overarching cohesive thesis. Chapters 2, 3 and 4 were published as peer-reviewed papers in the *Journal of Cleaner Production*, the *Cleaner Environmental Systems* journal and the *Environmental Science & Policy* journal, respectively.

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[4] ‘Mixed methods’ is a research approach that consists of collecting and analysing quantitative and qualitative data within the same study (Creswell and Plano Clark, 2017).

A full copy of these publications can be found in Appendix A. Chapter 5 has recently been submitted to the *Land Use Policy* journal.

Chapter 2

Soil organic carbon sequestration rates in vineyard agroecosystems under different soil management practices: A meta-analysis

2.1. Abstract

Vineyards are usually cultivated in soils characterised by low SOC content and have high risks of soil erosion and degradation. Increasing SOC stocks in these cropping systems has the potential to contribute to climate change mitigation through SOC sequestration and enhance soil quality. A meta-analysis comparing the SOC stock response ratio, the SOC stock rate of change, and the SOC sequestration rate in vineyards under different SCS practices relative to conventional management was conducted. SCS practices included OA, BC, PR, NT, CC, and several combinations of these practices. The average SOC sequestration rate of SCS management was 7.53 Mg CO_2-eq. ha^{-1} yr^{-1} to a 30-cm soil depth. The highest SOC sequestration rate (11.06 Mg CO_2-eq. ha^{-1} yr^{-1}) was achieved under a combination of OA+NT and the lowest (2.82 Mg CO_2-eq. ha^{-1} yr^{-1}) was observed under PR treatments. Field experiments performed in particularly hot and dry bioclimatic zones were associated with lower SOC sequestration rates relative to those performed in more temperate areas. The high SOC sequestration rates obtained for many SCS practices, and the large land area dedicated to viticulture worldwide (7.45 Mha), imply that the adoption of SCS practices in vineyards can contribute to the global efforts to offset atmospheric greenhouse gas concentrations via SOC sequestration to mitigate climate change.

2.2. Introduction

Viticulture represents an economically and culturally important sector of agricultural production in regions of the world with climates compatible with grape (*Vitis vinifera* L.) cultivation (Eldon and Gershenson, 2015). Vineyards constitute one of the most widespread agricultural production systems in several European countries such as Spain, France and Italy (Brunori et al., 2016). In France, viticulture covers 3% of agricultural land, but in 2018 the sector generated 15% of the total agricultural revenue (CNIV, 2019), estimated at €77.5 billion (Insee, 2019), and wine exports achieved €12.2 billion in revenue in the same year (CNIV, 2019). Viticulture is also present outside of Europe and many non-European winegrowing countries (*e.g.*, China, Chile, India) have been expanding their vineyard land areas and increasing their grape production over the past decade (OIV, 2019).

Vineyards are managed with a broad range of practices, which vary across regions and have a differentiated influence on SOC content (Carlisle et al., 2010). Conventional practices (*e.g.*, maintaining bare soil in the inter-rows through the use of tillage) result in SOC losses in vineyard systems (Eldon and Gershenson, 2015), but alternative viticultural practices (*e.g.*, using cover cropping) may lead to SOC sequestration (Nistor et al., 2018). SOC sequestration corresponds to the process of transferring CO_2 from the atmosphere into the soil through plants, plant residues and other organic solids which are stored or retained in the soil as part of the SOM (Olson et al., 2014). It assumes a net removal of CO_2 from the atmosphere (Chenu et al., 2019). Understanding SOC dynamics associated with different soil management practices in vineyards is crucial in identifying the most effective practices for SOC sequestration in viticultural soils.

The contribution of viticultural agroecosystems to SOC sequestration at the global scale is gaining increasing attention. Studies (*e.g.*, Brunori et al., 2016; Scandellari et al., 2016) show that properly managed vineyards could act as C sinks via SOC sequestration. Vines have specific structural features that allow them to potentially sequester higher quantities of OC than annual crops (Smaje, 2015). Due to their naturally long life cycle, vines accumulate OC in their woody biomass (Williams et al., 2011), including in their complex root systems (Agnelli et al., 2014), and the soil (*e.g.*, through rhizodeposition) (Brunori et al., 2016). Their extensive and deep-root systems (reaching down 2 to 5 m on average) also allow for direct transfer of OC into the subsoil (Agnelli et al., 2014), which reduces risks of SOC mineralisation by physically isolating the OC from the activity of soil microorganisms (Ledo et al., 2020).

The global viticultural land area was 7.45 Mha in 2018 (OIV, 2019). Although only a fraction of the global arable land area, around 1.39 Gha in 2017 (FAO, 2019), it may contribute to SOC sequestration in countries with large winegrowing regions. French vineyards have been identified as offering substantial sequestration potential as part of the ‘4 per 1000’ initiative[5]

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[5] The ‘4 per 1000’ is an international initiative gathering public and private stakeholders under the Lima-Paris Action Plan framework. It aims to achieve an annual growth rate of 0.4% in the global SOC stocks (to a depth of 40 cm) for food security and climate (4p1000, 2018). The initiative’s ambition is to encourage stakeholders to transition towards a productive and resilient agricultural system, which ensures food security and contributes to mitigating climate change (4p1000, 2018).

(Minasny et al., 2017). The interest in viticulture and SOC sequestration is supported by broader studies (*e.g.*, Pergola et al., 2017; Ledo et al., 2019; Ledo et al., 2020) seeking a better understanding of the effects of perennial crop systems on SOC stocks and GHG emissions, and how these effects vary depending on management practices.

There is a substantial body of research considering potential SCS practices in agriculture. Several meta-analyses and reviews (*e.g.*, Poeplau and Don, 2015; Liu et al., 2016; Sykes et al., 2020) have estimated the effects of single or combined soil management practices on SOC stock change. Relative to arable and pasture systems, SOC sequestration in vineyards has received less attention. Most studies relating to SOC sequestration have not taken vineyard agroecosystems into account (*e.g.*, Poeplau and Don, 2015) or have not differentiated them as separate crop systems in the analysis (*e.g.*, Aguilera et al., 2013). Information on SOC sequestration in vineyards remains fragmented and incomplete. There is currently no published meta-analysis evaluating the global potential of vineyards to enhance SOC sequestration under SCS practices applicable to viticulture. Vicente-Vicente et al. (2016) considered field experiments performed in vineyards and analysed the influence of some SCS practices specifically for vineyards as part of their meta-analysis in woody croplands, but their study focused on a limited number of SCS practices (cover cropping, organic amendments and a combination of both) and on specific bioclimatic zones (non-Mediterranean vineyards were excluded from their analysis).

Understanding and quantifying the mitigation potential of vineyards is important for future policy decisions in the agriculture sector. This chapter presents a meta-analysis of the response of SOC stocks in 0-30 cm depth in vineyards to different SCS management practices from a global sample of individual field studies. It also compares the changes in SOC stocks depending on climate and study length. To my knowledge, this is the first meta-analysis dealing with the influence of SCS management on SOC stocks in vineyards at the global level. The novelty of this study is to consider all SCS practices applicable to vineyard agroecosystems and to estimate the SOC sequestration rate associated with their implementation in viticultural soils located under all types of climates. This study also represents the first attempt to assess, through meta-analysis, the effect of biochar amendments, pruning residue return and no-tillage on SOC stocks in vineyards specifically.

The chapter is structured as follows. The next section describes the materials and methods used to perform the meta-analysis. Section 2.4 presents the results of the meta-analysis, categorised by SCS management, sub-climate and study length. Section 2.5 discusses and compares the results of the meta-analysis to those of previous studies on permanent crops. Section 2.6 covers conclusions.

2.3. Materials and methods

2.3.1. Data collection

A literature search focusing on publications reporting pairwise comparisons between conventional management and SCS practices in vineyards was conducted in October 2019. The search covered the electronic databases of ISI Web of Knowledge and Scopus, using the keywords “soil organic carbon”, “soil organic matter” or “soil carbon sequestration” and “vineyard” or “*Vitis vinifera*”. Seeking complete coverage, a second search of the same databases used the keywords “cover crop”, “no-tillage”, “amendment”, “biochar”, “hedge”, “agroforestry”, “pruning”, “soil erosion” or “pH” in combination with “vineyard” or “*Vitis vinifera*”. These keywords correspond to SCS practices applicable to viticultural soils, to soil properties playing a role in SOC sequestration, or to phenomena affecting SOC sequestration.

Selected studies fulfilled the following criteria: (i) they included experiments measuring SOC or SOM levels within existing vineyards or through experimental manipulation of vineyard management practices; (ii) they were performed under field conditions (laboratory studies and pot experiments were excluded) for a minimum period of three years; and (iii) they were published in or after 2000. When several studies contained data from the same field experiment, only the longest study was selected to avoid redundancy in the data.

2.3.2. Definition of categories

2.3.2.1. Soil management practices

Five different SCS practices were found during the literature search: OA, BC, PR, NT and CC. Other SCS practices applicable to viticulture (*e.g.*, using contour hedges) were not considered by any of the field experiments gathered in the literature search and were, therefore, not included in this study.

- OA included comparisons where organic amendments (*e.g.*, compost, manure, green waste, sludge, etc.) were applied to the vineyard. Biochar amendments and pruning residues were both excluded from this category and constituted a category of their own. The amount of OC incorporated into the soil under this practice was not considered in the analysis due to the low number of studies reporting how much organic amendment was used in the field experiments. As a result, the extent to which the SOC sequestration rate might have varied based on how much organic amendment was used in the field could not be analysed and the SOC sequestration efficiency (*i.e.* the percentage of the OC that is fixed into the soil after the implementation of OA) could not be calculated.
- BC included comparisons where biochar amendments were applied to the vineyard. As with OA, the amount of OC added to the soil under BC was not included in the analysis.
- PR included comparisons in which pruning residues were left on the ground or were incorporated into the soil after being crushed.
- NT included comparisons where no-tillage was implemented continuously in the vineyard, meaning that the soil was not disturbed by tillage during the experiment. When used as a single practice, weeds were controlled using pre-emergence herbicides to ensure no vegetation cover in the inter-rows.
- CC included comparisons in which a cover crop was grown in the inter-rows of the vineyard. Cover crops were either native vegetation growing spontaneously or sown. In the latter case, different varieties of crops were chosen depending on the experiment, such as barley (*Hordeum vulgare*), clover (*Trifolium pratense*), vetch (*Vicia sativa*), etc. The cover crops were permanent or allowed to grow temporarily between early autumn and mid-spring. In all the experiments, the plant residues from the cover crops were left on the soil surface or incorporated into the soil, which means that the produced OM was not removed from the agroecosystem by the experiment observers. When used as a single practice, the inter-row soil was ploughed at least once a year to control the vegetation, usually during spring.

The comparisons were classified by soil management according to the SCS practices used in the experiment. The comparisons included either a single SCS practice (*i.e.* OA, BC, PR, NT or CC) or a combination of two or three SCS practices (*e.g.*, OA+NT or PR+NT+CC); a category was created for each combination of practices. Conventional management was used as a control group and was characterised by the use of frequent tillage and, in most cases, the application of mineral fertilisers. All SCS treatments were cultivated under conventional management before the start of the experiments. The control groups showed no or a negligible change in SOC stocks throughout the duration of the experiments, suggesting that the soil of control and SCS treatments was in equilibrium before the introduction of SCS management.

2.3.2.2. Climate classification

Comparisons between SCS and conventional management in field experiments were also classified depending on their sub-climate using the Köppen-Geiger classification (Peel et al., 2007). The classification differentiates 30 sub-climate types gathered into 5 broader categories (Table 2.1). Vineyards are commonly found under B-, C- and D-type climates. Grape is also grown in tropical regions (A-type climates), though to a lesser extent. Viticulture is, however, not conducted in polar regions.

2.3.2.3. Duration of the experiments

Each pairwise comparison was, in addition, classified according to the duration of the experiment. Three categories were created: short-term studies (*i.e.* < 6 years), medium-term studies (*i.e.* between 6 and 10 years) and long-term studies (*i.e.* > 10 years).

Table 2.1. Defining criteria of the Köppen-Geiger classification and climate symbols (Peel et al., 2007). MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10 °C, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter. If 70% of MAP occurs in winter, then $P_{threshold}$ = 2 x MAT; if 70% of MAP occurs in summer, then $P_{threshold}$ = 2 x MAT + 28; otherwise, $P_{threshold}$ = 2 x MAT + 14.

1st	2nd	3rd	Description	Criteria
A			Tropical	$T_{cold} \geq 18$ °C
	f		- Rainforest	$P_{dry} \geq 60$ mm
	m		- Monsoon	Not (Af) & $P_{dry} \geq (100 – MAP/25)$
	w		- Savannah	Not (Af) & $P_{dry} < (100 – MAP/25)$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$ °C
		k	- Cold	$MAT < 18$ °C
C			Temperate	$T_{hot} > 10$ °C & 0 °C $< T_{cold} < 18$ °C
	s		- Dry summer	$P_{sdry} < 40$ mm & $P_{sdry} < P_{wwet}/3$
	w		- Dry winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot summer	$T_{hot} \geq 22$ °C
		b	- Warm summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ °C & $T_{cold} \leq 0$ °C
	s		- Dry summer	$P_{sdry} < 40$ mm & $P_{sdry} < P_{wwet}/3$
	w		- Dry winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot summer	$T_{hot} \geq 22$ °C
		b	- Warm summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold summer	Not (a, b or d)
		d	- Very cold winter	Not (a or b) & $T_{cold} < –38$ °C
E			Polar	$T_{hot} < 10$ °C
	T		- Tundra	$T_{hot} > 0$ °C
	F		- Frost	$T_{hot} \leq 0$ °C

2.3.3. Data management and estimation methods

Data on SOC stocks (in Mg C ha^{-1}) at the beginning and the end of the experiment were collected for all the treatments included in the selected studies (Appendix B). In cases where the initial SOC stock values for SCS treatments were unavailable or could not be calculated, initial SOC stocks from conventional treatments were used instead, assuming that both the control and experimental plots had similar initial SOC stocks considering that they were established on the same soil and under similar pedoclimatic conditions. Only a limited number of studies provided values of SOC stocks; in most cases, SOC was given as a concentration. SOC stocks were, thus, derived from the concentration using Equation (1), in which *SOC stock* represents the SOC stock (in Mg C ha^{-1}), d_i the soil depth (in m), ρ_i the bulk density (in Mg m^{-3}) and $[SOC]_i$ the SOC concentration (in g C kg^{-1} of soil) for all the different soil layers included in each field experiment (*i.e.* from *i* to *n* soil layers).

$$SOC\ stock = \sum_{i=1}^{n} \frac{d_i \rho_i [SOC]_i}{10} \tag{1}$$

Whenever the bulk density was not provided by the studies, values were estimated using the pedotransfer function in Howard et al. (1995) for vineyards located in non-Mediterranean climates (Equation (2)) and, for vineyards located in Mediterranean climates, the same function but re-parametrised by Aguilera et al. (2013) with data from Mediterranean soils (Equation (3)), in which ρ represents the bulk density (in g cm^{-3}) and $[SOC]$ the SOC concentration (in g C kg^{-1} of soil). When SOC concentrations were not determined by the study, they were derived from the SOM concentrations using the relationship developed by Pribyl (2010): [SOC] = [SOM] x 0.5.

$$\rho = 1.3 - 0.275\ log10([SOC]) \tag{2}$$

$$\rho = 1.84 - 0.443\ log10([SOC]) \tag{3}$$

Since studies reported SOC stocks (and SOC or SOM concentrations) for different soil depths, a quadratic density function, based on Smith, Milne, et al. (2000) and used by Abdalla et al. (2018), was used to derive a scaling cumulative distribution function (cdf) for soil density as a function of soil depth up to 1 m. This allowed measured or calculated SOC stocks (Mg C ha^{-1}) at the beginning and the end of each experiment at a given depth d (in m) to be scaled to the equivalent values at 0.3 m following Equations (4) and (5). A depth of 0.3 m was chosen since the great majority of the change in SOC occurs in the top 0.3 m of soil, even though some changes may also occur below 0.3 m (Smith, Powlson, et al., 2000). Besides, scaling all studies to a depth of 0.3 m provided a standardised analysis compatible with the Tier 1 methods of the IPCC (2006) guidelines.

$$cdf(d) = (22.1 - \frac{33.3d^2}{2} + \frac{14.9d^3}{3})/10.41667 \tag{4}$$

$$SOC\ stock\ (0.3\ m) = SOC\ stock\ (d)\ \times\ cdf\ (0.3)/cdf\ (d) \tag{5}$$

2.3.4. Statistical analyses

The collected data harmonised to a depth of 0.3 m was used to calculate three effect sizes for SOC stock comparisons: (i) the SOC stock response ratio (RR), to estimate the change in SOC stocks under SCS practices relative to conventional management, (ii) the SOC stock rate of change (R), as a measure of the annual growth rate in SOC stocks under SCS management relative to conventional management, and (iii) the raw difference in means of SOC stocks for SOC sequestration rate comparisons. Statistical analyses were performed in the R environment software (R Core Team, 2019). When several treatments with similar management shared the same control, one composite effect size was computed for these treatments to ensure that all the comparisons in the meta-analysis were independent. The composite effect size was calculated by averaging the effect sizes of the non-independent treatments. When these treatments had different sample sizes, a weighted mean was used to give more importance to the treatments with a higher sample size (Borenstein et al., 2009).

RR was defined by the methods of Hedges et al. (1999) as the natural logarithm of the ratio of the SOC stock at the end of the experiment under SCS management ($(SOC\ stock)_f$ in Mg C ha^{-1}) to the SOC stock at the beginning of the experiment ($(SOC\ stock)_i$), according to Equation (6). The use of the natural logarithm allowed for linearization of the metric, leading to a more normal sampling distribution (Hedges et al., 1999). The SOC stock was preferentially chosen for RR calculation over the SOC concentration to reduce the impact of the differences in soil depth and bulk density between studies. Data on the absolute amount of

SOC change is also required to assess the contribution of SOC sequestration to climate change mitigation.

$$RR = \ln\big((SOC\ stock)_f\big) - \ln((SOC\ stock)_i) \tag{6}$$

R, expressed in yr^{-1}, was computed following Equation (7), according to the methods used by Abdalla et al. (2018). *t* stands for the duration of the experiment (in years).

$$R = RR/t \tag{7}$$

The SOC sequestration rate (in Mg C ha^{-1} yr^{-1}) corresponds to the change in the SOC stock per hectare and per year for a 0.3 m depth under SCS management relative to conventional management. It was calculated following Equation (8), in which $(SOC\ stock)_f$ stands for the SOC stock (in Mg C ha^{-1}) at the end of the experiment, $(SOC\ stock)_i$ for the SOC stock at the beginning of the experiment and *t* for the duration of the experiment (in years). The unit of the SOC sequestration rate was converted into CO_2 equivalent (CO_2-eq. ha^{-1} yr^{-1}) by multiplying the results by the ratio of the molecular weight of CO_2 to the molecular weight of carbon (44/12).

$$SOC\ sequestration\ rate = \frac{(SOC\ stock)_f - (SOC\ stock)_i}{t} \tag{8}$$

Weighted mean effect sizes of each category of SCS practices, bioclimatic zones and study length were calculated. The studies were weighted by sample size (Adams et al., 1997) according to Equation (9), where w_i refers to the weight of a given comparison i, and N_i^{SCS} and N_i^{CON} refer to the sample sizes of the SCS treatment and the control treatment in the comparison, respectively. In meta-analyses, studies are usually weighted by the inverse of their variance (Borenstein et al., 2009); however, the variance was not provided in many of the studies. Sample size, on the contrary, was available in all references. Its use allowed for the inclusion of all the studies gathered during the literature search while maintaining the reasoning of the meta-analysis, which relies on attributing more weight to larger studies in effect sizes.

$$w_i = \frac{N_i^{SCS} N_i^{CON}}{N_i^{SCS} + N_i^{CON}} \tag{9}$$

Bias-corrected 95% confidence intervals were generated for each weighted mean effect size by bootstrapping procedure with 10,000 iterations (Adams et al., 1997), using the R package ‘boot’ (Canty and Ripley, 2019).

2.4. Results

2.4.1. General findings

A total of 50 studies were compiled, providing 146 independent comparisons between SCS and conventional management practices. An overview of the studies can be found in Appendix C. Almost all studies were peer-reviewed articles published in scientific journals (n = 46); only a few were conference papers (n = 2) or book chapters (n = 2). Most of the studies were published over the last ten years. Overall, the initial SOC stock was reported in 70% of the studies selected and the bulk density in 30%. The mean experiment duration was 8.5 years (StDev = 5.8), with most comparisons being in the medium term (n = 70), slightly fewer in the short term (n = 57), and fewer again in the long term (n = 19); the longest field experiments (n = 5) had a duration of 28 years. The mean soil depth was 0.31 m (StDev = 0.18), with values ranging from 0.05 to 1 m.

The SCS management practices were very diverse, with a mix of single and combined practices. A combination of two SCS practices was used in the majority of the comparisons (n = 83). The most prominent combination was NT+CC (n = 70), followed by OA+NT (n = 6), OA+BC (n = 3), PR+CC (n = 3) and PR+NT (n = 1). The number of comparisons associated with the use of a single SCS practice was lower (n = 52). OA was the most commonly used single SCS practice, with 27 comparisons, followed by CC (n = 9), NT (n = 7), PR (n = 5) and BC (n = 4). The number of comparisons dealing with a combination of three SCS practices was substantially lower, with only 11 comparisons: OA+NT+CC (n = 7), PR+NT+CC (n = 3) and OA+PR+NT (n = 1).

Most studies (39 out of 50) were conducted in countries of the European Union (Fig. 2.1). The largest number of studies was from Spain (n = 17), followed by Italy (n = 11), France (n = 10), the USA (n = 5), South Africa (n = 4), and Australia (n = 1), Germany (n = 1) and Turkey (n = 1). The sub-climate Cfb, which corresponds to a temperate oceanic climate, was the most represented in the meta-analysis with 38 comparisons, followed by Csa (n = 25), Csb (n = 24), BSk (n = 17), BWh (n = 17), Cfa (n = 17), Csc (n = 5) and Dfa (n = 3). The majority of comparisons (n = 105) were conducted under a Mediterranean climate (which includes the sub-climates BSk, BWh, Cfa, Csa, Csb and Csc), while fewer comparisons (n = 41) were undertaken under a non-Mediterranean climate (which includes the sub-climates Cfb and Dfa).

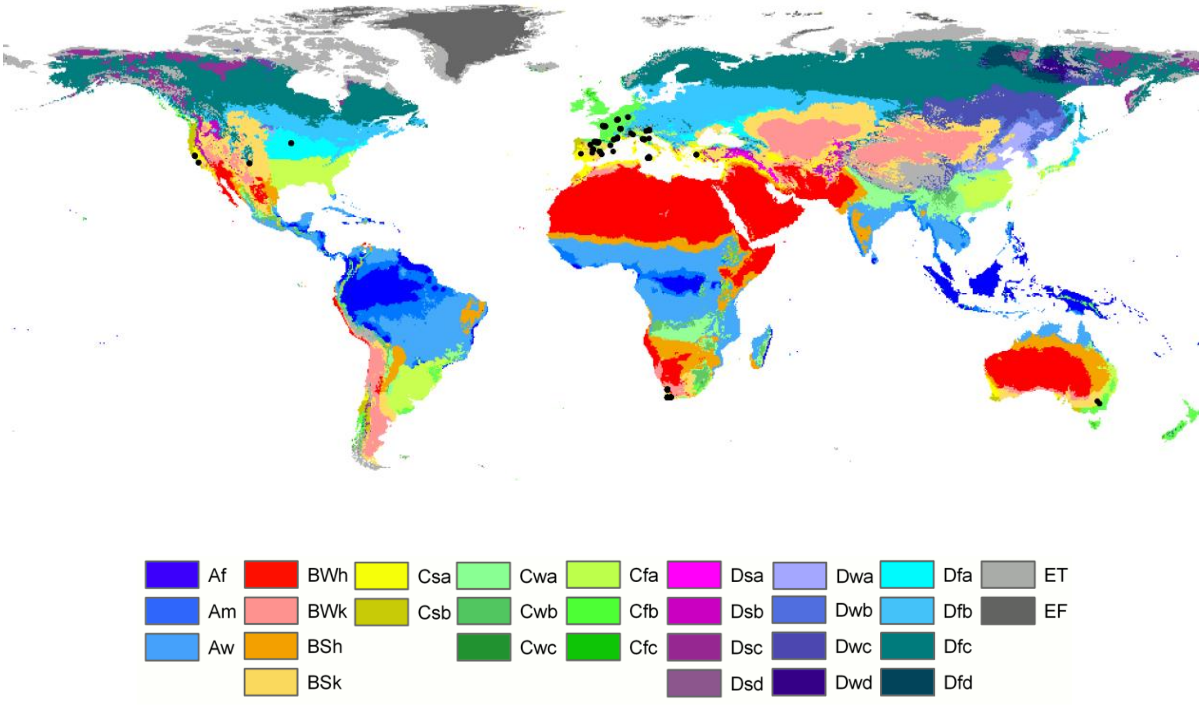


Fig. 2.1. Map of the present Köppen-Geiger classification (Beck et al., 2018) with the locations of the experimental vineyards considered in this meta-analysis.

2.4.2. Impacts of soil management, climate and study length on the SOC stock response ratio

The RR was significantly higher than 0 for all SCS practices (Fig. 2.2). This implies that all SCS practices analysed in this study were, on average, associated with an increase in SOC stocks in vineyards relative to conventional management. The average RR for all SCS practices was 0.40, which corresponded to an average increase in SOC stocks by +40% under SCS management relative to conventional management. The lowest RR (0.09) was observed in vineyards in which OA+BC had been used, whereas the highest RR (0.60) was found in vineyards in which a combination of OA+NT had been put in place.

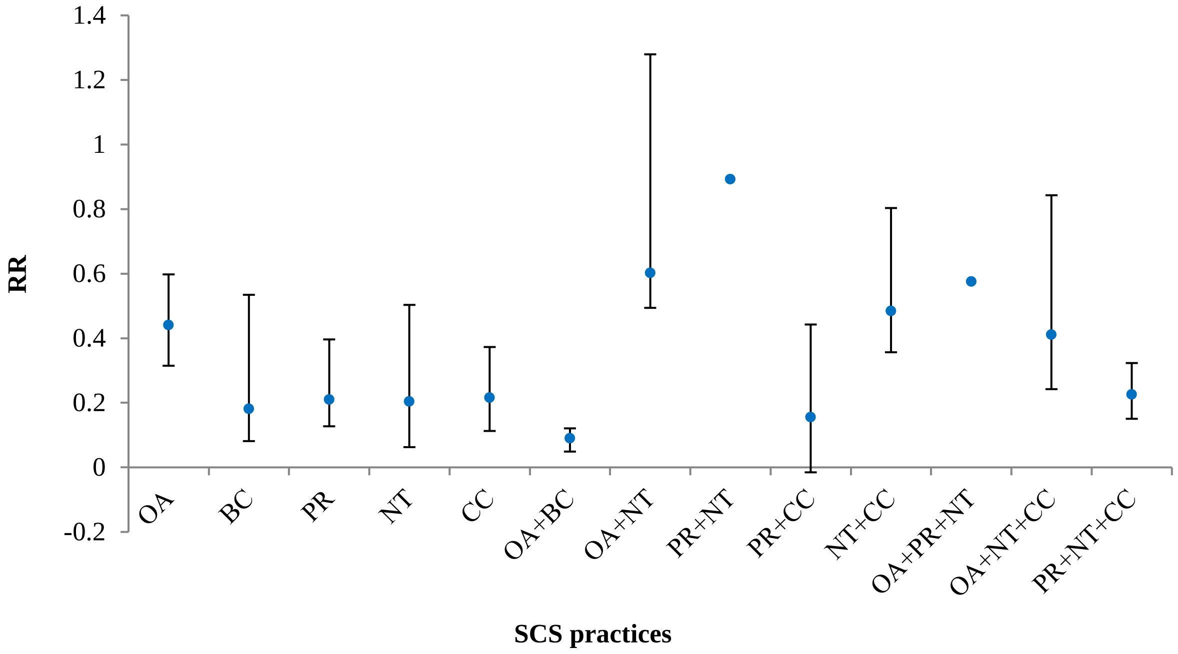


Fig. 2.2. Influence of SCS practices (OA, organic amendments; BC, biochar; PR, pruning residues; NT, no-tillage; and CC, cover cropping) on the SOC stock response ratio (RR) to 30-cm depth. PR+NT and OA+PR+NT were not included in the analysis, since only one comparison was observed for these categories. Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

Changes in SOC stocks under SCS management differed between Köppen-Geiger sub-climates (Fig. 2.3). The RR was significantly higher than 0 for all sub-climates, ranging from 0.13 (obtained under Csc) to 0.71 (obtained under BSk). This means that the use of SCS practices was associated with an increase in SOC stocks under all sub-climates, but to a lesser extent under certain sub-climates (*e.g.*, Cfa, a humid subtropical climate, and Csc, a cold-summer Mediterranean climate) than under others (*e.g.*, BSk, a cold semi-arid climate, and Csa, a hot-summer Mediterranean climate).

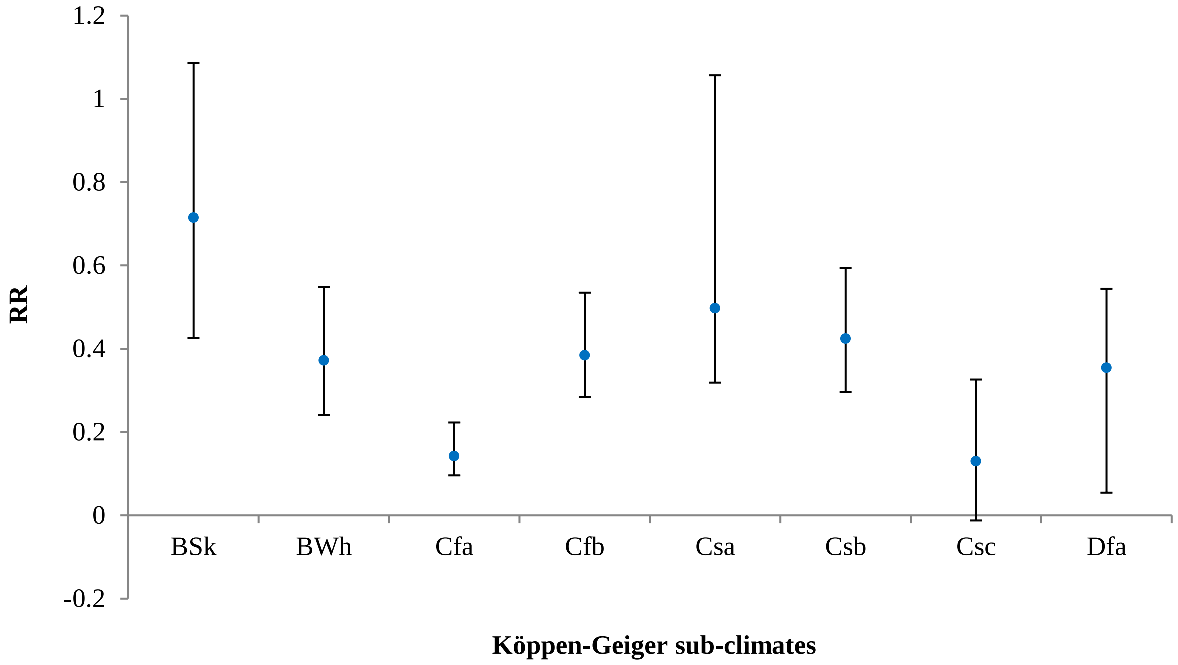


Fig. 2.3. SOC stock response ratio (RR) per Köppen-Geiger sub-climate (BSk, cold semi-arid climate; BWh, hot desert climate; Cfa, humid subtropical climate; Cfb, temperate oceanic climate; Csa, hot-summer Mediterranean climate; Csb, warm-summer Mediterranean climate; Csc, cold-summer Mediterranean climate; Dfa, hot-summer humid continental climate). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

Management duration also affected the change in SOC stocks under SCS management relative to conventional management (Fig. 2.4). The RR was significantly lower for short-term experiments (0.27) than for medium- (0.58) and long-term ones (0.53).

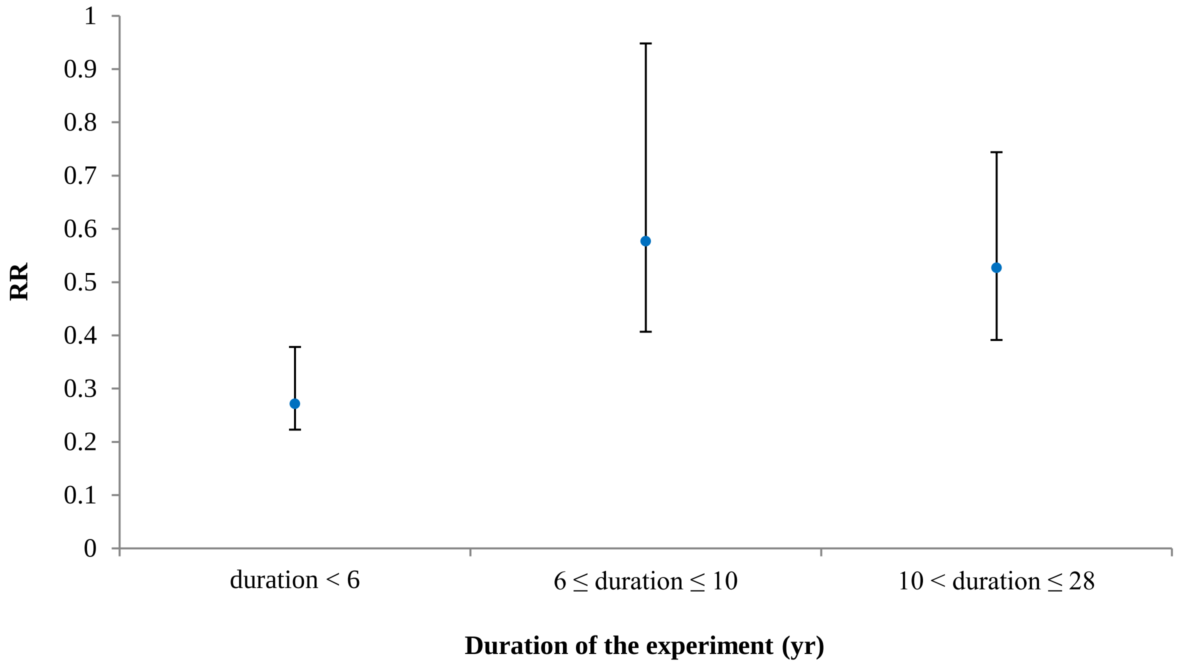


Fig. 2.4. Influence of management duration on the SOC stock response ratio (RR). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

2.4.3. Effects of soil management, climate and study length on the SOC stock rate of change

All SCS management practices were associated with a positive SOC stock change rate relative to conventional management (Fig. 2.5). The R averaged 0.058 yr^{-1} for all SCS practices. This corresponded to an annual SOC stock growth rate of +5.8% yr^{-1} under SCS management. The R ranged from 0.019 to 0.074 yr^{-1} and was significantly higher than 0 for all SCS management practices. The lowest R (+1.9% yr^{-1}) was found under PR, while the highest value (+7.4% yr^{-1}) was observed under OA+NT+CC.

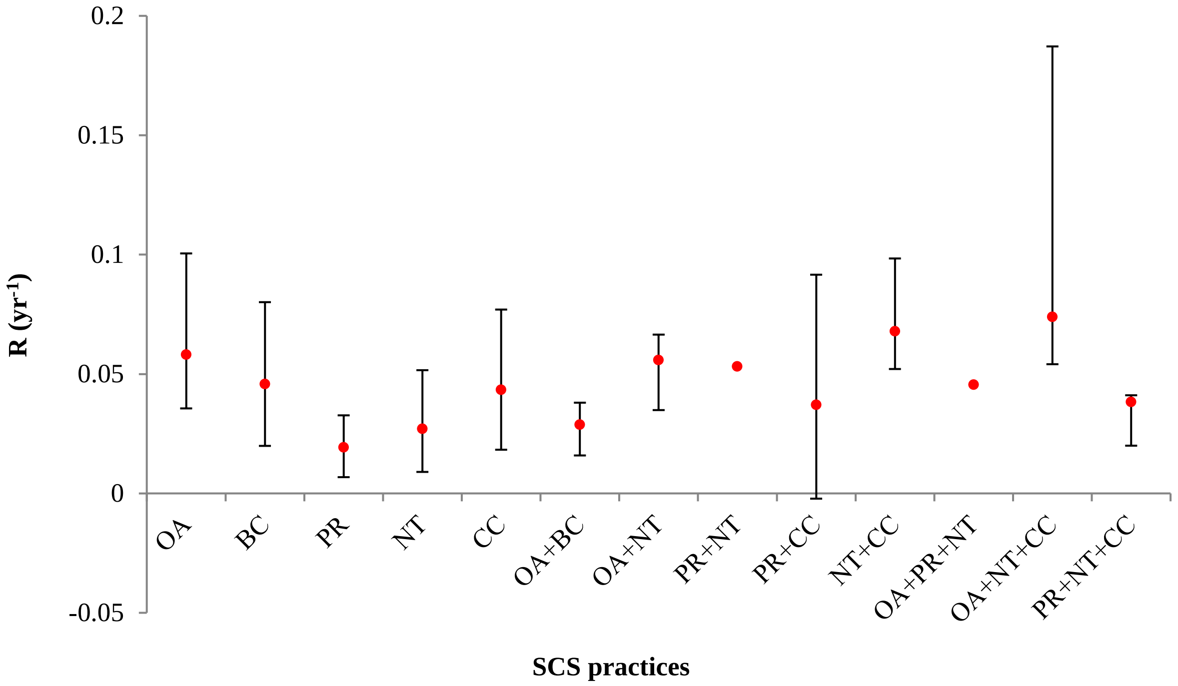


Fig. 2.5. Effects of SCS practices (OA, organic amendments; BC, biochar; PR, pruning residues; NT, no-tillage; and CC, cover cropping) on the SOC stock rate of change (R) to 30-cm depth. PR+NT and OA+PR+NT were not included in the analysis, since only one comparison was observed for these categories. Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

The R varied significantly depending on the sub-climate of the field experiment (Fig. 2.6). The BSk sub-climate was associated with the highest R (0.095 yr^{-1}). On the contrary, the Csc sub-climate was associated with the lowest R (0.021 yr^{-1}).

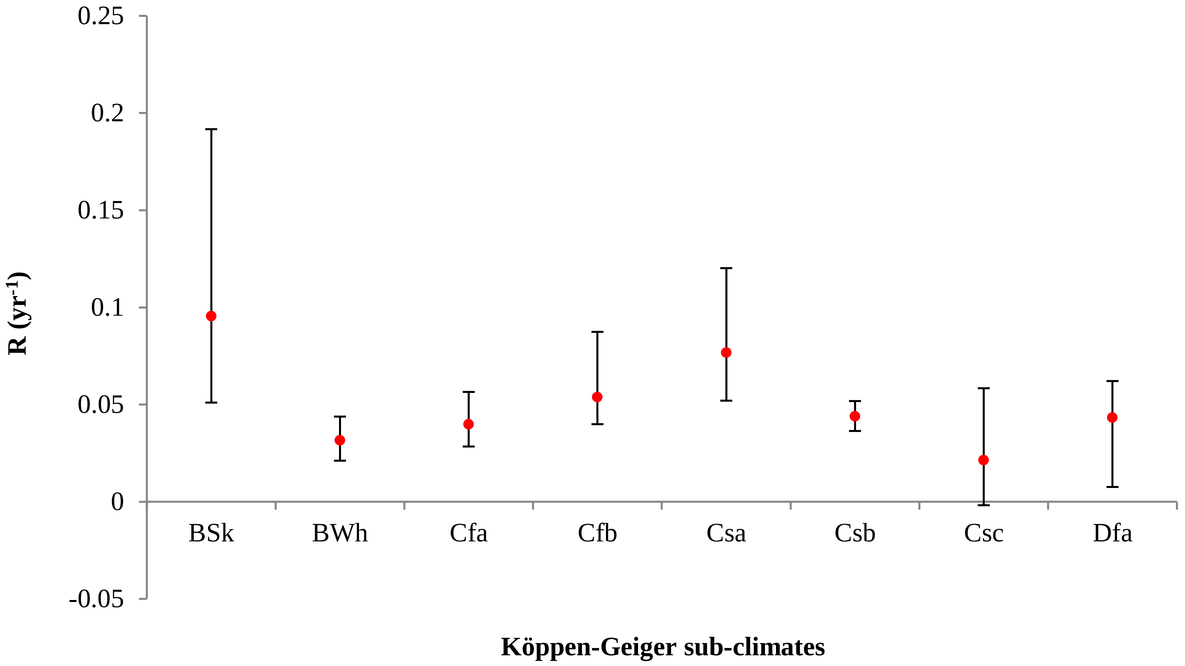


Fig. 2.6. SOC stock rate of change (R) per Köppen-Geiger sub-climate (BSk, cold semi-arid climate; BWh, hot desert climate; Cfa, humid subtropical climate; Cfb, temperate oceanic climate; Csa, hot-summer Mediterranean climate; Csb, warm-summer Mediterranean climate; Csc, cold-summer Mediterranean climate; Dfa, hot-summer humid continental climate). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

The SOC stock change rate differed significantly according to the study length (Fig. 2.7). Short-term comparisons were associated with the highest R (0.064 yr^{-1}), followed closely by medium-term comparisons (0.059 yr^{-1}). Inversely, the R of long-term comparisons (*i.e.* between 10 and 28 years) was low (0.025 yr^{-1}): it was 2.6 and 2.4 times lower than that of short- and medium-term studies, respectively.

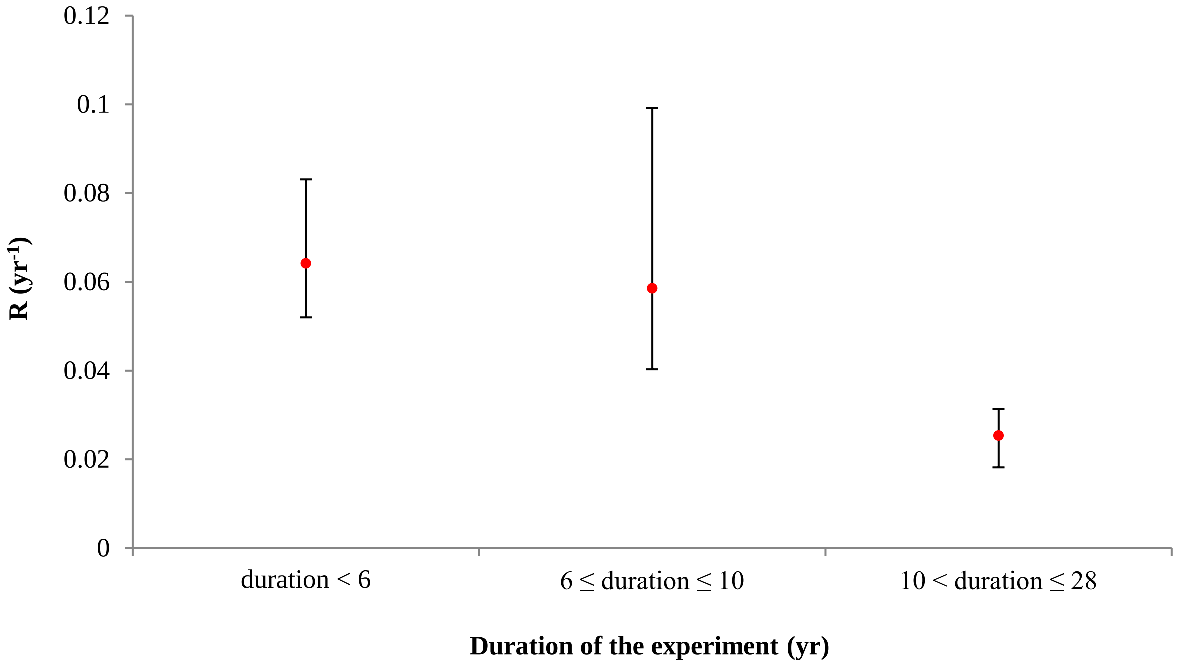


Fig. 2.7. Effects of management duration on the SOC stock rate of change (R). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

2.4.4. Influence of soil management, climate and study length on the SOC sequestration rate

Annual SOC sequestration rates averaged 7.53 Mg CO_2-eq. ha^{-1} yr^{-1} for all SCS management practices, ranging from 2.82 to 11.06 Mg CO_2-eq. ha^{-1} yr^{-1} (Fig. 2.8). The highest value was found under OA+NT. It was 3.9 times higher than the lowest value observed under PR treatments. Across all comparisons, only 3 out of 146 had a negative annual SOC sequestration rate (observed under NT, CC and PR+CC); the annual SOC sequestration rate of all the other comparisons was positive.

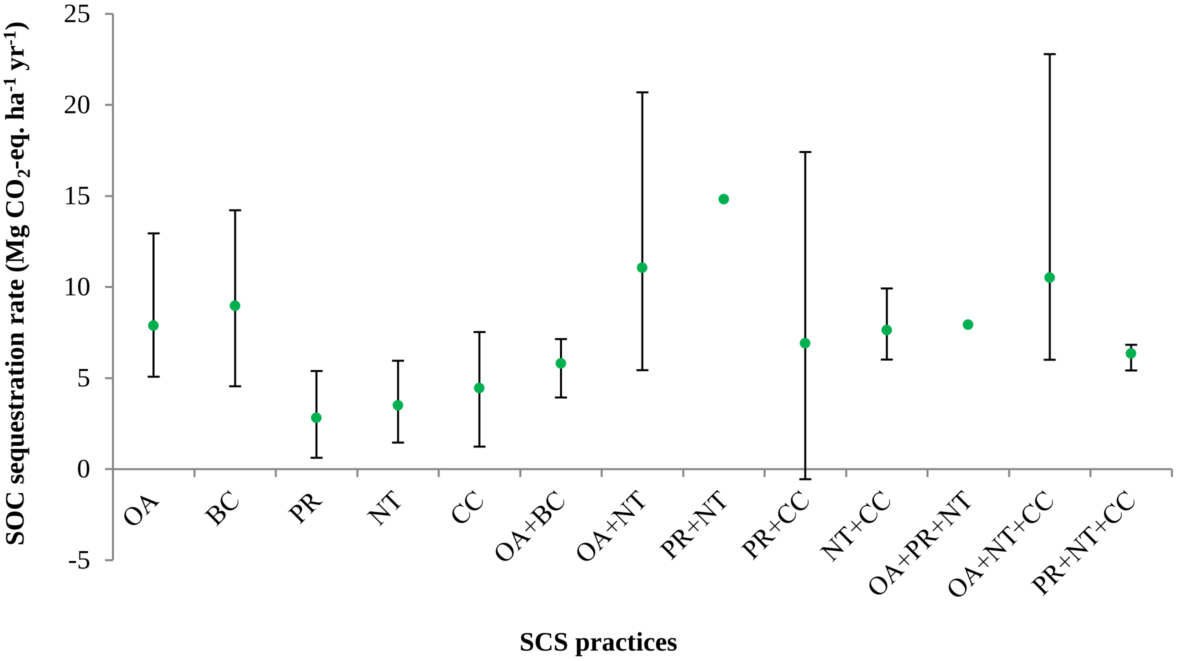


Fig. 2.8. Impacts of SCS practices (OA, organic amendments; BC, biochar; PR, pruning residues; NT, no-tillage; and CC, cover cropping) on the SOC sequestration rate to 30-cm depth. PR+NT and OA+PR+NT were not included in the analysis, since only one comparison was observed for these categories. Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

The SOC sequestration rate varied significantly according to the sub-climates under which field experiments were undertaken (Fig. 2.9). The highest SOC sequestration rate was found under the BSk sub-climate (11.40 Mg CO_2-eq. ha^{-1} yr^{-1}), while the lowest rate was found under the BWh sub-climate (0.79 Mg CO_2-eq. ha^{-1} yr^{-1}), which corresponded to a hot desert climate with low mean annual precipitation.

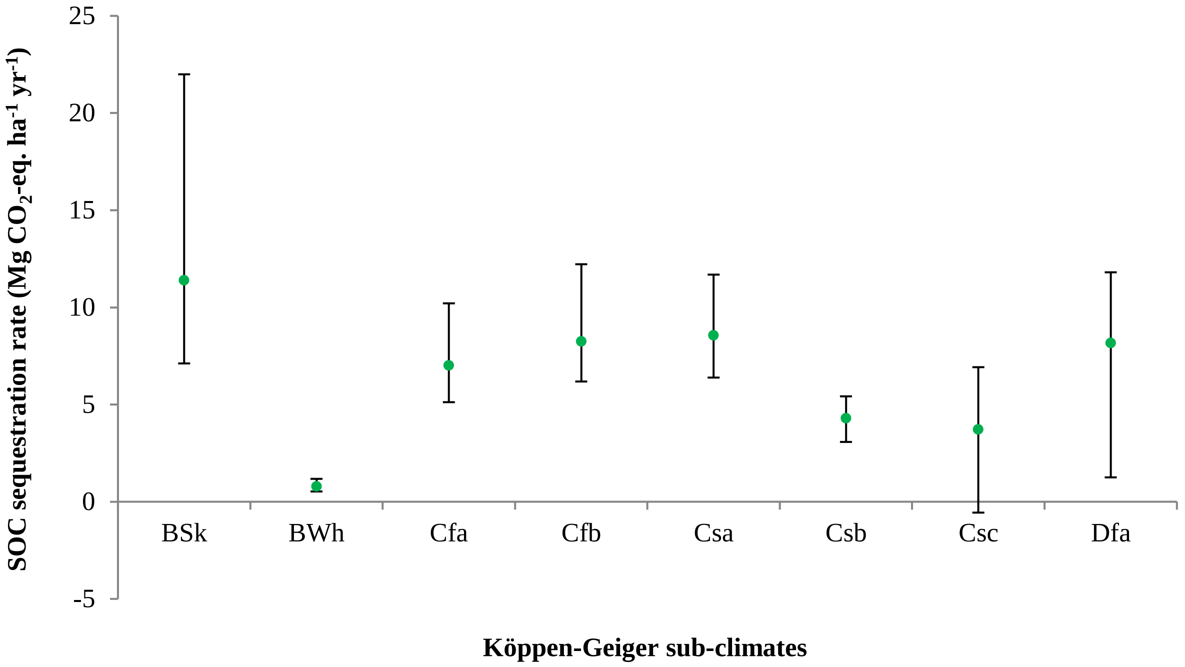


Fig. 2.9. SOC sequestration rate per Köppen-Geiger sub-climate (BSk, cold semi-arid climate; BWh, hot desert climate; Cfa, humid subtropical climate; Cfb, temperate oceanic climate; Csa, hot-summer Mediterranean climate; Csb, warm-summer Mediterranean climate; Csc, cold-summer Mediterranean climate; Dfa, hot-summer humid continental climate). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

The SOC sequestration rate significantly differed depending on the experiment duration, with long-term comparisons being associated with lower SOC sequestration rates than medium- or short-term comparisons (Fig. 2.10). The SOC sequestration rate averaged 8.66 Mg CO_2-eq. ha^{-1} yr^{-1} for short-term studies, 6.95 Mg CO_2-eq. ha^{-1} yr^{-1} for medium-term studies and 3.99 Mg CO_2-eq. ha^{-1} yr^{-1} for long-term studies. It was 25% and 117% higher for short-term studies than for medium- and long-term experiments, respectively.

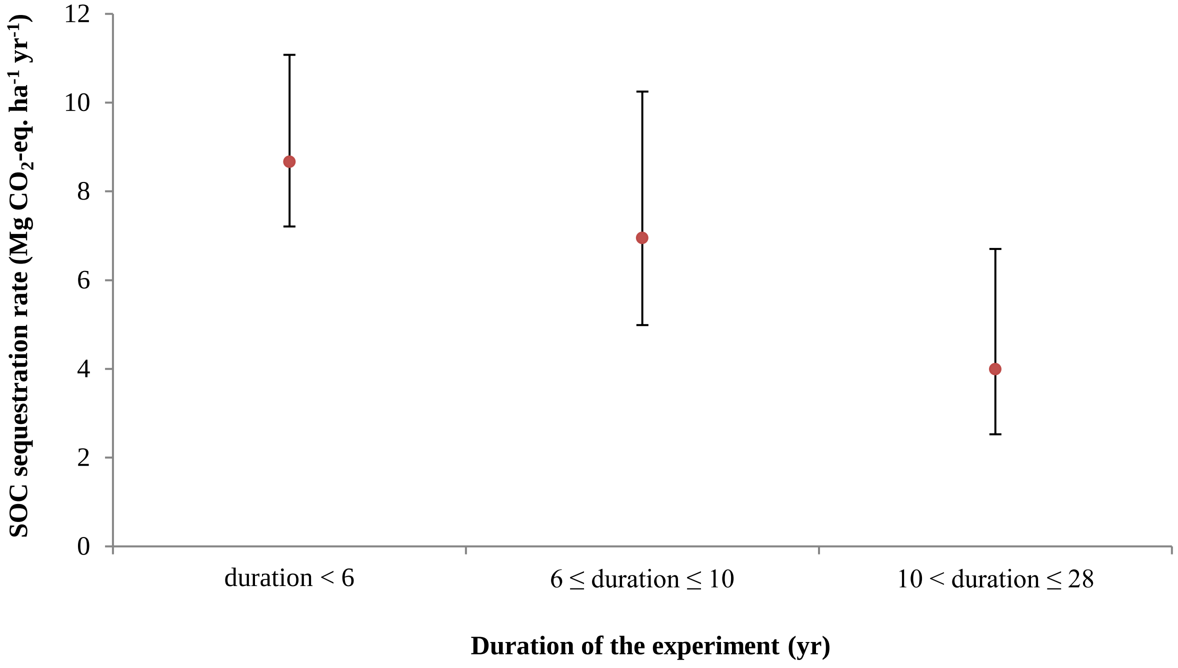


Fig. 2.10. Impacts of management duration on the SOC sequestration rate. Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

2.5. Discussion

2.5.1. Effects of soil management, climate and study length on the change in SOC stocks

2.5.1.1. SCS management practices

SCS management aims to increase SOC stocks in different ways: by increasing OC inputs to the cropping system, by reducing OC losses from the cropping system, or both (Sykes et al., 2020). The type of SCS practices adopted decides which of these options is realised in a given cropping system. The adoption of OA and that of BC both lead to increased OC inputs to the cropping system by increasing the primary productivity of the crop and adding OC produced outside the cropping system to the soil (Sykes et al., 2020). Implementing CC also increases OC inputs to the cropping system through the integration of additional biomass producers within the system. PR and NT both intend to reduce OC losses from the cropping system, the former by minimising the deliberate removal of OC from the system and the latter by reducing soil disturbance, which lessens the atmospheric release of CO_2 from microbial mineralisation (Sykes et al., 2020). OA and CC may also reduce OC losses by minimising the lateral transport of SOC via erosion processes.

The use of OA had a positive effect on the SOC stock, which increased by +44%, with an average SOC sequestration rate of 7.89 Mg CO_2-eq. ha^{-1} yr^{-1}. Vicente-Vicente et al. (2016) also found a positive effect of OA on SOC stocks in vineyards. The value they estimated for the SOC sequestration rate of this practice (2.38 Mg CO_2-eq. ha^{-1} yr^{-1}) was 3.3 times lower than that found in this meta-analysis, which could be due to the small number of comparisons for OA treatments gathered by Vicente-Vicente et al. (2016) in their meta-analysis (n = 8) and to the exclusion of vineyards located in non-Mediterranean regions from their analysis. Mohamad et al. (2016) found a similar SOC sequestration rate to that of this meta-analysis (7.33 Mg CO_2-eq. ha^{-1} yr^{-1}) for the use of OA in olive (*Olea europea* L.) orchards located in southern Italy. Baldi et al. (2018) estimated a slightly higher average SOC sequestration rate in a nectarine (*Prunus persica* L.) orchard under compost amendment in Italy (9.35 Mg CO_2-eq. ha^{-1} yr^{-1}). This shows that the application of OA may have a similar effect on SOC stocks in vineyard systems as in other woody crop systems (such as olive and citrus orchards). However, a net reduction in atmospheric CO_2 using this practice in vineyards would happen only if the added organic amendments were developed specifically for vineyard agroecosystems and were not displaced from another area where they would have otherwise been applied to the soil or if they were diverted from an alternative use that would cause the OC in the amendments to be rapidly lost to the atmosphere, *e.g.*, through burning (Powlson et al., 2011).

The long-term impact of BC on SOC stocks has been proven to be positive in agricultural soils (*e.g.*, Liu et al., 2016; Bai et al., 2019), though neutral or negative effects have also been observed (*e.g.*, Majumder et al., 2019). The effects of BC on SOC stocks are BC-, climate- and soil-specific, which makes the application of this practice in agricultural soils at the global level context-dependent. This meta-analysis showed that the application of BC in vineyards led to an increase in SOC stocks by +18%, with a SOC sequestration rate of 8.96 Mg CO_2-eq. ha^{-1} yr^{-1}. These values were higher than those found by Safaei Khorram et al. (2019) in an apple (*Malus domestica* Borkh.) orchard in Iran, where the use of BC increased SOC stocks by +8% and was associated with a SOC sequestration rate of 4.48 Mg CO_2-eq. ha^{-1} yr^{-1}. Results from this meta-analysis suggest that BC can be used in vineyards as a way to enhance SOC sequestration. The use of BC in viticultural soils may also lead to increased vineyard productivity with no negative impact on grape quality as observed by Genesio et al. (2015), though more comprehensive and long-term evidence is required. However, all the field experiments included in the BC category in this meta-analysis had a short duration (≤ 5 years); further studies with long-term experiments are, thus, needed to improve our knowledge of the effect of BC on SOC stocks in vineyards in the long term.

The SOC sequestration rate obtained under PR (2.82 Mg CO_2-eq. ha^{-1} yr^{-1}) was the smallest among all SCS practices. Though small, it was nevertheless significantly positive, suggesting that the practice led to an accumulation of SOC relative to conventional management. The use of PR is particularly relevant in winegrowing regions where the removal of pruning residues for burning is quite common and results in residue-removal-induced SOC losses, *e.g.*, in Burgundy and Beaujolais in France (Agreste, 2017). In these winegrowing regions, incorporating the pruning residues into the soil is likely to increase SOC stocks (Wang et al., 2015) since crop residues are precursors for SOM, which constitutes the main store of OC in the soil (Smith et al., 2008). The use of this practice may also be associated with an increase in crop yield (García-Orenes et al., 2016) while maintaining wine quality (Morlat and Chaussod, 2008).

The introduction of NT practices in agricultural systems may have many benefits for sustainable soil management, including reducing soil erosion, improving soil structure and enhancing soil moisture (Derpsch et al., 2010). Adopting NT management may also increase SOC stocks (Ogle et al., 2019), as NT helps to preserve soil aggregates, physically protecting SOC from mineralisation (Merante et al., 2017). Nevertheless, the adoption of NT is not universally applicable for increasing SOC stocks; its effects on SOC stocks are context-specific and depend on climate and soil characteristics (Ogle et al., 2019). This meta-analysis indicated that, in the case of viticultural soils, the use of NT led to an average positive change in SOC stocks by +20%, resulting in a SOC sequestration rate of 3.50 Mg CO_2-eq. ha^{-1} yr^{-1}. In comparison, Morugán-Coronado et al. (2020) reported a higher SOC sequestration rate (5.13 Mg CO_2-eq. ha^{-1} yr^{-1}) under NT management in Mediterranean fruit orchards (including vineyards and almond, olive and citrus orchards). This confirms the positive effect of NT on SOC stocks in vineyards as well as in other woody crop systems. These results, which were based on field experiments with varying climates and different soil types, helped to reduce the large uncertainties associated with the use of NT in agricultural soils (Ogle et al., 2019).

The use of CC in viticultural soils resulted in an increase in SOC stocks by +22%, with a SOC sequestration rate of 4.45 Mg CO_2-eq. ha^{-1} yr^{-1}. Comparatively, Vicente-Vicente et al. (2016) calculated a SOC sequestration rate of 2.86 Mg CO_2-eq. ha^{-1} yr^{-1} in Mediterranean vineyards under CC. Winter et al. (2018) also reported a positive change in SOC stocks in viticultural soils under CC relative to conventional management. These results confirm the positive effect of CC on SOC stocks in viticultural soils observed by previous studies. Besides, Pardo et al. (2017) reported that the use of CC in orchards located in Spanish Mediterranean coastal areas (including citrus trees, fruit trees, olive groves and vineyards) resulted in a SOC sequestration rate of 1.61 Mg CO_2-eq. ha^{-1} yr^{-1}. Morugán-Coronado et al. (2020) found a SOC sequestration rate of 2.64 Mg CO_2-eq. ha^{-1} yr^{-1} in Mediterranean fruit orchards under CC. Vicente-Vicente et al. (2016) estimated that CC in Mediterranean olive and almond orchards was associated with a SOC sequestration rate of 4.03 and 7.48 Mg CO_2-eq. ha^{-1} yr^{-1}, respectively. The SOC sequestration rate found in this chapter aligns with the broad range of values reported by the literature on woody crop systems. These variations in SOC sequestration rates could be due to differences in the area covered by the cover crop, which may lead to differing amounts of above- and belowground biomass between woody crop systems.

Combinations of SCS practices increased SOC stocks relative to conventional management and were associated with higher SOC sequestration rates than single SCS practices. The combination of SCS practices with the strongest change in SOC stocks (+60%) was OA+NT, with a SOC sequestration rate of 11.06 Mg CO_2-eq. ha^{-1} yr^{-1}, which was 1.4 and 3.2 times higher than that of OA and NT used as single practices, respectively. A slightly lower change in SOC stocks was found under OA+NT+CC (by +41%, for a SOC sequestration rate of 10.51 Mg CO_2-eq. ha^{-1} yr^{-1}). These values were higher than those observed in fruit tree orchards put under similar combined management practices. In a peach (*Prunus persica* L.) orchard under a Mediterranean climate, the use of OA+NT+CC increased SOC stocks by +19% and was associated with a SOC sequestration rate of 3.15 Mg CO_2-eq. ha^{-1} yr^{-1} (Montanaro et al., 2017), which was more than 3 times lower than that observed in vineyards in this chapter. This suggests that OA+NT+CC is a recommended SCS management option in viticultural agroecosystems, where it may have the potential to increase SOC stocks even more than in other woody cropping systems (*e.g.*, peach orchards).

Combined SCS practices without the use of external organic amendments had a lower positive impact on SOC stocks than OA+NT and OA+NT+CC (+48% for NT+CC and +23% for PR+NT+CC) and were associated with lower SOC sequestration rates (7.63 Mg CO_2-eq. ha^{-1} yr^{-1} for NT+CC and 6.35 Mg CO_2-eq. ha^{-1} yr^{-1} for PR+NT+CC). Though lower, the SOC sequestration rates of these combined practices rely only on carbon inputs produced within the vineyard system and are not subject to the availability of organic amendments. Moreover, in the case of NT+CC, the SOC sequestration rate was 1.7 times higher than that of CC used with conventional tillage. This shows the importance of tillage with regards to OC accumulation in the soil: under a combination of NT+CC, the cover crop residues are left on the soil surface, which leads to slower incorporation and decomposition of OM than when the residues are mechanically incorporated into the soil by tillage and to an overall higher accumulation of SOC in the upper soil layers (Reicosky et al., 1995). In contrast, however, conversion from conventional tillage to NT may result in a decline in SOC stocks at deeper depths and modify the distribution of SOC in the soil profile (Luo et al., 2010).

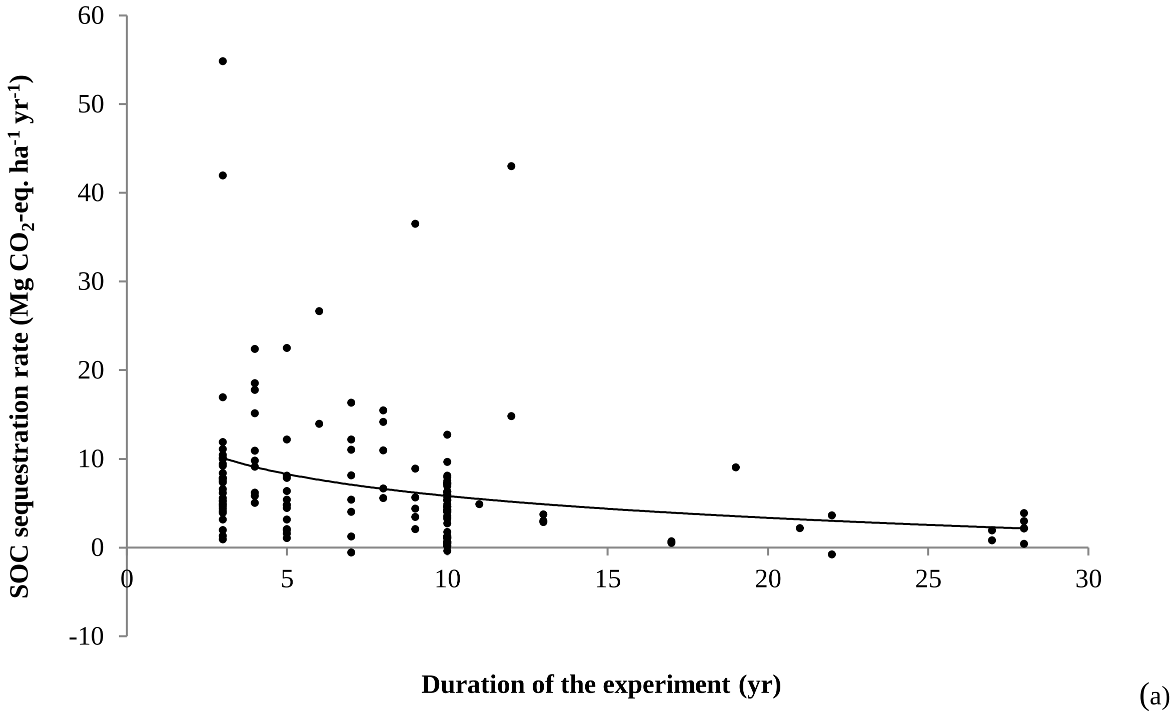
2.5.1.2. Köppen-Geiger sub-climates

The comparison of SOC stock responses to SCS management under different climates showed that the BWh sub-climate was associated with the lowest SOC sequestration rate (averaging 0.79 Mg CO_2-eq. ha^{-1} yr^{-1}) among all sub-climates. Vicente-Vicente et al. (2016) also observed, in their meta-analysis, that the SOC sequestration rate of CC treatments in woody croplands (including vineyards, and olive and almond orchards) under the BWh sub-climate was lower than those under temperate climates, with values averaging 1.43 Mg CO_2-eq. ha^{-1} yr^{-1} for BWh, while Cfb, Csb and Csa were associated with SOC sequestration rates of 4.33, 4.47 and 4.66 Mg CO_2-eq. ha^{-1} yr^{-1}, respectively. The authors attributed the lower SOC sequestration rate measured under the BWh sub-climate to low net primary crop productivity caused by the water limitations and physical and chemical constraints to carbon accumulation found in hot and dry locations (Post et al., 1996). Water limitations may explain the differences in SOC stock change observed between BSk and BWh treatments, with the SOC sequestration rate of BWh, a hot desert climate with low mean annual precipitation, being significantly lower than that of BSk, a cold semi-arid climate which is wetter than BWh.

Results suggested that SCS management was particularly effective at sequestering OC in vineyards located in cold semi-arid winegrowing regions (*e.g.*, in the Western Cape Province in South Africa), where it was associated with a SOC sequestration rate of 11.40 Mg CO_2-eq. ha^{-1} yr^{-1}. In comparison, the effects of SCS management on SOC stocks were lower in vineyards located in temperate winegrowing regions without a dry season in summer (Cf-type sub-climates, found for instance in the French Loire Valley or Mosel, Germany) and with a dry season in summer (Cs-type sub-climates, found for example in Sicily, Italy or Setúbal, Portugal), where SOC sequestration rates averaged 7.98 (n = 58) and 7.22 (n = 54) Mg CO_2-eq. ha^{-1} yr^{-1}, respectively. These findings could serve to inform policymaking relating to the adoption of SCS practices in vineyards based on bioclimatic zones.

2.5.1.3. Study length

The analysis of the impacts of study length on SOC stock change showed that short-term experiments were associated with a SOC sequestration rate 1.2 and 2.2 times higher than that of medium- and long-term experiments, respectively. The same trend was observed for the SOC stock rate of change, whose value for short-term studies was 1.1 and 2.6 times higher than that for medium- and long-term ones, respectively. Plotting the SOC sequestration rate (a) and the SOC stock rate of change (b) against the study length highlighted a negative correlation between the variables, with the SOC sequestration rate and the SOC stock rate of change decreasing as the study length increases (Fig. 2.11). It aligns with the observations of Francaviglia et al. (2019), who also found a negative correlation between the SOC stock rate of change and the duration of SOC sequestration in woody perennial crops under Mediterranean climates. This negative relationship can be due to the specific pattern that the change in SOC stocks follows after the implementation of a SCS practice: the SOC stock, if in equilibrium, increases quickly after new soil management is implemented and progressively declines thereafter until a new equilibrium in the soil is reached (Smith, 2014). According to the IPCC (2006) guidelines, it is considered that most of the change in SOC stocks happens over the 20 years following the adoption of new soil management, though soil equilibrium may take a century to reach (Poeplau and Don, 2015). Thus, studies taking place in the short term only capture the early stage of the SOC response to a change in soil management, *i.e.* when the SOC stock increases rapidly, which leads to overly high SOC sequestration rates calculated. The studies gathered in this study mainly had a short- (< 6 years) or medium-term (between 6 and 10 years) experiment length (n = 127) and were not long enough to approach SOC stock equilibrium. Results found in this meta-analysis are valid for a period of 10 years following the adoption of SCS management and, to avoid overestimating SOC sequestration rates in the viticulture sector, should not be generalised to the long term.



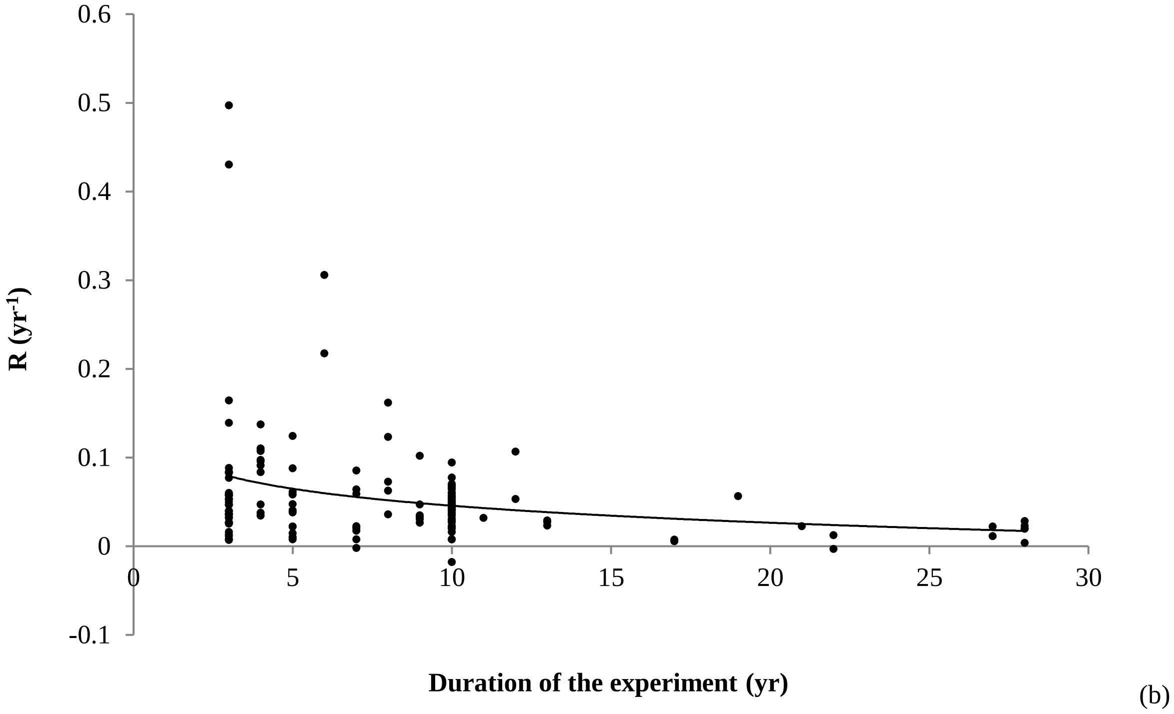


Fig. 2.11. Variation of the SOC sequestration rate (a) and R (b) according to the duration of the experiment.

In addition, changes in SOC stocks must be observed over large temporal scales since the inter-annual variability of climatic factors (*e.g.*, inter-annual or seasonal temperature and precipitation patterns) have large effects on C cycling (Chou et al., 2008). Long-term studies are more reliable than short- or medium-term studies to estimate SOC stock change, but they are rarer in the case of vineyards. Despite the growing number of field experiments in vineyards published over the past two decades, most studies with an experiment length of 10 years or longer were published before 2012. This highlights the need for more long-term experiments in vineyards to be undertaken and published. However, because SOC sequestration has a finite potential and is non-permanent, it is a riskier long-term strategy for climate change mitigation than direct GHG emission reduction (Smith, 2004a). Actions to reduce GHG emissions in the wine sector must, therefore, accompany efforts to increase SOC sequestration in viticultural soils.

2.5.2. Implications of findings regarding the carbon footprint of viticulture and the ‘4 per 1000’ initiative

Overall, the SOC sequestration rates estimated in this meta-analysis averaged 7.53 Mg CO_2-eq. ha^{-1} yr^{-1} for all SCS practices. This suggests that the use of SCS management is an effective way to sequester OC in viticultural soils, particularly for a crop that is commonly cultivated under low input conditions. This value can be compared to area-based life-cycle GHG emissions in vineyard systems: Aguilera et al. (2015) estimated that 0.96 Mg CO_2-eq. ha^{-1} yr^{-1} was emitted in conventional vineyards in Spain (including direct emissions and inputs production); Ponstein et al. (2019) estimated GHG emissions from conventional wine grape production in Germany to reach, on average, 1.70 Mg CO_2-eq. ha^{-1} yr^{-1} (including direct emissions and inputs production); Litskas et al. (2017) estimated emissions from conventional vineyards in Cyprus to be 3.37 Mg CO_2-eq. ha^{-1} yr^{-1} (taking into account different types of grapevine variety and their varying input requirements). These values, which are considerably smaller than the average SOC sequestration rate calculated in this chapter, indicate that the introduction of SCS practices in vineyards could offset GHG emissions from viticultural activities. Assuming that area-based life-cycle GHG emissions from vineyard systems are unchanged under SCS management, the use of SCS practices may result in an average GHG emission balance of –6.57 Mg CO_2-eq. ha^{-1} yr^{-1} in Spanish vineyards (ranging from –1.86 under PR to –10.10 Mg CO_2-eq. ha^{-1} yr^{-1} under OA+NT), of –5.83 Mg CO_2-eq. ha^{-1} yr^{-1} in German vineyards (ranging from –1.12 under PR to –9.36 Mg

CO_2-eq. ha^{-1} yr^{-1} under OA+NT), and of –4.16 Mg CO_2-eq. ha^{-1} yr^{-1} in Cypriot vineyards (ranging from 0.55 under PR to –7.69 Mg CO_2-eq. ha^{-1} yr^{-1} under OA+NT). This is in line with the results from Bosco et al. (2013) and Chiriacò et al. (2019), who also estimated a negative GHG emission balance in vineyards under SCS management, though it is considerably higher than the GHG emission balance of –0.03 Mg CO_2-eq. ha^{-1} yr^{-1} estimated by Chiriacò et al. (2019) in Italian vineyards under PR+NT+CC.

However, these values do not consider the possible variations in GHG emissions induced by a change in soil management. Previous studies (*e.g.*, Rochette et al., 2008; Lugato et al., 2018) reported increased N_2O emissions associated with positive changes in SOC stocks. The use of NT, for instance, can lead to higher N_2O emissions under SCS management than under conventional management (Rochette et al., 2008), though not always (He et al., 2019). Further research on GHG emissions associated with the use of SCS practices would be necessary to better estimate the GHG emission balance in viticultural soils under SCS management. These values also only take into account GHG emissions from the viticultural phase of wine production and not that of the whole production of a bottle of wine. The viticultural phase represents about 30% of the product carbon footprint for wine, with values ranging from 19% in Germany (Ponstein et al., 2019) and 25% in Nova Scotia, Canada (Point et al., 2012) to 40% in Italy (Vázquez-Rowe et al., 2013). This suggests that SOC sequestration would not suffice to offset the totality of GHG emissions resulting from wine production. Further actions should, thus, be implemented to reduce GHG emissions in the wine sector, such as switching to light-weighted glass bottles, implementing energy efficiency measures at the vineyard and winery level, and reducing the carbon footprint associated with the transportation of bottled wine (CSWA, 2011).

Furthermore, this study provided the SOC stock rate of change of different SCS management practices in viticultural soils (Fig. 2.5). The average SOC stock rate of change for all SCS practices was +5.8% yr^{-1} to a 30-cm soil depth, which was much higher than the ‘4 per 1000’ target of increasing SOC stocks by +0.4% annually to a 40-cm soil depth. It suggests that vineyards could play an important role in meeting the annual target of the initiative, especially in countries with large viticultural land, such as Spain or France. Reaching the ‘4 per 1000’ objective in France would require a SOC sequestration rate of 14.4 Tg C yr^{-1} (*i.e.* 52.8 Tg CO_2-eq. yr^{-1}) in the 0-30 cm soil layer (Minasny et al., 2017). Considering that there are 0.793 Mha dedicated to viticulture in France (OIV, 2019), the use of SCS management in all French vineyards could potentially sequester 5.97 Tg CO_2-eq. yr^{-1} on average in the 0-30 cm soil layer (with values ranging from 2.24 under PR to 8.77 Tg CO_2-eq. yr^{-1} under OA+NT). This means that French viticultural soils may sequester 11% of the total amount of carbon needed to reach the target of the initiative at the national level annually (or between 4 and 17% depending on the SCS practices considered). However, the feasibility of this SOC sequestration in French viticultural soils depends on the initial SOC stocks in vineyards, as soils with an already high SOC stock might not store much more carbon, while it might be hard to increase SOC stocks in soils with low OC due to climatic or management constraints (Minasny et al., 2017).

2.5.3. Gaps and uncertainty

The high representation of Spain, Italy and France in the studies collected occurred as these countries have a large area dedicated to viticulture: 0.969 Mha for Spain, 0.705 Mha for Italy and 0.793 Mha for France in 2018 (OIV, 2019). Together, these three countries represent 33% of the global land area dedicated to viticulture and are all in the top five countries by viticultural land. However, no experiment taking place in China was found in the literature search, even though China’s area dedicated to viticulture is the second biggest in the world with 0.875 Mha in 2018 (OIV, 2019). This could be explained by the fact that grape cultivation has expanded in China only recently, growing from 10,000 ha in the 1960s (FAO, 2019) to 875,000 ha in 2018 (OIV, 2019), and is mainly dedicated to the production of table (84.1%) and dried (5.6%) grapes (OIV, 2019). Turkey, whose area under vines is the fifth in the world with 0.448 Mha in 2018 (OIV, 2019), was also underrepresented in the meta-analysis with a single study taking place in the country. The other countries (the USA, South Africa, Australia and Germany), by comparison, have a smaller land area dedicated to viticulture (< 0.450 Mha), which is coherent with the number of studies found for these countries.

Other gaps have been identified relating to the SCS practices and bioclimatic zones included in the meta-analysis. Though several SCS practices applicable to viticulture were analysed, not all of them were covered in this study (*e.g.*, using contour hedges, optimising soil pH and water management were missing), which underlines the need for further research about SCS practices in viticultural soils to be undertaken. In addition, the sub-climates included in the study were consistent with the climatic distribution of vineyards at the global level: most vineyards producing high-quality wine are located in regions where the average temperature during the growing season (*i.e.* between April and October in the Northern Hemisphere and between October and April in the Southern Hemisphere) is between 13 and 21 °C (Jones, 2006). However, other sub-climates under which viticulture is also found were missing (*e.g.,* BSh in Pantelleria, Italy or Dfb in Styria, Austria).

Some sources of uncertainty in this study were due to the fact that the methodology used an approach based on fixed depth to calculate SOC stocks. Bulk density, which was used with SOC concentration and sampling depth to estimate SOC stocks, was only provided in a few studies (30%). Pedotransfer functions (Equations (2) and (3)) were, thus, used to estimate this parameter from the SOC concentration reported in the studies. However, there is high uncertainty in the prediction of bulk density using these functions since specific management practices may affect differently bulk density within a given land use, according to the IPCC (2019) guidelines. Efthimiadou et al. (2010) proved that the use of OA generally decreases the bulk density, while reducing tillage is usually associated with a positive change in bulk density (Hernanz et al., 2009). The uncertainty related to the effect of bulk density changes on SOC stock estimation may lead to an overestimation or an underestimation of the SOC stock in the experiment (IPCC, 2019). A more accurate way to estimate SOC stocks would be to use a soil-mass equivalent approach instead of a soil-volume equivalent approach, as recommended by the IPCC (2019) guidelines. Unfortunately, most studies gathered in this meta-analysis did not provide the necessary information required to use a soil-mass equivalent approach (*i.e.* dry sample mass, area sampled by the probe or auger, etc.).

In addition, the average sampling depth in field experiments was 0.31 m. This value is in line with the IPCC (2006) guidelines, which recommend the sampling of the top 0.3 m of soil to estimate changes in SOC stocks under new soil management. However, a number of studies included in the meta-analysis showed that changes in SOC stocks occurred deeper than 30 cm (*e.g.,* Peregrina et al., 2014) and, in some cases, deeper than 60 cm (*e.g.,* Agnelli et al., 2014). Field experiments reporting shallower depths (< 30 cm) tended to underestimate the SOC sequestration potential by overlooking changes in SOC stocks in deeper soil layers. Luo et al. (2010) also showed that the adoption of NT may provoke a redistribution of SOC in the soil profile, with increases in SOC stocks in surface layers and decreases in SOC stocks in deeper layers. Focusing only on the top 0.3-m soil layer may have led to an overestimation of OC sequestration in viticultural soils under NT since potential net losses occurring in deeper soil layers were not accounted for in SOC stock change calculations.

2.6. Conclusions

This research could serve to inform policymaking with regards to climate change mitigation in the viticulture sector by estimating potential SOC sequestration rates in 0-30 cm depth that could be obtained in viticultural soils following the adoption of SCS practices. Findings indicated that the use of SCS practices may increase SOC stocks in viticultural soils, with an average SOC sequestration rate of 7.53 Mg CO_2-eq. ha^{-1} yr^{-1} to 30-cm depth for all SCS practices relative to conventional management. The increase in SOC stocks was the highest under a combination of OA+NT, which was associated with a SOC sequestration rate of 11.06 Mg CO_2-eq. ha^{-1} yr^{-1}. This combination of SCS practices may, therefore, be a suitable management option for increasing SOC sequestration in vineyards. The lowest SOC sequestration rate for 0-30 cm depth was found under PR (2.82 Mg CO_2-eq. ha^{-1} yr^{-1}). However, even though the change in SOC stock associated with this practice was low, it was positive and non-negligible. This suggests that vineyards can play a crucial role in the global efforts to enhance SOC sequestration in agricultural land to mitigate climate change, even though their global land area is not as extensive as that of grasslands or annual croplands.

This study also showed that the adoption of SCS practices in vineyards may offset GHG emissions from viticultural activities and contribute to reducing the carbon footprint of the wine sector at the global level. Findings from this study indicated that the use of SCS practices in vineyard agroecosystems may help to achieve the target of the ‘4 per 1000’ initiative, particularly in regions with large viticultural land, as SCS management may be associated with an increase of +5.8% yr^{-1} in SOC stocks in viticultural soils to a 30-cm soil depth. More exhaustive field experiments providing measurements of all necessary data to calculate changes in SOC stocks and GHG fluxes in vineyards under SCS management are needed, however, to improve the accuracy of these findings. Further research is also needed to quantify the change in SOC stocks in vineyards under SCS management using modelling approaches to complement the findings from this meta-analysis. Mechanistic models (*e.g.*, RothC) or machine-learning models (*e.g.*, random forest regressions) could be used to project changes in SOC stocks in vineyards over longer timeframes and investigate how these changes differ in the long term between vineyards under SCS and conventional management. Modelling could also be conducted at the regional level to investigate the variations of SOC stock response under SCS management according to the differences in climate, soil texture, initial SOC stocks, etc. between and within winegrowing regions. By using such models, changes in GHG emissions under SCS management relative to conventional management could also be estimated, which would allow for the mitigation potential of SCS practices in viticultural soils to be calculated (and not only their SOC sequestration potential).

Chapter 3

Predicting the abatement rates of soil organic carbon sequestration management in Western European vineyards using random forest regression

3.1. Abstract

The implementation of SCS practices on agricultural land has the potential to help to mitigate climate change at the global level. However, our understanding of the extent to which viticultural soils can contribute to this global effort remains limited. In this study, a random forest regression was used to predict the change in SOC stocks in vineyards of Western Europe under five SCS practices: OA, CC, OA+NT, NT+CC and OA+NT+CC. The abatement rate of each SCS practice was modelled and mapped for six countries in Western Europe: Spain, France, Italy, Portugal, Germany and Austria. Overall, the highest abatement rate was reached under OA+NT+CC (8.29 Mg CO_2-eq. ha^{-1} yr^{-1}), whereas the lowest was observed under CC (7.03 Mg CO_2-eq. ha^{-1} yr^{-1}). Results showed major differences in abatement rates at the regional and national levels. Despite these differences, the adoption of SCS practices was associated with a high abatement potential in the six countries and should be encouraged in the viticulture sector as a way to offset GHG emissions via SOC sequestration.

3.2. Introduction

Soil carbon sequestration in agricultural soils has the potential to contribute substantially to mitigating climate change, provided that specific changes in soil management are implemented (Smith, 2016). SOC is the largest pool of OC in terrestrial ecosystems, containing globally over 1,500 Pg C in the upper one-meter layer of soil, which is more than the carbon stock in the above-ground vegetation and the atmosphere combined (FAO and ITPS, 2015). About 45% of global soils are used for agriculture, either in the form of cropland or grassland (Paustian et al., 2019); changes in SOC content in these soils can, therefore, have profound impacts on climate change mitigation. The mitigation potential of SCS practices (including biochar) was estimated to range from 4 to 6 Pg CO_2-eq. yr^{-1} at the global level (Smith, 2016). Paustian et al. (2016) suggested that the maximum mitigation potential of SCS practices could even be as high as 8 Pg CO_2-eq. yr^{-1}, while in a more recent review of the literature Fuss et al. (2018) showed that it would more likely be 7 Pg CO_2-eq. yr^{-1}. For comparison, UNEP (2018) estimated total anthropogenic emissions to be 53.5 Pg CO_2-eq. yr^{-1} in 2017. This indicates that soil carbon sequestration in agricultural soils could offset up to 13% of global greenhouse gas emissions annually.

Despite the widespread comprehension of SCS practices in the agriculture sector (Sykes et al., 2020), information about soil carbon sequestration in vineyard agroecosystems remains sparse. Yet, changes in soil management practices have an important potential to increase SOC sequestration in viticultural soils. Results of Chapter 2 showed that the SOC sequestration rate of SCS practices in vineyards could be as high as 11.06 Mg CO_2-eq. ha^{-1} yr^{-1} for a combination of organic amendments and no-tillage. This high SOC sequestration rate could be due to the particularly low OC levels in vineyards under conventional management (Eldon and Gershenson, 2015). Enhancing SOC sequestration in vineyard agroecosystems, thus, represents a promising strategy for mitigating climate change in countries with an important land area dedicated to viticulture. SOC sequestration in viticultural soils could, more precisely, play an important role in greenhouse gas offsetting at the regional level, in areas where viticulture represents a substantial share of the agricultural land use. This is the case for the Languedoc-Roussillon region in France, for instance, where viticulture represents 26% (*i.e.* 233,069 ha) of the regional total agricultural land (*i.e.* 882,995 ha) and grapevine is the most cultivated crop, with 62% of the agricultural farms in the region growing grapevine (Agreste Languedoc-Roussillon, 2015).

Since the equilibration of SOC after a change in management takes several decades, a deeper understanding of the expected changes in SOC stocks associated with SCS practices is needed if these practices are to be implemented as long-term strategies to mitigate climate change. Many tools have been developed to predict the changes in SOC stocks under diverse soil management in various agroecosystems. Process-based models, including RothC (Coleman and Jenkinson, 1996), ECOSSE (Smith et al., 2010) and DALEC (Bloom and Williams, 2015), have been developed and run to project changes in SOC over different timeframes for different soil management. These models have the advantage to overcome the issues associated with costly and extensive field experiments (Francaviglia et al., 2012). Statistical techniques, such as linear mixed models (Doetterl et al., 2013), partial least square regressions (Amare et al., 2013) and multiple linear regressions (Meersmans et al., 2008), have also been applied to estimate and map SOC stocks. More recently, new methods from the machine learning field have been adapted to the context of SOC stock prediction. They include random forest regressions (Grimm et al., 2008), support vector machines (Viscarra Rossel and Behrens, 2010) and artificial neural networks (Aitkenhead and Coull, 2016). Machine-learning approaches bear the advantage of overcoming flaws of parametric and nonparametric statistical methods, such as overfitting, non-linearity and autocorrelation (Drake et al., 2006), which improves the prediction accuracy of spatial models (Were et al., 2015).

There have been few attempts at modelling changes in SOC stocks under SCS management in vineyard agroecosystems. Bleuler et al. (2017) applied the RothC model to predict the effects of SCS management on SOC stocks under different crop types, including vines. However, their analysis only considered two SCS practices (compost addition and cover cropping), while other SCS practices applicable to viticulture (such as returning pruning residues to the soil, implementing no-tillage, and applying biochar amendments to the soil) were not considered in the study. Their study area was also limited to the Foggia province in southern Italy. Similarly, other modelling studies including viticultural soils only took into account a few SCS practices (*e.g.*, no-tillage coupled with cover cropping in Francaviglia et al., 2012, or compost amendment in Mondini et al., 2012) and were limited to very specific regions within wine-producing countries (*e.g.*, to the north-east of Sardinia, Italy in Francaviglia et al., 2012, or Spain’s Mediterranean coastal areas in Pardo et al., 2017).

There is a need to extend the modelling of SOC change under SCS management in vineyards to all the SCS practices applicable to vineyard agroecosystems and to all the different types of climates where viticulture is conducted. The aim of this chapter is (i) to develop a model based on a machine-learning approach to estimate the annual change in SOC stocks in vineyards under SCS management relative to conventional practices and (ii) to predict the annual change in SOC stocks in vineyards for a set of specific SCS practices and map the results for the winegrowing regions of six European countries (Spain, France, Italy, Portugal, Germany and Austria) representative of viticulture in Western Europe. Machine learning was chosen over mechanistic modelling as a way to further the use of the dataset created in Chapter 2, which provided comprehensive empirical data on changes in SOC stocks specifically in vineyards under SCS management. Using a machine learning approach allows for unseen patterns existing in the data to be easily extracted in an inductive process (Baker et al., 2018). The results from this machine learning modelling can be combined, in a synergetic way, with the results obtained using mechanistic models in previous studies (*e.g.*, Bleuler et al., 2017; Francaviglia et al., 2012; Mondini et al., 2012; Pardo et al., 2017) to create an exhaustive picture of how SOC stocks in vineyards change with time under SCS management.

The chapter is structured as follows. Section 3.3 covers materials and methods. It includes a short description of the modelling approach used in the chapter. Section 3.4 provides results from the modelling (model evaluation, model predictions and spatial representations) and discusses the importance of the values predicted in the context of climate change mitigation. Section 3.5 covers conclusions.

3.3. Materials and methods

3.3.1. Study area

Six European countries were chosen to predict and map the change in SOC stocks under SCS management in vineyards: Spain, France, Italy, Portugal, Germany and Austria. These countries were selected due to their important land area dedicated to viticulture: 0.969 Mha in Spain, 0.793 Mha in France, 0.705 Mha in Italy, 0.192 in Portugal, 0.103 in Germany and 0.049 Mha in Austria in 2018 (OIV, 2019). They represent 82% of the viticultural land of the European Union and 35% of the total viticultural land worldwide. These countries also present a good variety of climates (Mediterranean, oceanic, continental, etc.) under which viticulture is undertaken.

3.3.2. Building the random forest model using data from field experiments

3.3.2.1. Response variables

The data collected in Chapter 2 for the meta-analysis was used for model building in this chapter. Two rates measuring the change in SOC stocks were calculated from the data and used as response variables in the model: the SOC stock rate of change and the SOC sequestration rate. The SOC stock rate of change (R), expressed in yr^{-1}, was calculated by the methods of Hedges et al. (1999) and Abdalla et al. (2018) following Equation (1), where $(SOC\ stock)_f$ corresponds to the SOC stock (in Mg C ha^{-1}) at the end of the experiment under a specific SCS practice, $(SOC\ stock)_i$ to the SOC stock at the beginning of the experiment and t to the duration of the field experiment (in yr). The SOC sequestration rate (in Mg C ha^{-1} yr^{-1}) was calculated following Equation (2).

$$R = \frac{\ln\left((SOC\ stock)_f/(SOC\ stock)_i\right)}{t} \quad (1)$$

$$SOC\ sequestration\ rate = \frac{(SOC\ stock)_f - (SOC\ stock)_i}{t} \quad (2)$$

The SOC stock rate of change was modelled without further transformation, whereas the values of the SOC sequestration rate were first normalised using a feature scaling method: the range of values was rescaled into [0, 1] following Equation (3), where x' represents the SOC sequestration rate value rescaled, x the SOC sequestration rate value calculated, x_{min} the minimum value of the SOC sequestration rate in the dataset, and x_{max} the maximum value. The natural logarithm function was then applied to the results of the feature scaling to obtain a normal distribution of the values. Once the model was trained, the actual and predicted values were back-transformed for analysis.

$$x' = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (3)$$

3.3.2.2. Explanatory variables

Fourteen explanatory variables were included in the model:

- **Soil texture (in %)**. Sand and Clay constituted two explanatory variables representing the soil texture of the experiment. Silt was not included in the model, since it decreased the overall predictive power of the model and its value is correlated to the value of Sand and Clay. Percentages of Sand and Clay of each field experiment were extracted from the world raster soil grids created by Hengl et al. (2017) and available on the ISRIC – World Soil Information website, using geographic coordinates. The raster grids had a resolution of 250 m x 250 m for a soil depth of 30 cm.
- **Bulk density (in kg m^{-3}).** The bulk density of each field experiment was extracted from the world raster soil grid created by Hengl et al. (2017). The raster grid had a resolution of 250 m x 250 m for a soil depth of 30 cm.
- **Initial SOC stock (in Mg C ha^{-1})**. The initial SOC stock was given in a few studies; in studies where it was not available, it was calculated using the SOC concentration, bulk density and soil depth. The complete methodology is described in Chapter 2.

- **Mean annual air temperature (in °C) and mean annual precipitation (in mm)**. Both were retrieved from the world raster climate data grids developed by Fick and Hijmans (2017) and available on the WorldClim – Global Climate Data website. The raster grids had a resolution of 1 km x 1 km.
- **Slope (in %)**. The field experiment slope was calculated using the world raster soil databases available on the Food and Agriculture Organisation of the United Nations website (Fischer et al., 2008). The databases consisted in eight raster files corresponding to a different slope class: 0% ≤ slope ≤ 0.5%, 0.5% ≤ slope ≤ 2%, 2% ≤ slope ≤ 5%, 5% ≤ slope ≤ 10%, 10% ≤ slope ≤ 15%, 15% ≤ slope ≤ 30%, 30% ≤ slope ≤ 45%, and slope > 45%. Each raster file provided, for each cell, the percentage of land with a slope included in the different slope classes. The raster grids had a resolution of 10 km x 10 km. The overall slope for each comparison in the dataset was retrieved by summing the percentages extracted from each raster file multiplied by the mean value of the slope class.
- **Potential evapotranspiration (in mm day^{-1})**. The PET of each field experiment was extracted from the world raster soil grid developed by Trabucco and Zomer (2018) and available on the CGIAR – Consortium for Spatial Information website. The raster grid had a resolution of 1 km x 1 km for a soil depth of 30 cm.
- **SCS practice**. Each single SCS practice (OA, BC, PR, NT and CC) was implemented in the model as an explanatory binary variable. It was coded 1 if the practice was implemented in the field experiment and 0 if it was not. This allowed the different combined SCS practices to be integrated into the model easily.
- **Duration of the experiment (in yr)**. The length of the field experiment was provided in all studies.

3.3.2.3. Random forest regression

A random forest (RF) regression was used to model the SOC stock rate of change and SOC sequestration rate under SCS management. RF regression is a machine-learning algorithm, proposed by Breiman (2001) and popularly applied to the fields of yield prediction in precision agriculture (*e.g.*, Iqbal et al., 2018), soil parameters quantification (*e.g.*, de Santana et al., 2018), and soil organic matter stock estimation and mapping (*e.g.*, Wiesmeier et al., 2011). It is commonly used to aid in the selection of optimal variables when the number of variables is substantial and needs to be reduced to the most influential variables only. The RF algorithm uses a bootstrapping method based on the classification and regression tree analysis to predict a continuous response variable (Iqbal et al., 2018). It fits a collection of decision tree models to the dataset. Each tree, trained using different bootstrap samples of the training data, acts as a regression function on its own and the final output given by the regression corresponds to the average of the individual tree outputs (Adusumilli et al., 2013). The samples that are not in the bootstrap sample are called out-of-bag (OOB) samples; they are used to test the accuracy of the decision trees and estimate the overall model's misclassification error and variable importance (Adam et al., 2014).

Due to its cross-validation capability, RF regression provides realistic prediction error estimates during the training process, which makes it suitable for real-time implementation (Adusumilli et al., 2013). It is also largely insensitive to noisy datasets and has a good predictive capability for high dimensional datasets (Breiman, 2001). Other advantages of RF include its minimised risk of overfitting, the possibility to include categorical along with continuous explanatory variables, and the small number of model parameters that need to be specified compared to other modelling approaches (Hutengs and Vohland, 2016). RF also provides several metrics to aid in interpretation: for instance, it automatically computes a variable importance score that assesses the contribution of individual predictors to the final model. This makes random forests more interpretable than other modelling methods such as artificial neural networks (Prasad et al., 2006).

The RF regression was implemented within the R environment software (R Core Team, 2019), using the 'tidyverse' (Wickham et al., 2019), 'randomForest' (Liaw and Wiener, 2002) and 'caret' (Kuhn, 2020) packages. The predictive power and stability of the model were, for each response variable, validated by ten-fold cross-validation (James et al., 2017). The accuracy and predictive power of the RF regression were measured by four indicators: the root mean square error (RMSE), the mean absolute error (MAE), the mean square error (MSE), and the predictive coefficient of determination (R^2 or Var_{ex}). These indicators also served to identify which response variable was the most suitable for predicting change in SOC stocks in viticultural soils.

The RMSE and the MAE were calculated according to Equations (4) and (5), respectively, where $z'(x_i)$ corresponds to the predicted output for a given input sample x_i, z_i to the observed output for the same input sample x_i, and n to the total number of OOB samples in the regression. RMSE assessed the accuracy of the model predictions, whereas MAE determined the bias of the predictions (Wiesmeier et al., 2011). The RMSE was also normalised (NRMSE) by the mean for the two response variables so they could be compared. The model's misclassification error was obtained by calculating the MSE according to Equation (6). The MSE estimated how effective the model would be at predicting the response variable when exposed to new samples (Adusumilli et al., 2013). The percentage of explained variance Var_{ex} (or R^2) was calculated following Equation (7), where Var_z stands for the total variance of the response variable (Wiesmeier et al., 2011). Var_{ex} was used to evaluate the fit of the regression.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(z_i - z\prime(x_i))^2}{n}} \tag{4}$$

$$MAE = \sum_{i=1}^{n} \frac{(z_i - z\prime(x_i))}{n} \tag{5}$$

$$MSE = n^{-1} \sum_{i=1}^{n} (z'(x_i) - z_i)^2 \tag{6}$$

$$Var_{ex} = 1 - \frac{MSE}{Var_z} \tag{7}$$

To improve the classification accuracy of the model, the RF parameters – *i.e.* the number of trees built in total by the algorithm (n_{tree}) and the number of random input variables used to build each tree (m_{try}) – were optimised for the two response variables based on the OOB estimate of error, similarly as in Adam et al. (2014). The importance of the different explanatory variables as predictors of SOC stock change in the model was also measured using the percentage increase in the MSE (%IncMSE), which assesses, for each explanatory variable, how much the model accuracy decreases when that variable is dropped (Iqbal et al., 2018). A high change in %IncMSE when a variable is permuted means that this variable plays an important role in the model prediction (Prasad et al., 2006; Siroky, 2009).

3.3.3. Predicting and mapping the total change in soil organic carbon stocks under different SCS practices

The different steps described below were conducted in the R environment software (R Core Team, 2019), using the ‘tidyverse’ (Wickham et al., 2019) and ‘raster’ (Hijmans, 2019) packages. Once the raster files were created, the ArcGIS software (ESRI, 2019) was used to generate the final maps.

3.3.3.1. Input data for prediction and mapping

The CORINE Land Cover 2018, version 20, was used to identify and isolate land use dedicated to viticulture in the six countries. The CORINE database provides an inventory of all the different land uses in the European Union, classified into 44 classes and presented as a cartographic raster file with a resolution of 100 m x 100 m in the ETRS89/LAEA1052 standard European coordinate reference system (EEA, 2020). It was projected into the WGS 84, EPSG:4326 standard world coordinate reference system (NGA, 2019) so that geographic coordinates could be retrieved and used.

Digital shapefiles of each winegrowing region of the six countries were then created, using ArcGIS (ESRI, 2019), to group vineyards displayed on the CORINE Land Cover into the winegrowing regions they belong to. By doing so, it was possible to analyse how the changes in SOC stocks under SCS management varied between winegrowing regions, which are characterised by different soil composition, initial SOC content, climate, etc., and to investigate the reasons at the root of these variations. A total of 81 shapefiles were created (15 for Spain, 16 for France, 20 for Italy, 13 for Portugal, 13 for Germany and 4 for Austria) and used to reclassify the CORINE Land Cover with codes for each winegrowing region. The geographic coordinates of each raster cell corresponding to a vineyard were extracted for each winegrowing region. An overall data frame of 5,804,376 observations was obtained, giving the longitude and latitude of all the vineyards located in Spain, France, Italy, Portugal, Germany and Austria, along with a code specifying the winegrowing region of each set of coordinates.

These coordinates were used to extract the input data for the model from raster maps. Soil texture, bulk density, mean annual air temperature, mean annual precipitation and slope were extracted from the same raster grids as presented in section 3.3.2.2. Initial SOC stock was extracted from the raster soil grids developed by Hengl et al. (2017).

3.3.3.2. Predictions and mapping

The RF model was used to generate the predictions of change in SOC stocks for the 5,804,376 sets of coordinates retrieved. The SOC stock rate of change was chosen as a response variable since it was associated with a higher predictive power and accuracy than the SOC sequestration rate (see section 3.4.1.2). The duration variable was set at 20 years for all predictions since it is assumed, under the IPCC (2006) guidelines, that SOC stocks, following a change in soil management, stabilise after twenty years. Five different combinations of SCS practices were modelled: OA, CC, OA+NT, NT+CC and OA+NT+CC.

To make the results more comparable with the emission reduction targets of the Paris Agreement and to re-contextualise SCS practices as greenhouse gas removal technologies, the RF predictions were converted into abatement rate (AR), which corresponds to the total annual increase in SOC stocks per hectare expressed in CO_2 equivalent of C (Mg CO_2-eq. ha^{-1} yr^{-1}). The AR was calculated following Equation (8), where *iSOC* corresponds to the initial SOC stock for a specific set of coordinates (in Mg C ha^{-1}) and *R* to the SOC stock rate of change (in yr^{-1}).

$$AR = iSOC \times (\exp(R) - 1) \times 44/12 \quad (8)$$

These predictions were used to (i) estimate the average abatement rate of each SCS practice at the regional and national level, (ii) estimate the total abatement potential (AP) of viticultural land in Spain, France, Italy, Portugal, Germany and Austria for each SCS practice, and (iii) map the abatement rate associated with the use of SCS management in vineyards in these wine-producing countries. (i) The average abatement rate for each winegrowing region ($AR_{\text{winegrowing region}}$) was calculated using Equation (9), where $AR_{winegrowing\ region}$ corresponds to the average abatement rate for a specific SCS practice in a given winegrowing region (in Mg CO_2-eq. ha^{-1} yr^{-1}), $area_i$ to the size of a given vineyard cell *i* (in ha), AR_i to the abatement rate associated with a given vineyard cell *i* (in Mg CO_2-eq. ha^{-1} yr^{-1}), and *n* to the total number of vineyard cells in a given winegrowing region. The average abatement rate at the national level (AR_{country}) was also calculated for the six countries using Equation (9), where *n* stands for the total number of vineyard cells in a given country.

$AR_{\text{winegrowing region}}$ and AR_{country} are valid for a period of 20 years and a soil depth of 30 cm. (ii) The abatement potential (in Tg CO_2-eq. yr^{-1}) of the total viticultural land in the six countries, noted $AP_{country}$, was calculated for each SCS practice, using Equation (10). It was assumed that the SCS practices would be adopted in all vineyards and the current adoption rates of the practices were ignored. (iii) Five raster files, one for each SCS practice, were created and mapped at the European level. They displayed the predicted AR for each set of coordinates from the data frame.

$$AR_{winegrowing\ region} = \frac{\sum_{i=1}^{n} area_i \times AR_i}{\sum_{i=1}^{n} area_i} \quad (9)$$

$$AP_{country} = \sum_{i=1}^{n} area_i \times AR_i \quad (10)$$

3.4. Results and discussion

3.4.1. Random forest performance in predicting changes in soil organic carbon stocks under SCS management

3.4.1.1. Random forest tuning

Results from the model tuning showed that a m_{try} value of 6 combined with a n_{tree} value of 3,500 produced the lowest OOB error rate (0.06%) for the SOC stock rate of change. For the SOC sequestration rate, a m_{try} value of 3 combined with a n_{tree} value of 1,500 generated the lowest OOB error rate (36.6%). These values were, therefore, selected as input parameters to train the RF regression for the two response variables.

3.4.1.2. Random forest accuracy and prediction performance

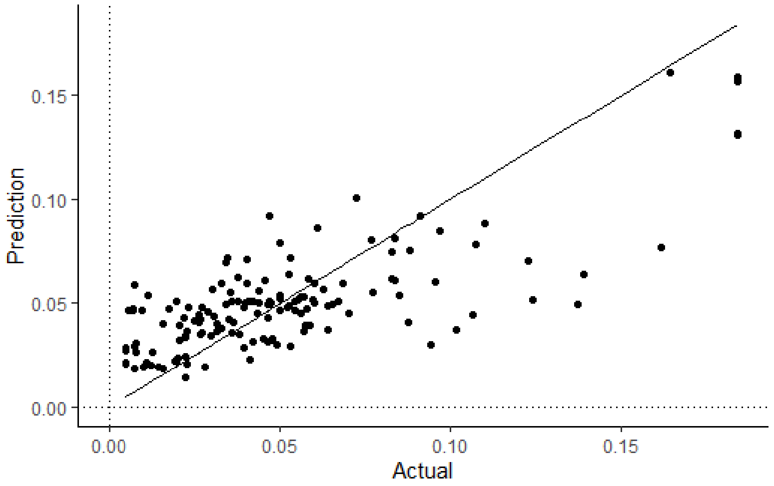
Indicators showing the performance of the model for the two response variables are presented in Table 3.1. The RMSE and MAE values obtained for the SOC stock rate of change were 0.03 and 0.02, respectively, whereas those found for the SOC sequestration rate were 1.65 and 0.92, respectively. The different explanatory variables used to build the RF regression explained 58 and 52% of the variation for the SOC stock rate of change and the SOC sequestration rate, respectively.

Table 3.1. Performance of the RF regression in modelling changes in SOC stocks.

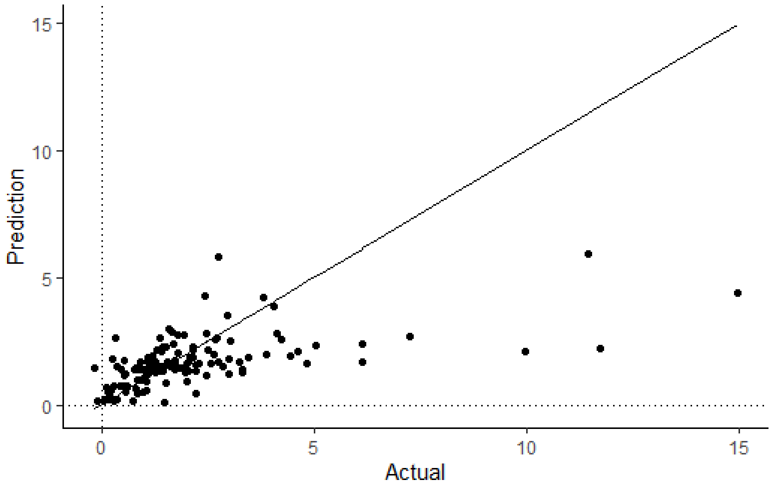
Indicator	SOC stock rate of change (yr^{-1})	SOC sequestration rate (Mg C ha^{-1} yr^{-1})
RMSE	0.0253	1.6498
NRMSE	0.4979	0.8472
MAE	0.0190	0.9166
MSE	0.0006	0.3659
R^2	0.58	0.52

The prediction performance of the RF model is represented in Fig. 3.1 for the two response variables. Based on Fig. 3.1, the model appears to underestimate high values of SOC stock rate of change and SOC sequestration rate. This may be due to the spread of the data, with considerably fewer datapoints in high values than in low values. Due to the way the model is trained using a random forest regression and the high number of SCS practices considered, it is to be expected that the model performance is reduced when fewer values have been used in the model building.

Predicted values of the SOC stock rate of change (Fig. 3.1 (a)) were associated with a higher accuracy overall than those of the SOC sequestration rate (Fig. 3.1 (b)). NRMSE values (50% for the SOC stock rate of change and 85% for the SOC sequestration rate) confirmed that the prediction accuracy of the model was higher with the SOC stock rate of change than with the SOC sequestration rate since NRMSE values close to 40% are satisfactory, while values above 71% are not considered accurate (Hengl, 2007). The SOC stock rate of change was, therefore, preferentially used over the SOC sequestration rate as a response variable in this study.



(a)



(b)

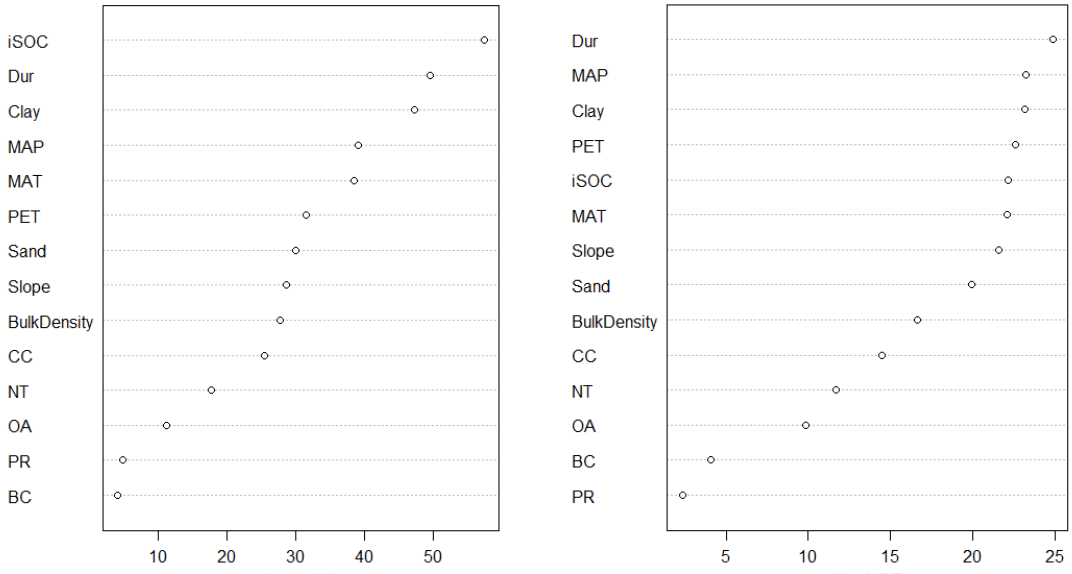
Fig. 3.1. Scatter plot representing the performance of the RF regression in predicting the SOC stock rate of change (a) and SOC sequestration rate (b). The values predicted by the RF model are compared to the measured values of the response variables for each of the 146 comparisons.

The prediction performance of the RF regression was satisfactory. The R^2 value of 0.58 compared with the previous study by Were et al. (2015), whose RF regression predicted SOC stocks in western Kenya with an R^2 value of 0.53. It was also similar to the R^2 of 0.51 obtained by Aksoy et al. (2012), though they used a hybrid Regression-Kriging method to predict SOC stocks in Crete, Greece, instead of a RF regression. This suggests that RF regression is an adequate tool for predicting the SOC stock rate of change over time depending on different soil management options. The prediction performance of the model was, however, somewhat lower than several previous studies using RF regression to predict SOC stocks in various regions (*e.g.*, R^2 = 0.82, Sreenivas et al., 2016; R^2 = 0.74, Wiesmeier et al., 2011; and $R^2 = 0.71$, Viscarra Rossel and Behrens, 2010), though it was substantially higher than many other studies (*e.g.*, $R^2 = 0.18$, Gastaldi et al., 2012; $R^2 = 0.23$, Dharumarajan et al., 2017; and $R^2 = 0.29$, Gray et al., 2009). The fact that other studies found higher R^2 when predicting SOC stocks with RF might be due to the different extents of the study areas (local or regional vs. global) or to the quality of the auxiliary input data used to train the RF (Were et al., 2015). The high variability of the soil properties used as explanatory variables could also be a factor explaining lower R^2 values (Dharumarajan et al., 2017).

The prediction performance found in this study was coherent with the fact that R^2 values greater than 0.7 tend to be unusual in the case of quantitative soil spatial models, whereas values equal to or lower than 0.5 are more common (de Carvalho et al., 2014). The prediction performance of RF regression for SOC stock predicting and mapping also varies importantly from study to study, with reported values as low as 0.18 (Gastaldi et al., 2012) and as high as 0.82 (Sreenivas et al., 2016). This suggests that the prediction accuracy of RF models might depend on whether the explanatory variables taken into account to build the regression can model effectively the spatial variability of the response variable (Sreenivas et al., 2016). The fact that the R^2 in this chapter was not as high as in other studies could be because the input variables used to build the RF regression did not model the full extent of the spatial variability of the SOC stock rate of change. However, it is important to highlight that the other studies used as comparisons to assess the prediction performance of the RF model predicted SOC stocks from input parameters at a specific time in a particular region and not changes in SOC stocks over time due to changes in soil management.

3.4.1.3. Importance of explanatory variables to predict changes in soil organic carbon stocks

The variable importance varied notably between the two response variables modelled (Fig. 3.2). The initial SOC content was the most important variable in explaining the SOC stock rate of change since it was associated with the highest %IncMSE (Fig. 3.2 (a)). The duration of the field experiment was slightly less important but still of major dominance, while the percentage of clay in the soil was the third most important variable in explaining the SOC stock rate of change. The duration of the field experiment played the most important role in the model accuracy for the SOC sequestration rate, followed by the mean average precipitation and the percentage of clay in the soil (Fig. 3.2 (b)). This suggests that some of the explanatory variables had a very different weight in explaining the variation in the change in SOC stocks depending on the response variable: for instance, the initial SOC content, though the most important variable for the SOC stock rate of change, was classified as the fifth most important variable for the SOC sequestration rate.



(a)

(b)

Fig. 3.2. Variable importance in predicting the SOC stock rate of change (a) and the SOC sequestration rate (b) derived from the RF regression. (iSOC = initial SOC stock, Dur = duration of the field experiment, Clay = percentage of clay in the soil, MAP = mean average precipitation, MAT = mean average temperature, PET = potential evapotranspiration of the soil, Sand = percentage of sand in the soil, Slope = slope where the field experiment was conducted, BulkDensity = bulk density of the soil, CC = cover cropping, NT = no-tillage, OA = organic amendments, PR = returning pruning residues to the soil, and BC = biochar amendments).

3.4.2. Abatement rate and potential of viticultural land under SCS management

3.4.2.1. Abatement rates under SCS management

There were some differences between the abatement rates of the five SCS practices modelled in this study (Fig. 3.3). It was, however, surprising to notice the absence of additivity in the SOC sequestration rates when several SCS practices were combined, even though additivity should, to some extent, be expected. This may be because SCS practices are conducted differently when combined. For instance, when winegrowers use OA+CC in the same vineyard, they tend to reduce the amount of organic amendment introduced to the agroecosystem compared to when OA is used by itself since some OC is already being added to the soil via the cover crop. It may also be due to the specificities of viticulture for winemaking, which differs from other crop systems: in viticulture, winegrowers aim to maximise grape quality, which depends on controlled yields. SCS practices are, therefore, not used in vineyards with the ultimate objective of maximising SOC sequestration but for agronomic reasons.

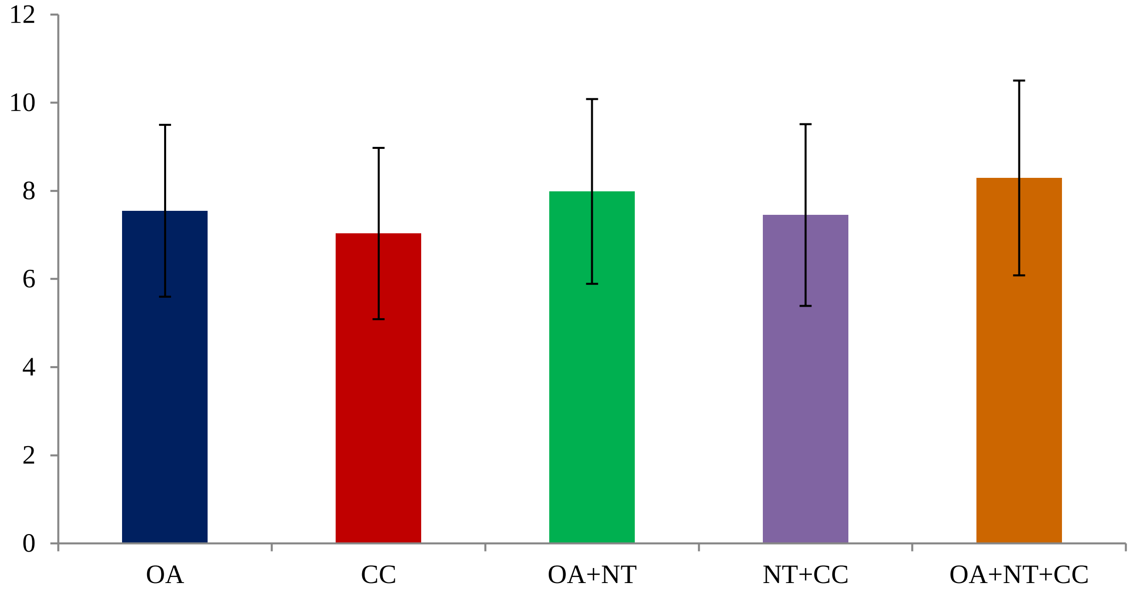


Fig. 3.3. Average abatement rate (in Mg CO_2-eq. ha^{-1} yr^{-1}) per SCS practice. Error bars represent standard deviation.

OA+NT+CC was associated with the highest abatement rate, followed by OA+NT, OA, NT+CC and, lastly, CC. The overall abatement rate of OA+NT+CC was 8.29 Mg CO_2-eq. ha^{-1} yr^{-1} (Fig. 3.3), which was 10% and 18% higher than that of OA and CC, respectively, and 4% and 11% higher than that of OA+NT and NT+CC, respectively. The use of OA+NT+CC has not been, to my knowledge, modelled before in the context of viticultural soils, but vineyards have been taken into account in a few meta-analyses performed for broader cropping systems. Aguilera et al. (2013) found an abatement rate of 4.07 Mg CO_2-eq. ha^{-1} yr^{-1} in Mediterranean cropping systems under OA+NT+CC management. This value is smaller than that found in this chapter, which suggests that vineyards show a particularly high SOC response under OA+NT+CC compared to other cropping systems. OA+NT+CC is, thus, a recommended management option for soil carbon sequestration in Western European vineyards.

On average across all winegrowing regions, OA was associated with an abatement rate of 7.55 Mg CO_2-eq. ha^{-1} yr^{-1} (Fig. 3.3). This was substantially higher than the abatement rate obtained in other studies for the same practice: Bleuler et al. (2017) predicted, using the RothC model, an abatement rate of 0.81 Mg CO_2-eq. ha^{-1} yr^{-1} (0.22 Mg C ha^{-1} yr^{-1}) for compost amendment in vineyards of the Foggia province in Italy and a period of 20 years; Mondini et al. (2012) observed an abatement rate of 2.06 Mg CO_2-eq. ha^{-1} yr^{-1} (0.56 Mg C ha^{-1} yr^{-1}) for compost amendment in Italian vineyards, using the RothC model. These differences might be due to the fact that, in the study by Bleuler et al. (2017), compost was introduced only where it is usually used under conventional practice (*i.e.* not in vineyards), and to the fact that Mondini et al. (2012) considered the effects of climate change into their modelling. They may also be because these two studies only focused on compost amendment, while all types of organic amendments have been taken into account in this study (*i.e.* manure, sludge, straw, bark, mushroom substrate, leonardite, microbial fertiliser); different types of organic amendments might have different impacts on OC accumulation in the soil and be applied in higher quantities than compost amendments. OA is, therefore, an effective practice to increase SOC sequestration in Western European vineyards.

The use of CC yielded an average abatement rate of 7.03 Mg CO_2-eq. ha^{-1} yr^{-1} (Fig. 3.3). It was notably higher than that found in previous studies: in the study by Bleuler et al. (2017), the abatement rate of CC in the Foggia province was estimated, using the RothC model, at 2.02 Mg CO_2-eq. ha^{-1} yr^{-1} (0.55 Mg C ha^{-1} yr^{-1}), while in the study by Pardo et al. (2017), the same practice in vineyards along the Spanish Mediterranean coast had an abatement rate of 1.91 Mg CO_2-eq. ha^{-1} yr^{-1} (0.52 Mg C ha^{-1} yr^{-1}). The abatement rate of CC in this chapter was, however, lower than that reached under OA, which could be because, in the case of CC, the carbon input comes from inside the vineyard agroecosystem and is, therefore, limited by the primary productivity of the vineyard, whereas, in the case of OA, it comes from outside the vineyard and is usually more substantial. Despite this, the use of CC remains a strategic SCS practice in vineyards of Western Europe considering its potential contribution to SOC sequestration, while providing additional benefits in terms of soil quality and winegrowing, such as reducing nutrient loss due to leaching and lowering soil evaporation by increasing soil moisture in the upper layer during critical phases of the grapevine cycle (Monteiro and Lopes, 2007).

The average abatement rates of OA+NT and NT+CC were 7.99 Mg CO_2-eq. ha^{-1} yr^{-1} and 7.45 Mg CO_2-eq. ha^{-1} yr^{-1}, respectively (Fig. 3.3). The use of NT in combination with OA or CC resulted in higher abatement rates (by +6% in both cases) than when the practices were implemented with tillage. This shows that the absence of tillage, when combined with OA or CC, is effective in reducing carbon losses and leads to an even greater carbon accumulation in viticultural soils.

Even though OA, CC, OA+NT, NT+CC and OA+NT+CC are associated with high abatement rates, their adoption may lead to varying implementation and maintenance costs, which may impact their cost-effectiveness: adopting NT may require capital investment in new equipment but may lead to a reduction in fuel and time costs; CC may induce additional input and time costs; and the use of OA may be associated with labour and time costs, in addition to costs related to the purchase of organic amendments (Sykes et al., 2020). A cost-effectiveness analysis of the adoption of these SCS practices in Western European vineyards is, thus, needed to evaluate which practices or combinations of practices are the most cost-effective while still allowing for high amounts of OC to be sequestered in the soil.

3.4.2.2. Abatement rates in viticultural soils under SCS management at the regional and national levels

The average abatement rates in viticultural soils at the regional and national levels of Spain, France, Italy, Portugal, Germany and Austria are presented in Table 3.2. There were notable variations in the abatement rate between winegrowing regions and SCS practices.

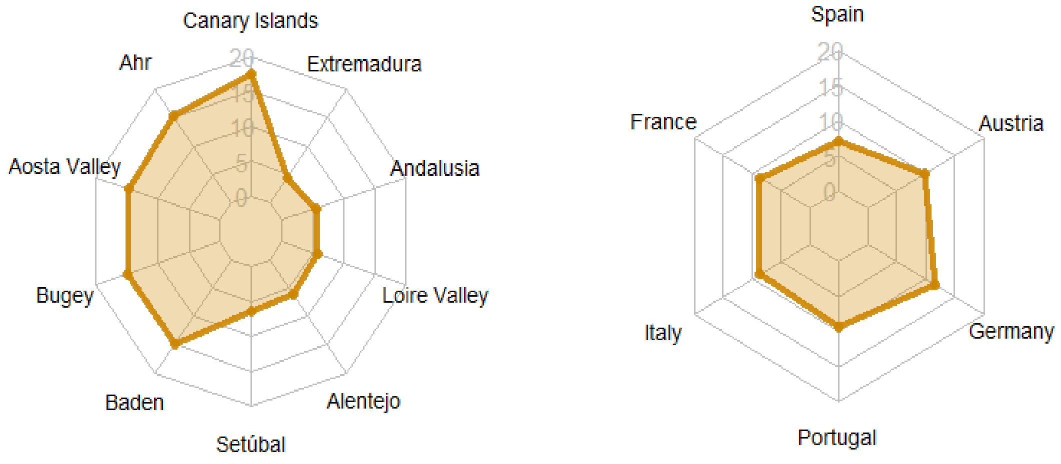
Table 3.2. Average abatement rate (in Mg CO_2-eq. ha^{-1} yr^{-1}) of each country and winegrowing region for the five SCS practices modelled.

Winegrowing region	**OA**	**CC**	**OA+NT**	**NT+CC**	**OA+NT+CC**
Spain	6.54	6.28	6.73	6.50	7.06
Andalusia	5.18	4.57	5.54	4.94	5.59
Aragon	7.42	7.26	7.59	7.46	8.08
Basque Country	12.71	12.54	13.80	13.57	14.65
Canary Islands	16.45	15.60	16.89	16.20	17.53
Castile and León	7.42	7.11	7.53	7.24	7.94
Castilla-La Mancha	5.86	5.76	5.96	5.91	6.31
Catalonia	6.99	6.30	7.37	6.68	7.57
Extremadura	4.31	3.73	4.58	4.00	4.56
Galicia	12.47	12.19	12.99	12.76	13.87
La Rioja	9.05	8.62	9.50	9.01	9.91
Madrid	7.92	7.74	8.00	7.88	8.51
Mallorca	7.55	6.47	8.08	7.00	8.09
Murcia	6.71	6.53	6.85	6.74	7.22
Navarre	7.64	7.28	8.08	7.65	8.47
Valencia	7.28	7.15	7.42	7.35	7.90
France	7.68	7.02	8.22	7.52	8.52
Alsace-Lorraine	11.17	10.71	11.74	11.26	12.23
Beaujolais	8.71	8.44	9.24	8.97	9.79
Bordeaux	6.76	6.10	7.17	6.50	7.44
Bugey	13.27	12.96	14.33	13.93	14.99
Burgundy	8.94	8.48	9.62	9.11	10.02
Champagne	9.34	8.66	9.90	9.16	10.16
Cognac	6.81	6.22	7.43	6.79	7.69
Corsica	8.74	8.10	9.21	8.61	9.59
Jura	12.60	12.22	13.76	13.24	14.31
Languedoc	8.09	7.40	8.70	7.92	8.97
Loire Valley	5.34	4.64	5.58	4.84	5.75
Provence	7.76	7.00	8.37	7.58	8.65
Rhône Valley	8.22	7.53	8.80	8.08	9.19
Roussillon	7.08	6.37	7.46	6.73	7.63
Savoy	11.76	11.52	12.51	12.26	13.23
South-West	7.44	6.75	8.02	7.29	8.37
Italy	7.78	7.15	8.41	7.72	8.63
Abruzzo	7.46	6.66	8.11	7.22	8.22
Aosta Valley	13.50	13.54	13.76	13.90	14.79

Apulia	6.96	6.18	7.34	6.54	7.38
Basilicata	7.05	6.22	7.61	6.71	7.72
Calabria	6.65	5.81	7.12	6.31	7.31
Campania	8.20	7.55	8.92	8.24	9.24
Emilia-Romagna	8.85	8.46	9.82	9.26	10.22
Friuli Venezia Giulia	8.76	8.49	9.64	9.27	10.15
Lazio	7.79	7.00	8.45	7.65	8.69
Liguria	10.62	10.23	11.51	11.04	12.03
Lombardy	8.91	8.60	9.88	9.41	10.32
Marche	7.56	6.93	8.25	7.45	8.44
Molise	9.41	8.77	9.73	9.11	10.02
Piedmont	8.58	8.17	9.53	8.95	9.92
Sardinia	7.65	6.82	8.04	7.26	8.20
Sicily	7.12	6.23	7.67	6.80	7.71
Trentino-South Tyrol	11.38	11.29	11.79	11.76	12.58
Tuscany	8.18	7.63	8.94	8.26	9.21
Umbria	8.34	7.69	9.00	8.22	9.18
Veneto	8.07	7.77	8.87	8.48	9.34
Portugal	8.45	7.87	8.82	8.29	9.27
Alentejo	5.74	5.08	6.03	5.38	6.15
Algarve	7.28	6.40	7.67	6.83	7.82
Beira atlântico	9.47	8.75	10.08	9.40	10.55
Beira interior	8.72	8.19	8.92	8.43	9.45
Dão	10.48	9.97	10.82	10.40	11.44
Douro Valley	9.04	8.62	9.41	9.05	9.98
Lisbon	7.84	7.10	8.38	7.69	8.70
Madeira	12.11	11.29	12.73	11.95	13.08
Minho	11.36	10.98	11.80	11.47	12.50
Setúbal	6.02	5.31	6.14	5.48	6.35
Tejo	6.97	6.06	7.22	6.34	7.40
Terras de Císter	9.50	9.18	9.73	9.49	10.41
Transmontano	8.83	8.40	9.07	8.70	9.65
Germany	10.61	10.04	11.18	10.58	11.57
Ahr	14.48	14.16	14.72	14.47	15.31
Baden	13.41	12.93	14.24	13.75	14.92
Franconia	10.41	9.75	11.04	10.31	11.32
Hessische Bergstrasse	10.08	9.50	10.57	10.02	11.05
Mittelrhein	13.03	12.60	13.52	13.11	14.06
Mosel	12.45	12.11	12.88	12.61	13.53
Nahe	10.73	10.06	11.29	10.57	11.54

Palatinate	8.88	8.33	9.27	8.69	9.56
Rheingau	10.70	10.06	11.27	10.58	11.53
Rheinhessen	9.61	8.91	10.23	9.42	10.41
Saale-Unstrut	11.76	10.98	12.48	11.61	12.71
Saxony	13.85	13.19	14.03	13.41	14.42
Württemberg	9.70	9.12	10.32	9.72	10.73
Austria	8.99	8.41	9.47	8.82	9.72
Burgenland	8.31	7.75	8.70	8.07	8.93
Lower Austria	9.04	8.44	9.54	8.86	9.77
Styria	11.73	11.31	12.50	12.08	13.06
Vienna	8.60	7.95	9.02	8.31	9.25

At the regional level, the adoption of CC in the Extremadura winegrowing region led to the lowest abatement rate (3.73 Mg CO_2-eq. ha^{-1} yr^{-1}), whereas the Canary Islands were associated with the highest abatement rate (17.53 Mg CO_2-eq. ha^{-1} yr^{-1}) under OA+NT+CC (Table 3.2). The abatement rate in the Canary Islands under OA+NT+CC was approximately 4.7 times higher than in Extremadura under CC. The abatement rate of the five SCS practices followed a similar pattern in all winegrowing regions, with OA+NT+CC being associated with the highest abatement rate, followed by OA+NT, OA or NT+CC, and finally CC. Overall, the Canary Islands, Ahr, the Aosta Valley, Bugey and Baden were the five winegrowing regions associated with the highest abatement rates across all SCS practices, whereas Extremadura, Andalusia, the Loire Valley, Alentejo and Setúbal were the five winegrowing regions associated with the lowest abatement rates (Table 3.2). The abatement rates obtained for these regions under OA+NT+CC are represented in Fig. 3.4 (a).



(a) (b)

Fig. 3.4. Average abatement rate (in Mg CO_2-eq. ha^{-1} yr^{-1}) under OA+NT+CC at the regional level (a) and the national level (b).

At the national level, the lowest abatement rate (6.28 Mg CO_2-eq. ha^{-1} yr^{-1}) was found in Spain under CC, while the highest abatement rate (11.57 Mg CO_2-eq. ha^{-1} yr^{-1}) was reached in Germany under OA+NT+CC (Table 3.2). The abatement rates of the five SCS practices followed the same pattern at the national level as they did at the regional level. Overall, Germany was the country associated with the highest abatement rates, followed by Austria, Portugal, Italy, France and finally Spain (Table 3.2). The abatement rates of the six countries under OA+NT+CC are represented in Fig. 3.4 (b).

3.4.2.3. Abatement potential of viticultural land in Western Europe

The abatement rates presented in Table 3.2 did not take into account the size of the viticultural land in a given winegrowing region or country; as a result, some very high values of abatement rate, if reached in small winegrowing regions, could have the same or a lower cumulated impact on SOC sequestration than lower abatement rates in larger winegrowing regions. This is why it is crucial to contextualise the abatement rate in relation to the total viticultural land in a winegrowing region or country. The abatement potential of viticultural land at the national level is presented in Table 3.3 for the six countries. Results showed that, though abatement rates in German winegrowing regions were consistently higher than in almost all other European winegrowing regions, the abatement potential of the total viticultural land in Germany was remarkably lower than in Spain, France and Italy, as the German viticultural land is much smaller than that of the other countries. The same was true for Austria, whose abatement potential was the lowest overall, even though the abatement rates in Austria were higher than those in Spain, France and Italy. Nevertheless, the values presented in Table 3.3 were calculated under the assumption that all winegrowers would implement the SCS practice in all vineyards. In reality, the abatement potential of the total viticultural land depends on the extent to which SCS practices have already been implemented in vineyards in each winegrowing region. For example, in France, OA is used at least once every fourth year on 27% of the total viticultural land (Agreste, 2017), which means that a more accurate estimate of the total abatement potential for viticulture in France under OA would be 4.45 Tg CO_2-eq. yr^{-1}, instead of 6.09. Investigating the adoption rate of SCS practices in vineyards is, thus, needed to better evaluate the abatement potential of winegrowing regions.

Table 3.3. Abatement potential (in Tg CO_2-eq. yr^{-1}) of the total viticultural land of Spain, France, Italy, Portugal, Germany and Austria for the five SCS practices, supposing that each SCS practice is adopted by all winegrowers in all vineyards. These predictions are valid for a period of 20 years and a soil depth of 30 cm. The viticultural land area (in Mha) is also given for each country as of 2018.

Winemaking country	OA	CC	OA+NT	NT+CC	OA+NT+CC	Area (Mha)
Spain	6.34	6.09	6.52	6.30	6.84	0.969
France	6.09	5.57	6.52	5.96	6.76	0.793
Italy	5.48	5.04	5.93	5.44	6.08	0.705
Portugal	1.62	1.51	1.69	1.59	1.78	0.192
Germany	1.09	1.03	1.15	1.09	1.19	0.103
Austria	0.44	0.41	0.46	0.43	0.48	0.049
Total	21.06	19.65	22.27	20.81	23.13	2.81

The availability of organic amendments was also not considered when using the model to calculate the potential for additional SOC sequestration at the regional level. However, the realisation of the abatement potential of OA-based practices presented in Table 3.3 is linked to the availability of organic amendments in each winegrowing region and to the capacity of winegrowers to procure and purchase these amendments. In practice, not all winegrowers would be able to use organic amendments in their vineyards, which would reduce the overall abatement potential of OA-based SCS management calculated for each country. Another limitation to the presented values stems from the fact that the amount of amendments used for experimental purposes is often higher than that used by farmers. More information about OC input to obtain specific abatement rates and potential would be crucial to have a clearer understanding of changes in SOC stocks in vineyards under SCS management, and particularly under SCS practices for which OC inputs originate from outside the vineyard.

3.3.4. Spatial distribution of abatement rate in Western European vineyards under SCS management

Maps displaying the abatement rate of viticultural land in Western Europe under the five SCS practices modelled are presented in Appendix D. The change in SOC stocks under SCS management tended to follow similar patterns within winegrowing regions but to a different extent depending on the practices implemented (*e.g.*, the vineyards associated with very high abatement rates were hotspots under all SCS practices, but with varying abatement rates under each SCS practice). This section focuses more specifically on maps representing the adoption of OA in the Mediterranean region of France (Fig. 3.5), CC in western Germany (Fig. 3.6), OA+NT in southern Italy and Sicily (Fig. 3.7), NT+CC in northern and central Portugal (Fig. 3.8), and OA+NT+CC in central Spain (Fig. 3.9). These five case studies provided a useful insight into the variations in abatement rates within winegrowing regions.

The impacts of OA adoption on SOC sequestration were shown in the vineyards located in the Mediterranean region of France (Fig. 3.5). The winegrowing regions of Roussillon, Languedoc and Provence appear in Fig. 3.5, as well as the southern half of the Rhône Valley. The distribution of abatement rate was very heterogeneous throughout the Mediterranean region of France, with a succession of patches of high (up to 25.87 Mg CO_2-eq. ha^{-1} yr^{-1}), medium (around 8 Mg CO_2-eq. ha^{-1} yr^{-1}) and low (down to 4.18 Mg CO_2-eq. ha^{-1} yr^{-1}) abatement rate present within each winegrowing region.

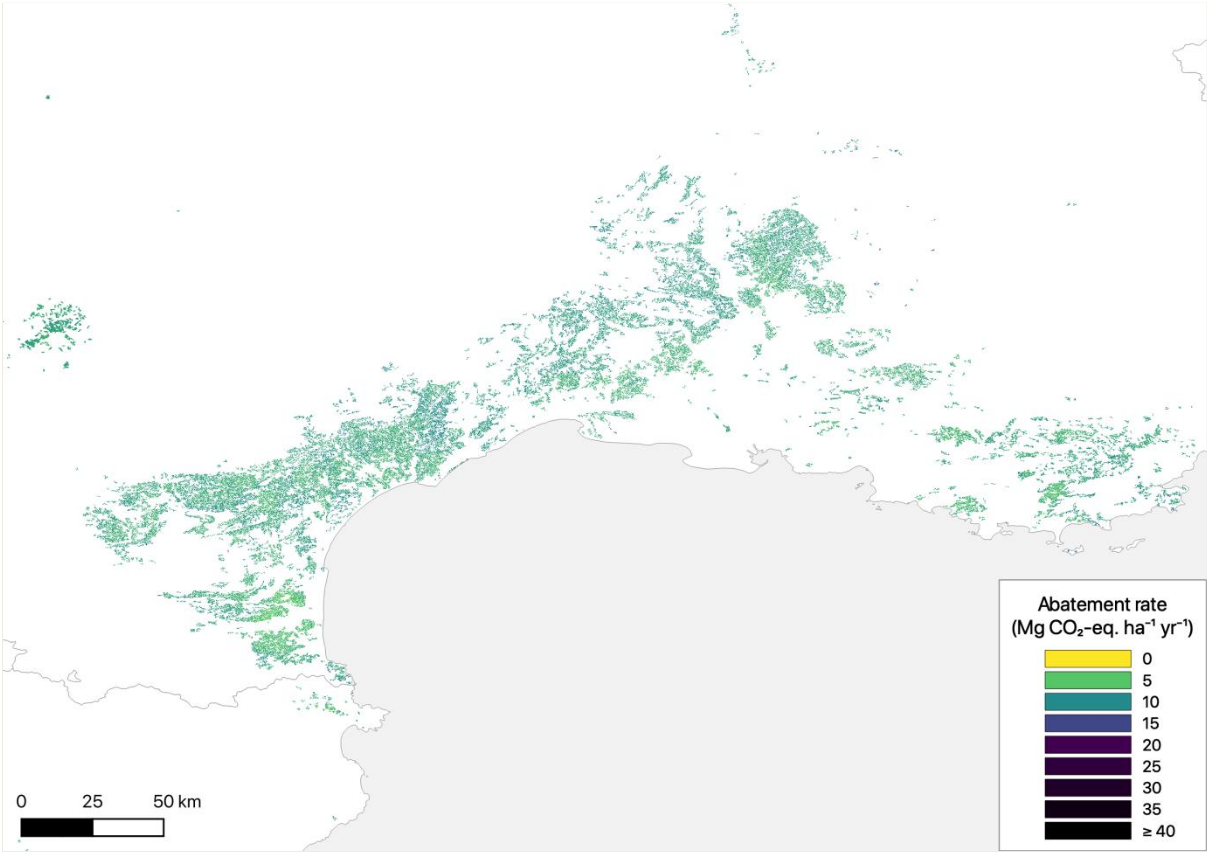


Fig. 3.5. Abatement rate of OA in viticultural soils in south-eastern France.

The influence of CC was shown in vineyards of western Germany, in the winegrowing regions of Mosel, Mittelrhein, Rheingau, Rheinhessen, Nahe, Palatinate, Hessische Bergstrasse, Württemberg and Franconia, and in parts of Baden (Fig. 3.6). The change in SOC stocks under CC was rather homogeneous throughout western Germany, which was associated with high values of abatement rate overall. The abatement rate did not vary much within each winegrowing region either, despite a few exceptions: it was slightly lower in the eastern section of the Palatinate and Rheinhessen winegrowing regions, while it was extremely high in southern Baden, with areas where the abatement rate was higher than 30 Mg CO_2-eq. ha^{-1} yr^{-1} and, in a few vineyards, higher than 40 Mg CO_2-eq. ha^{-1} yr^{-1}.

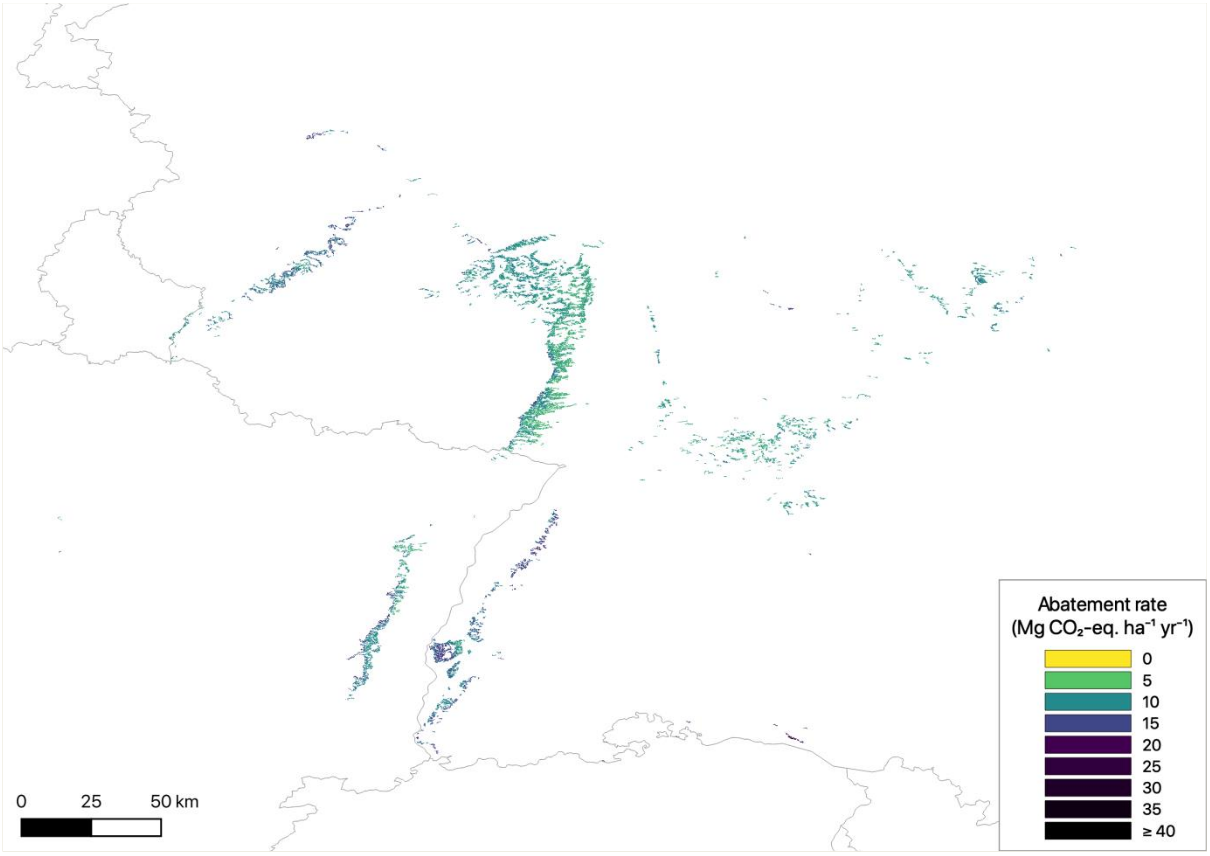


Fig. 3.6. Abatement rate of CC in the vineyards of western Germany.

The effects of OA+NT on SOC sequestration were mapped for vineyards located in southern Italy, more specifically in the winegrowing regions of Sicily, Calabria and Basilicata (Fig. 3.7). The abatement rates obtained in these regions were, on average, among the lowest in Italy for this practice (with values reaching only 7.61, 7.12 and 7.67 Mg CO_2-eq. ha^{-1} yr^{-1} in Basilicata, Calabria and Sicily, respectively). However, there are substantial differences in values within each of these winegrowing regions, with specific areas being among the highest hotspots for SOC sequestration in Italy under OA+NT. The abatement rate is particularly high on the west coast of Sicily, where a cluster of values higher than 15 Mg CO_2-eq. ha^{-1} yr^{-1} and, in some cases, higher than 20 Mg CO_2-eq. ha^{-1} yr^{-1} can be observed. In addition, the island of Pantelleria, off the western coast of Sicily, has a concentration of abatement rate values between 10 and 15 Mg CO_2-eq. ha^{-1} yr^{-1}. These hotspots are the areas where the adoption of OA+NT would yield the strongest benefits on viticultural land in Italy in terms of contribution to GHG mitigation via SOC sequestration.

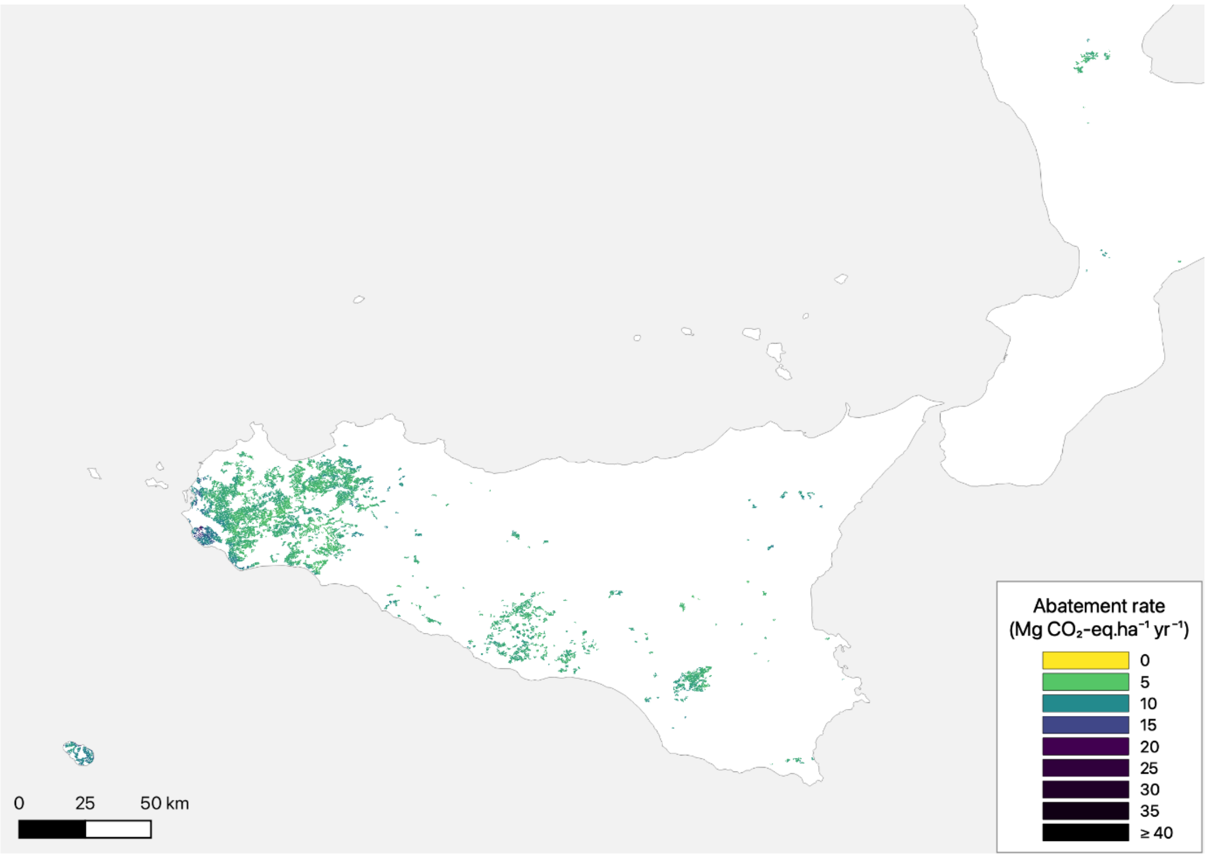


Fig. 3.7. Abatement rate of OA+NT in the winegrowing regions of southern Italy and Sicily.

Fig. 3.8 depicts the abatement rate of viticultural soils under NT+CC in winegrowing regions located in northern and central Portugal (*i.e.* Minho, Transmontano, the Douro Valley, Terras de Císter, Dão, Beira atlântico, Beira interior, Lisbon, Tejo, and parts of Alentejo and Setúbal). The abatement rate was very homogeneously distributed within each winegrowing region, with low variations in values, but was heterogeneously spread between regions. This suggests that there are fewer differences in soil and climatic characteristics within each of these winegrowing regions than within winegrowing regions located in the other countries studied in this chapter (see, *e.g.*, Fig. 3.7). Among the regions represented in Fig. 3.8, Minho and Dão were those with the highest average abatement rate (11.47 and 10.40 Mg CO_2-eq. ha^{-1} yr^{-1}, respectively); efforts to increase the uptake of NT+CC should, therefore, be encouraged in these areas.

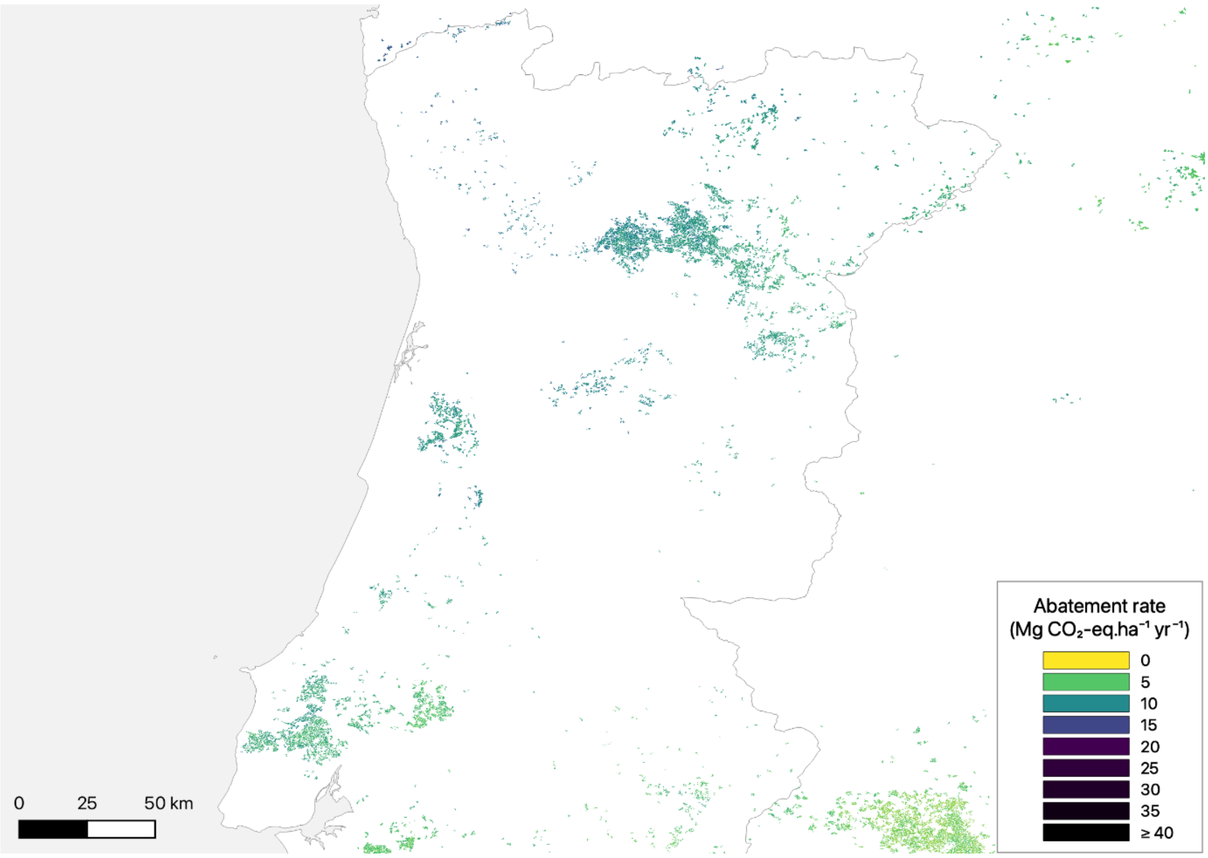


Fig. 3.8. Abatement rate of NT+CC in the viticultural soils of northern and central Portugal.

The effects of OA+NT+CC on SOC sequestration were illustrated in the vineyards of central Spain (Fig. 3.9). The depicted winegrowing regions include Madrid, Castilla-La Mancha, Valencia, Murcia, and parts of Andalusia. The abatement rate of OA+NT+CC in these regions was, on average, low, with values ranging from 5.59 Mg CO_2-eq. ha^{-1} yr^{-1} in Andalusia to 8.51 Mg CO_2-eq. ha^{-1} yr^{-1} in the Madrid winegrowing region. The distribution of abatement rate values within these regions was very homogenous, except for in Valencia, where a gradient was observed, with values increasing from west to east, reaching, in the centre of the region, up to 15 Mg CO_2-eq. ha^{-1} yr^{-1}, and then decreasing slightly toward the coast.

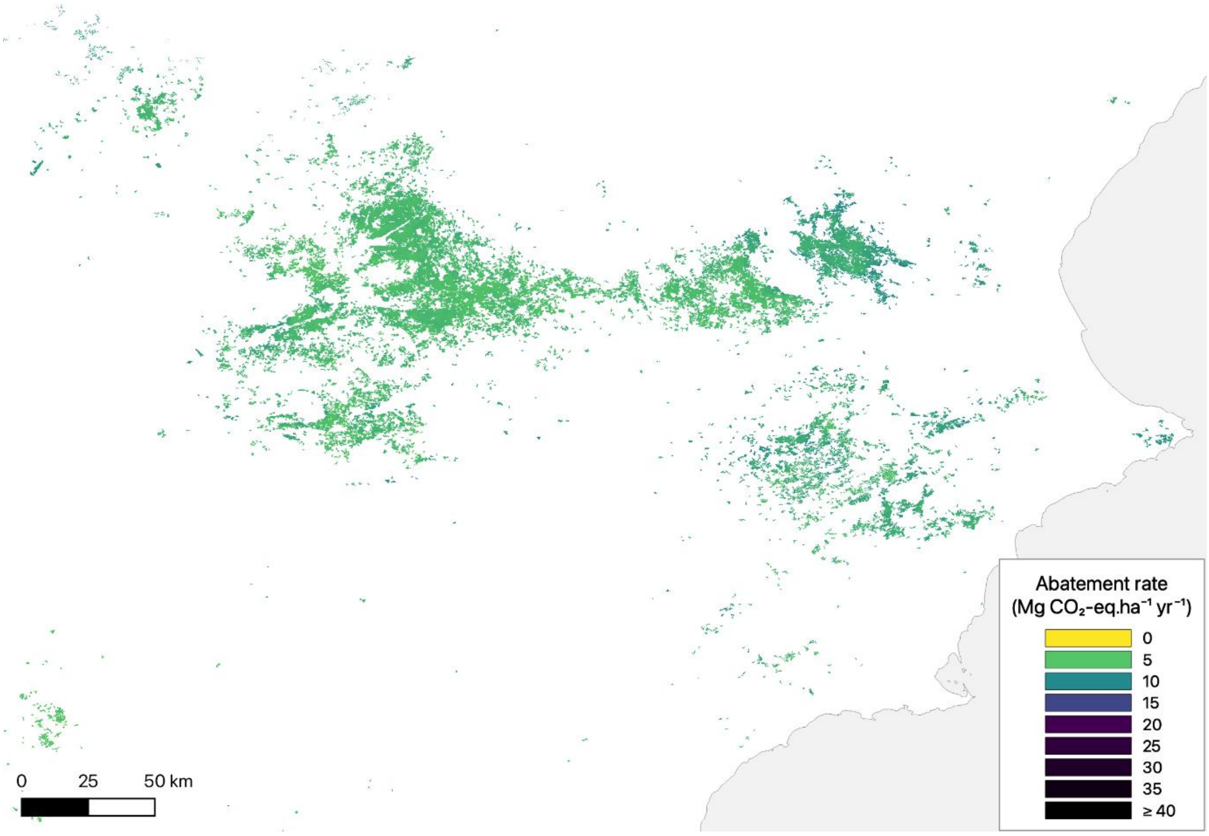


Fig. 3.9. Abatement rate of OA+NT+CC in the vineyards of central Spain.

In the winegrowing regions featured in Fig. 3.5–3.9, areas with high abatement rate values were characterised by lower bulk density and higher initial SOC content than areas with low abatement rates. This shows that viticultural soils with already relatively high SOC stocks have not reached their saturation capacity under current practices and can further increase their SOC levels. However, increasing SOC content in these areas may trigger a substantial decrease in bulk density since there is a negative relationship between SOC concentration and bulk density (Ruehlmann and Körschens, 2009). If bulk density decreases below 1,000 kg m^{-3}, soils become carbon-dense and are considered likely to lose SOC no matter the type of soil management implemented (Zomer et al., 2017). There is, therefore, a need to further develop SOC change modelling in viticultural soils under SCS management, so changes in soil parameters induced by changes in SOC stocks are also taken into account.

3.3.5. Gaps and uncertainty of modelling applications

The number of comparisons for each SCS practice varied between treatments. While a high number of observations was found for some SCS practices (*e.g.,* 70 observations for NT+CC), others presented a substantially lower number of observations (*e.g.,* BC had 4 observations). This indicated that the prediction accuracy of the model differed depending on the SCS practice considered. That is why only the SCS practices with the highest number of observations were modelled and mapped in this study: OA (n = 27), CC (n = 9), OA+NT (n = 6), NT+CC (n = 70) and OA+NT+CC (n = 7). However, there was still a strong difference in accuracy between these five options since the number of observations for NT+CC and OA was 11.7 and 4.5 times higher than that for OA+NT, respectively, 7.8 and 3 times higher than that for CC, respectively, and 10 and 3.9 times higher than that for OA+NT+CC, respectively.

The quality of the auxiliary data used for predicting the SOC stock rate of change varied depending on the accuracy of the raster files used to extract the data. For instance, the raster files used to retrieve input data on Initial SOC stock, Clay, Sand and Bulk density had a resolution of 250 m x 250 m, while the resolution for PET was 1 km x 1 km, which makes the accuracy of extracted Initial SOC stock, Clay, Sand and Bulk density higher than that of PET. In addition, the raster databases used to estimate the Slope variable had quite a low accuracy, as they were built by giving, for each cell, the percentage of land falling within a specific slope category, with a 10 km x 10 km resolution. The accuracy of the predictions could be improved by increasing the quality of the auxiliary data and, for example, by increasing the resolution of the raster files to 100 m x 100 m to match the resolution of the CORINE Land Cover.

3.5. Conclusions

Modelling results demonstrated that RF regression was a satisfactory method for predicting changes in SOC stocks associated with SCS management in vineyards. The SOC stock rate of change was used as a response variable in the model to optimise prediction accuracy and model performance. The initial SOC content was the most important variable explaining the observed variability in the SOC stock rate of change under SCS management: having reliable data on vineyards' SOC stocks is, therefore, essential to ensure that model predictions have high accuracy. Overall, the model created in this study had a good prediction accuracy (R^2 = 0.58; RMSE = 0.03); it could serve in further studies as a predictive tool to quantify the abatement rate of SCS practices in vineyards in countries with important winegrowing regions in the other Member States of the European Union (*e.g.*, Romania) or in other parts of the world (*e.g.*, the USA).

The predictions of changes in SOC stocks following the adoption of SCS management suggested that OA+NT+CC was the practice associated with the highest abatement rate across all winegrowing regions, with values ranging from 4.56 Mg CO_2-eq. ha^{-1} yr^{-1} in Extremadura (Spain) to 17.53 Mg CO_2-eq. ha^{-1} yr^{-1} in the Canary Islands (Spain). The other SCS practices also yielded high abatement rates, though to a lesser extent. The results of this chapter can serve to inform policymaking regarding the adoption of SCS practices at the European level and, more particularly, in the viticulture sector. Further research is needed, however, to evaluate the cost-effectiveness of the different SCS practices taken into account in this study.

Chapter 4

Factors influencing winegrowers' adoption of soil organic carbon sequestration practices in France

4.1. Abstract

The adoption of SCS practices on agricultural land offers the double advantage of offsetting GHG emissions and improving soil quality. However, little is known about the drivers that might influence winegrowers to adopt these practices, whose uptake remains low on viticultural land. This chapter identified factors influencing the adoption of SCS practices by winegrowers in France. A survey of 400 winegrowers investigated current rates of adoption and winegrowers' perceptions of the practices. A binary logistic model suggested that winegrower's age, being an independent winegrower, farm size, the number of workers hired, vine's age, being certified High Environmental Value (HVE), being certified organic, practising irrigation, receiving subsidies, and winegrower's perceived resources, attitude towards SCS practices and confidence significantly influenced the decision to adopt the practices, though their influence differed depending on the practice. The findings provide insights for GHG mitigation planning targeting the viticulture sector.

4.2. Introduction

SCS practices are management practices that aim to sequester SOC in agroecosystems to offset GHG emissions. SCS practices can also increase soil quality; as a result, their implementation represents an important strategy for both climate change mitigation and sustainable food production (Smith et al., 2019; Sun et al., 2020). However, how much the mitigation potential of SCS practices will have an impact at the farm, territorial and landscape levels depends largely on the adoption of the practices by farmers. This is why it is important to further our understanding of the factors influencing the adoption of these practices.

An extensive literature on farmer decision making regarding the adoption of agronomic practices and innovations (*e.g.*, Garini et al., 2017; Barnes et al., 2019; Despotović et al., 2019) shows that a diverse range of interacting social, economic and cultural factors influence farmers' adoption decisions. Tradition, self-opinion and conflicts of interest are important considerations in explaining why farmers and stakeholders of the agricultural industry may not adopt measures, even in potential win-win scenarios (Moran et al., 2013).

Farmer behaviour with respect to adopting SCS practices on agricultural land has been widely researched over the past decade (*e.g.*, Knowler and Bradshaw, 2007; Calatrava and Franco, 2011; Ingram et al., 2014; Sánchez et al., 2016; Paul et al., 2017). These studies showed that financial incentives play a major role in adoption decisions (Sánchez et al., 2016), along with the cost associated with practice implementation and adequate information about the practice (Paul et al., 2017). Low awareness of SCS practices and variations in how well farmers and stakeholders understand the processes involved in SOC sequestration are also reasons for non-adoption at the European level (Ingram et al., 2014).

Compared to arable land and grasslands, there are relatively few studies considering viticultural land, where adoption rates of SCS practices are low. Garini et al. (2017) evaluated winegrowers' motivations to adopt agro-ecological practices (such as drip irrigation, reduced herbicide application, etc.) but did not focus specifically on SCS practices. Schütte and Bergmann (2019) investigated the attitudes of French and Spanish winegrowers towards the adoption of cover cropping, but their study was limited to a very specific area at the local level in each country. Accordingly, there is limited information on the factors affecting the adoption of SCS practices in vineyard agroecosystems. Yet, promoting the uptake of SCS practices in vineyards is important, especially in countries with large viticultural areas (*e.g.*, Spain, France, Italy, etc.), due to the substantial SOC sequestration potential of these practices in viticultural soils (see Chapter 2 and Chapter 3). Understanding farmer behaviours and practice adoption is arguably more complex in vineyard agroecosystems than in other agricultural systems, due to the strong traditions and cultural know-how embodied in the concept of *terroir*[6] in Europe. This implies that European winegrowers might face even greater cognitive barriers in their perceived need to observe specific intergenerational practices.

This chapter identifies the factors influencing the adoption of SCS practices by French winegrowers. France, whose viticultural area is the third-largest worldwide, with 0.793 Mha in 2018 (OIV, 2019), and includes different soil types, climates, grapevine varieties and viticultural practices, was chosen as a case study. A survey covering all winegrowing regions

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[6] A vitivinicultural *terroir* refers to an area where a collective knowledge of the interactions between the biophysical environment and the applied vitivinicultural practices has developed over time, giving distinctive characteristics to products originating from this area (OIV, 2010).

of France was administered online to determine the current use of SCS practices by winegrowers and their perceptions of these practices. A binary logistic regression was used to evaluate the influence of twenty predictors on the adoption of SCS practices. Findings from this chapter could be used to draw more generalised recommendations to facilitate the adoption of SCS practices in the viticulture sector, particularly in other countries with large viticultural land.

The chapter is structured as follows. The next section covers data collection and methods. Section 4.4 provides results from the binary logistic regressions, organised per SCS practice modelled. Section 4.5 discusses the significance (or absence of significance) of the different factors tested in the study and establishes comparisons between SCS practices. Finally, section 4.6 covers conclusions.

4.3. Materials and methods

4.3.1. Soil organic carbon sequestration practices

Six SCS practices were considered in this chapter: OA, BC, PR, NT, CC and HG. Evidence from Chapters 2 and 3 proved that the implementation of these practices leads to SOC sequestration on viticultural land; however, no data from field experiments were found for HG. Instead, the SOC sequestration potential calculated by Pellerin et al. (2019) for this practice (0.061 Mg CO_2-eq. ha^{-1} yr^{-1}) specifically in the context of French soils was taken into account and applied to viticultural soils. In their study, Pellerin et al. (2019) also showed that SCS practices (excluding BC) could play a crucial role in reaching the target of the ‘4 per 1000’ initiative at low (*e.g.*, NT and HG) or even negative (*e.g.*, OA and CC) costs at the national level of France.

4.3.2. Study area: France

Vineyards are widely distributed throughout France (Fig. 4.1), covering a variety of agro-ecological zones with notably different climates: Mediterranean in the southeast, continental in the east, and temperate oceanic in the rest of the country. Viticultural practices differ between winegrowing regions, each having its own, traditional methods of cultivation

(Agreste, 2017). This is due to the strong socio-cultural history associated with winemaking in the country, embodied in the concept of *terroir*. Age-old viticultural management practices at the regional or local levels have evolved across centuries and are crucial elements of distinct regional *terroirs* (OIV, 2010).

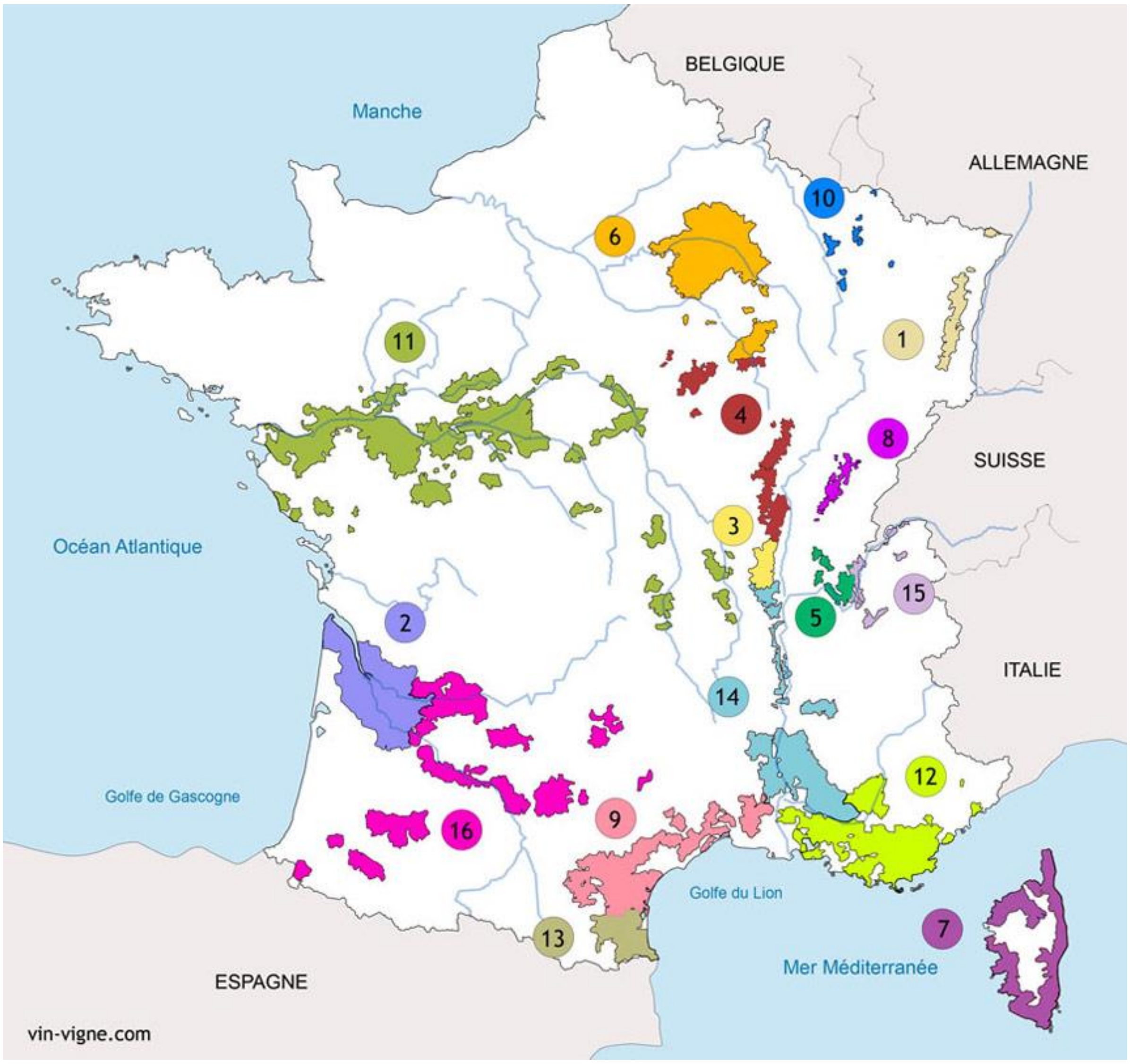

Fig. 4.1. French winegrowing regions (Vin-Vigne, 2015). (1), Alsace; (2), Bordeaux; (3), Beaujolais; (4), Burgundy; (5), Bugey; (6), Champagne; (7), Corsica; (8), Jura; (9), Languedoc; (10), Lorraine; (11), Loire Valley; (12), Provence; (13), Roussillon; (14), Rhône Valley; (15), Savoy and (16), South-West.

The adoption rate of SCS practices on viticultural land is low at the national level in France, except for PR (Fig. 4.2). Uptake varies, however, at the regional level, with specific winegrowing regions displaying higher or lower adoption of certain practices. The use of OA, for instance, is as low as 3% in Roussillon and 4% in Beaujolais but reaches 19% in Champagne and 20% in Alsace (Agreste, 2017). The adoption of NT also varies between winegrowing regions, ranging from 9% in Provence to 65% in Champagne (Agreste Primeur, 2016). There is no existing data on the adoption rates of BC and HG on viticultural land in France.

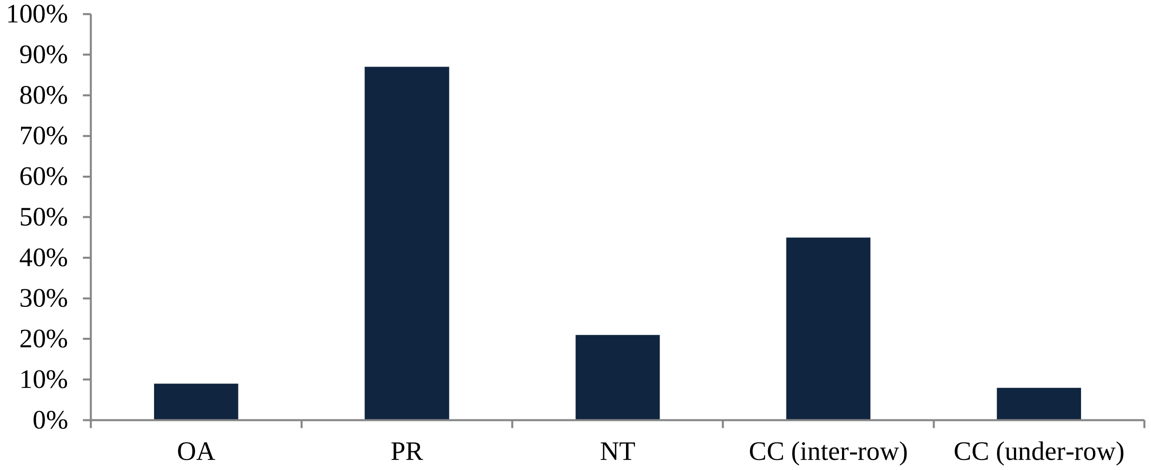

Fig. 4.2. Percentage of France's viticultural land where SCS practices are implemented (Agreste, 2017). OA, applying organic amendments; PR, returning pruning residues to the soil; NT, implementing no-tillage; CC, cover cropping.

4.3.3. Survey design

To understand the adoption of SCS practices by winegrowers, a survey was conducted between April and September 2019. The survey data was collected using a structured questionnaire developed after a literature review, expert consultations and a pilot study. The final questionnaire was divided into five sections (Appendix E). The first section was designed to collect data on winegrowers' socio-economic profiles (*e.g.*, age, education, workforce hired, etc.). The second section enquired about vineyard structure and characteristics (*e.g.*, vineyard size, vine's age, organic certification, etc.). The third section collected information on winegrowers' incentives for adopting new viticultural practices, such as subsidy or participation in agri-environment measures[7] (AEMs). Section four addressed the adoption or otherwise of SCS practices. The last section asked winegrowers to evaluate various statements to reveal their beliefs and attitudes towards SCS practices.

The survey targeted farm managers (*chefs d'exploitation*) and co-managers (*co-exploitants*) who cultivate grapes. It only considered vineyards categorised as "viticultural farms", *i.e.* when grape production represents more than two-thirds of the revenues of the farm (Legouy, 2014). The survey was administered online via SurveyMonkey, using a random method. 1,380 winegrowers were contacted by email using viticultural databases, wine shops and personal contacts. The French Institute of Vine and Wine, the French Confederation of GPI Wines (*Confédération des vins IGP de France*) and several regional inter-professional councils of wine (*e.g.*, the *Bureau interprofessionnel des vins de Bourgogne* and the *Conseil interprofessionnel du vin de Bordeaux*) were contacted and agreed to circulate the questionnaire through their networks or to publish the link to the questionnaire on their website and newsletter. A total of 400 fully-completed responses were collected across France, giving a return rate of 29%. Responses were anonymous and handled in accordance with the General Data Protection Regulation.

4.3.4. Principal component analysis

Statements included in the questionnaire assessed winegrowers' attitudes toward SCS practices both from an economic and environmental point of view, their perception of the resources needed to implement the practices, and their confidence towards adoption. Respondents were asked to choose the extent to which they agreed with the statements using a five-point Likert scale, from strongly disagree (–2) to strongly agree (2). A principal component analysis (PCA) was used to condense the information contained in the statements. PCA is a data reduction technique that converts a given number of correlated variables into a smaller number of uncorrelated components, with a minimum loss in information (Jolliffe, 2002). The components created, or principal components, account for most of the variation in the responses.

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[7] Agri-environment measures are incentive-based instruments developed by the EU that provide payments to farmers to reward their voluntary commitments to preserving or restoring aspects of the environment or landscape (European Commission, 2017).

Before conducting the PCA, the suitability of the statements for this type of analysis was checked using the Kaiser-Meyer-Olkin (KMO) test and Bartlett's test of sphericity. The KMO test, which provides a measure of the adequacy of the data for PCA, yielded a value of 0.74, which was considered acceptable (*i.e.* > 0.6). Bartlett's test of sphericity was used to assess whether the correlation matrix of the statement variables was different from an identity matrix. The test was statistically significant (p = .000), which means that the correlation matrix of the statements was significantly different from an identity matrix, which is consistent with the assumption that the correlation matrix should be treated as factorable.

The PCA was conducted using an eigenvalue higher than one to extract components. The varimax rotation was employed to simplify component interpretation. A total of three components were kept (Table 4.1). The value of 0.4 was chosen as a loading threshold for retaining statements in components. A total of ten statements loaded onto the components (Table 4.1). Once the PCA was completed, a Cronbach's Alpha was carried out for each component to assess internal consistency and reliability. Values higher than 0.6 are commonly considered acceptable for this test; the three components were, therefore, retained as explanatory variables for the rest of the analysis (Table 4.1).

Table 4.1. Results of the PCA for winegrowers' intentions to adopt SCS practices.

Statements	**Resources**	**Attitude**	**Confidence**
SCS practices increase viticultural productivity	0.070	**0.693**	0.054
SCS practices increase wine quality	0.225	**0.694**	0.038
SCS practices save time	**0.640**	0.095	-0.165
SCS practices enhance soil quality	0.083	**0.694**	0.233
SCS practices increase vineyard resilience	0.021	**0.624**	0.096
I have enough time to implement SCS practices	**0.770**	0.098	0.221
My current tools and technologies are sufficient to implement SCS practices	**0.609**	0.068	0.219
I have a clear understanding of how to implement SCS practices	0.109	0.169	**0.886**
I trust my skills to implement SCS practices	0.175	0.178	**0.879**
My current tools and technologies make it easy to implement SCS practices	**0.722**	0.116	0.129
Eigen value	3.096	1.393	1.207
Cronbach's Alpha	0.655	0.637	0.835

The first component, 'resources', consisted of statements reflecting the adequacy of the respondents' current resources to implement SCS practices. These related mostly to time (*e.g.*, "I have enough time to implement SCS practices") and tools (*e.g.*, "My current tools and technologies are sufficient to implement SCS practices"). The second component, 'attitude', measured the respondents' beliefs towards SCS practices. Statements with the highest loadings towards this component included "SCS practices increase viticultural productivity" and "SCS practices enhance soil quality". The final component, 'confidence', assessed the respondents' confidence in the implementation of SCS practices, with statements such as "I have a clear understanding of how to implement SCS practices" and "I trust my skills to implement SCS practices".

4.3.5. Explanatory variables

Table 4.2 presents the explanatory variables used in the qualitative choice modelling. Three types of variables were chosen to explain the adoption of SCS practices, based on the literature about the adoption of new practices in the agriculture sector, and interviews with experts from the French Institute of Vine and Wine as well as members of regional Chambers of Agriculture. The first category of variables related to winegrowers' socio-economic characteristics, such as gender, age, education (general or viticultural) and landownership, and vineyard attributes, including farm size, workforce hired, certification labels – HVE[8] and organic agriculture (European label 'AB') – and irrigation use. Age is commonly used in studies investigating farmers' adoption of new practices, as older farmers are prone to being more conservative towards the adoption of alternative farm practices (Prokopy et al., 2008). Farm size is also considered to be an important factor in the adoption of new practices since smaller farms cannot benefit from the same cost advantages as larger farms when implementing management practices (Knowler and Bradshaw, 2007; Tambo and Abdoulaye, 2012). The second category of variables concerned respondents' access to information and involvement in policy instruments. These types of variables have proved to be crucial in the adoption of innovative measures and their diffusion (Luo et al., 2014). A policy variable (AECM) was created to assess the participation of respondents in AEMs. Some AEMs in France set up specifically for viticultural land (*e.g.*, COUVER_11, which provides financial support to winegrowers for the implementation of cover cropping in the inter-rows of vineyards) are likely to influence the adoption of SCS practices. The third category of variables was linked to specific aspects of viticultural production systems, such as the date when the majority of the vines were planted, and whether the respondent is an independent winegrower[9]. The three components 'resources', 'attitude' and 'confidence' resulting from the PCA were also used as explanatory variables in the modelling.

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[8] The High Environmental Value (*Haute Valeur Environnementale* in French) label is a French certification awarded to farmers using sustainable and environmental-friendly practices on their farms (IFV, 2019).

[9] An independent winegrower is a winegrower who grows grapevine, harvests grapes, makes wine and directly sells it (Vignerons indépendants de France, 2020).

Table 4.2. Explanatory variables used in the modelling for the full sample of respondents (n = 400).

Variable	Description	Mean	SD	Min	Max
Gender	Gender of the farm manager (1 = male, 0 = female)	0.82	0.38	0	1
Age	Age of the farm manager (continuous)	49.94	11.47	24	86
Education	Level of formal education received by the farm manager (1 = primary education, 2 = secondary education, 3 = higher education)	2.76	0.47	1	3
Viticultural education	Farm manager has a viticultural degree (1 = yes, 0 = no)	0.74	0.44	0	1
Landowner	Farm manager owns (at least partially) their vineyard (1 = yes, 0 = no)	0.81	0.39	0	1
Inherited vineyard	Farm manager inherited the vineyard from a family member (1 = yes, 0 = no)	0.46	0.50	0	1
Independent winegrower	Farm manager is an independent winegrower (1 = yes, 0 = no)	0.67	0.47	0	1
Farm size	Size of the viticultural farm (1 = < 5 ha, 2 = 5-15 ha, 3 = 15-30 ha, 4 = 30-50 ha, 5 = > 50 ha)	2.77	1.20	1	5
Workforce hired	Number of regular labour (working part- or full-time) employed (continuous)	3.94	9.01	0	92
Vine planting	Date when the majority of vine was planted (1 = 2011-2019, 2 = 2000-2010, 3 = 1990-1999, 4 = 1970-1989, 5 = 1950-1969, 6 = before 1950)	3.30	1.09	1	6
HVE	Vineyard is certified High Environmental Value (1 = yes, 0 = no)	0.17	0.38	0	1
AB	Vineyard is certified organic (1 = yes, 0 = no)	0.33	0.47	0	1
Irrigation	Irrigation is used in the vineyard (1 = yes, 0 = no)	0.13	0.33	0	1
AECM	Farm manager participates in an agri-environment measure (1 = yes, 0 = no)	0.16	0.37	0	1
Subsidy	Farm manager receives subsidies (1 = yes, 0 = no)	0.49	0.50	0	1
Viticultural advisor	Farm manager is in contact with a viticultural advisor (1 = yes, 0 = no)	0.67	0.47	0	1
4per1000	Farm manager is familiar with the '4 per 1000' initiative (1 = yes, 0 = no)	0.07	0.26	0	1
Resources	Component variable built from ordinal responses (5-point Likert scale)	-	-	-	-
Attitude	Component variable built from ordinal responses (5-point Likert scale)	-	-	-	-
Confidence	Component variable built from ordinal responses (5-point Likert scale)	-	-	-	-

4.3.6. Qualitative choice model

The interest of this chapter was in modelling the binary choice of SCS practice adoption (1 = adoption of the practice, 0 = non-adoption of the practice). A binary logistic regression was used for each of the six SCS practices to assess the contribution of the explanatory variables to the adoption process of the practice without considering the adoption of the other practices. This type of econometric model is commonly used to assess the factors influencing the adoption of agricultural practices by farmers (*e.g.*, Tey et al., 2014; Timprasert et al., 2014; Paul et al., 2017; Daxini et al., 2018). In the logit model (Equation (1)), P_i corresponds to the probability of adoption of a SCS practice, $(1 - P_i)$ to the probability of non-adoption of the practice, α to the intercept, and β_1, β_2, ..., β_{20} to the regression coefficients of variables X_1, X_2, ..., X_{20}, respectively. i refers to the values of respondent i.

$$\ln \frac{P_i}{(1-P_i)} = \alpha + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_{20} X_{20i} \qquad (1)$$

The parameters in the logit model were estimated using the maximum likelihood method. The sign of the β coefficients represents how the variables influence the likelihood of adoption of SCS practices: if β is positive, when the value of the associated variable increases, the likelihood of adoption of the SCS practice increases as well, and vice versa.

The model was run with all the explanatory variables presented in Table 4.2; however, some variables (*e.g.*, gender or education) were not significant predictors of adoption for any of the SCS practices. A likelihood-ratio test was carried out to see whether the goodness of fit of the model was altered when removing these variables. The test was significant, which implies that permuting these variables significantly alters the model fit. All the explanatory variables were, therefore, integrated into the model.

4.4. Results

4.4.1. Descriptive statistics

Sample summary data for all the variables used in the regressions are presented in Table 4.2. The mean age of respondents was 50 years. The level of education in the sample was very high: the majority of respondents had a higher education degree (78%), while 20% stopped after secondary education, and only a small percentage did not have secondary education (2%). Most respondents had a viticultural degree (74%). 12% of the viticultural farms in the sample were less than 5 ha, 37% between 5 and 15 ha, 26% between 15 and 30 ha, 12% between 30 and 50 ha, and 13% higher than 50 ha. Most vines were planted between 1970 and 1989 (35.25%) and between 1990 and 1999 (29.75%). Fewer were planted between 2000 and 2010 (19.75%). A few were planted between 1950 and 1969 (8.5%) and between 2011 and 2020 (4.5%). The sample included a small number of vines planted before 1950 (2.25%). 33% of viticultural farms were certified organic and 17% were certified HVE. 16% of the respondents were involved in an AEM. Awareness of the ‘4 per 1000’ initiative was, overall, very low, with only 7% of the respondents stating that they were familiar with the initiative.

4.4.2. Adoption of soil organic carbon sequestration practices in the sample

The adoption rate varied considerably between practices. PR was the most commonly adopted practice, with 91% of respondents incorporating pruning residues into the soil of their vineyard. The adoption of OA and CC was lower (73% and 69%, respectively). NT and HG were adopted by about half the respondents (50% and 52%, respectively). The adoption of BC was exceptionally low, with only 2% of the respondents stating that they use biochar amendments. Most respondents were not familiar with BC.

There were also variations in the adoption rate of SCS practices at the regional level. For instance, in Languedoc-Roussillon, the adoption rate of CC (57%) was lower than at the national level (69%). This may be due to the high competition for water and nutrients between the vine and the cover crop during the growing period of the vine in this region, which is characterised by dry summers and soils that are low in humus. Inversely, CC was used by 88% of respondents in Alsace-Lorraine, which is more than at the national level and substantially more than in Languedoc-Roussillon. This higher adoption rate in Alsace-

Lorraine can be explained by the lower competition between vines and cover crops in the vineyard during the important stages of the vine cycle compared to Languedoc-Roussillon.

4.4.3. Factors influencing the adoption of soil organic carbon sequestration practices

The significance of the model fit was assessed for each practice using model chi-square. The chi-square values were significant at the 0.1% level for OA, PR, NT and HG and at the 5% level for CC, which indicates that the model fit for these practices is significantly better than a null model (*i.e.* without any predictors). However, the chi-square was not significant (p = .430) for the adoption of BC; BC was, therefore, excluded from the analysis. The goodness of the model fit was assessed for each practice using the Nagelkerke R^2 and the level of accuracy (*i.e.* the percentage of respondents classified correctly between adopters and non-adopters by the model). The Nagelkerke R^2 was 0.23 for OA, 0.25 for PR, 0.22 for NT, 0.13 for CC and 0.20 for HG. These were reasonable values for this type of regression and study (Barnes et al., 2019), though the explanatory power was lower for CC than for the other practices. The level of accuracy (75% for OA, 91% for PR, 65% for NT, 70% for CC and 66% for HG) was considered acceptable for all the practices. Collinearity between the predictors was controlled by calculating the variance inflation factor (VIF). The VIFs were between 1.05 and 1.71 for all the variables, which suggests low multicollinearity in this study (James et al., 2017).

4.4.3.1. Organic amendments

Only four explanatory variables significantly influenced the decision to adopt OA, holding the other variables constant: independent winegrower, vine planting, AB and irrigation (Table 4.3). The effect of independent winegrower and AB was positive, while that of vine planting and irrigation was negative. The variables AB and independent winegrower exerted the strongest impact on the adoption process of OA, with an odds ratio of 3.02 and 2.52, respectively.

Table 4.3. Results of the binary logistic regression for the prediction of winegrowers' adoption of OA.

OA	**Coefficient**	**Standard error**	**Wald**	**Odds ratio**
Gender	-0.140	0.338	0.171	0.870
Age	-0.014	0.011	1.629	0.986
Education	0.075	0.273	0.076	1.078
Viticultural degree	0.144	0.291	0.246	1.155
Landowner	-0.126	0.382	0.108	0.882
Inherited vineyard	0.150	0.285	0.277	1.162
Independent winegrower	0.923***	0.274	11.311	2.516
Farm size	0.232	0.146	2.541	1.262
Workforce hired	0.050	0.037	1.782	1.051
Vine planting	-0.246**	0.121	4.120	0.782
HVE	-0.594	0.391	2.307	0.552
AB	1.104***	0.319	11.959	3.016
Irrigation	-0.797**	0.385	4.288	0.450
AECM	-0.001	0.346	0.000	0.999
Subsidy	0.395	0.290	1.863	1.485
Viticultural advisor	-0.258	0.285	0.817	0.773
4per1000	0.157	0.546	0.083	1.170
Resources	0.084	0.125	0.452	1.088
Attitude	0.012	0.134	0.008	1.012
Confidence	-0.012	0.126	0.009	0.988
Constant	0.928	1.222	0.576	2.529
Chi-square	70.509 (p = .000)			
Nagelkerke R^2	0.234			
Log-likelihood	400.026			
Accuracy	74.8%			

p < .1 = *; p < .05 = **; p < .01 = ***

4.4.3.2. Pruning residues

Age, farm size, workforce hired and HVE had a significant impact on the decision to adopt PR (Table 4.4). The effect of farm size and HVE was positive, while that of age and workforce hired was negative. HVE was, by far, the predictor with the highest impact on the decision to adopt PR: respondents whose vineyard is certified HVE are extremely more likely, by a factor of 7.29, to adopt PR than respondents whose vineyard is not certified HVE.

Table 4.4. Results of the binary logistic regression for the prediction of winegrowers' adoption of PR.

PR	**Coefficient**	**Standard error**	**Wald**	**Odds ratio**
Gender	0.208	0.487	0.183	1.232
Age	-0.047***	0.018	6.578	0.954
Education	0.140	0.415	0.114	1.150
Viticultural degree	-0.724	0.471	2.359	0.485
Landowner	0.299	0.566	0.279	1.349
Inherited vineyard	0.062	0.435	0.020	1.064
Independent winegrower	-0.717	0.453	2.507	0.488
Farm size	0.771***	0.240	10.333	2.163
Workforce hired	-0.078***	0.023	11.636	0.925
Vine planting	-0.220	0.183	1.456	0.802
HVE	1.987*	1.063	3.496	7.293
AB	0.760	0.490	2.407	2.137
Irrigation	-0.707	0.631	1.256	0.493
AECM	-0.592	0.548	1.166	0.553
Subsidy	0.525	0.476	1.218	1.691
Viticultural advisor	0.180	0.410	0.193	1.197
4per1000	0.402	1.124	0.128	1.495
Resources	0.190	0.201	0.887	1.209
Attitude	0.319	0.209	2.330	1.376
Confidence	0.071	0.195	0.133	1.074
Constant	3.672	1.840	3.984	39.338
Chi-square	48.558 (p = .000)			
Nagelkerke R^2	0.248			
Log-likelihood	198.069			
Accuracy	91%			

p < .1 = *; p < .05 = **; p < .01 = ***

4.4.3.3. No-tillage

The decision to adopt NT was influenced significantly and in a positive way by resources, attitude and confidence but negatively by workforce hired, AB and irrigation (Table 4.5). Irrigation was the predictor with the greatest effect on the decision to adopt NT: respondents practising irrigation in their vineyard are notably less likely, by a factor of 0.31, to adopt NT than respondents not practising irrigation.

Table 4.5. Results of the binary logistic regression for the prediction of winegrowers' adoption of NT.

NT	**Coefficient**	**Standard error**	**Wald**	**Odds ratio**
Gender	-0.049	0.300	0.027	0.952
Age	0.006	0.010	0.299	1.006
Education	-0.368	0.259	2.025	0.692
Viticultural degree	0.049	0.271	0.032	1.050
Landowner	-0.443	0.340	1.699	0.642
Inherited vineyard	-0.167	0.255	0.428	0.846
Independent winegrower	0.198	0.255	0.606	1.219
Farm size	-0.147	0.122	1.441	0.863
Workforce hired	-0.039**	0.018	4.738	0.962
Vine planting	0.013	0.108	0.014	1.013
HVE	0.460	0.353	1.698	1.585
AB	-0.521**	0.254	4.212	0.594
Irrigation	-1.172***	0.394	8.865	0.310
AECM	0.110	0.307	0.128	1.116
Subsidy	-0.119	0.252	0.222	0.888
Viticultural advisor	0.334	0.249	1.798	1.397
4per1000	0.442	0.474	0.869	1.555
Resources	0.433***	0.119	13.291	1.541
Attitude	0.506***	0.123	16.868	1.659
Confidence	0.319***	0.113	7.936	1.376
Constant	1.556	1.117	1.941	4.742
Chi-square	71.827 (p = .000)			
Nagelkerke R^2	0.219			
Log-likelihood	482.681			
Accuracy	65.3%			

p < .1 = *; p < .05 = **; p < .01 = ***

4.4.3.4. Cover cropping

Farm size, vine planting, resources and confidence were the key predictors affecting the decision to adopt CC, while the other variables were not significant (Table 4.6). The effect of vine planting, resources and confidence on the decision to adopt CC was positive, whereas that of farm size was negative. The variable with the strongest effect on the decision to adopt CC was resources, with an odds ratio of 1.6.

Table 4.6. Results of the binary logistic regression for the prediction of winegrowers' adoption of CC.

CC	**Coefficient**	**Standard error**	**Wald**	**Odds ratio**
Gender	0.058	0.308	0.035	1.060
Age	0.003	0.011	0.075	1.003
Education	0.325	0.256	1.618	1.385
Viticultural degree	-0.175	0.278	0.396	0.839
Landowner	0.043	0.349	0.015	1.044
Inherited vineyard	-0.040	0.263	0.023	0.961
Independent winegrower	-0.113	0.260	0.190	0.893
Farm size	-0.252**	0.125	4.052	0.777
Workforce hired	0.029	0.023	1.603	1.029
Vine planting	0.198*	0.112	3.092	1.218
HVE	0.189	0.351	0.289	1.208
AB	0.207	0.261	0.631	1.230
Irrigation	-0.173	0.349	0.247	0.841
AECM	-0.423	0.310	1.868	0.655
Subsidy	0.365	0.264	1.917	1.440
Viticultural advisor	0.002	0.258	0.000	1.002
4per1000	-0.141	0.472	0.089	0.869
Resources	0.467***	0.124	14.137	1.596
Attitude	0.128	0.123	1.094	1.137
Confidence	0.281**	0.116	5.891	1.325
Constant	-0.286	1.127	0.065	0.751
Chi-square	37.356 (p = .011)			
Nagelkerke R^2	0.125			
Log-likelihood	461.078			
Accuracy	69.5%			

p < .1 = *; p < .05 = **; p < .01 = ***

4.4.3.5. Hedges

The decision to adopt HG was positively influenced by the predictors vine planting, HVE, AB, resources and confidence, and negatively influenced by the variable subsidy (Table 4.7). HVE had a particularly powerful effect on the decision to adopt HG compared to the other five variables: respondents whose viticultural farm is certified HVE are considerably more likely (by a factor of 4.38) to adopt HG than respondents whose farm is not certified HVE.

Table 4.7. Results of the binary logistic regression for the prediction of winegrowers' adoption of HG.

HG	**Coefficient**	**Standard error**	**Wald**	**Odds ratio**
Gender	0.065	0.295	0.049	1.067
Age	-0.013	0.010	1.489	0.988
Education	0.129	0.249	0.271	1.138
Viticultural degree	0.308	0.265	1.347	1.361
Landowner	0.479	0.339	2.001	1.614
Inherited vineyard	-0.333	0.253	1.734	0.717
Independent winegrower	0.231	0.251	0.848	1.260
Farm size	0.068	0.119	0.326	1.070
Workforce hired	-0.007	0.016	0.193	0.993
Vine planting	0.183*	0.107	2.905	1.200
HVE	1.478***	0.368	16.131	4.383
AB	0.627**	0.248	6.391	1.872
Irrigation	0.198	0.358	0.304	1.218
AECM	0.230	0.307	0.558	1.258
Subsidy	-0.482*	0.255	3.560	0.618
Viticultural advisor	-0.159	0.245	0.419	0.853
4per1000	-0.170	0.465	0.134	0.843
Resources	0.419***	0.117	12.739	1.520
Attitude	0.082	0.118	0.480	1.085
Confidence	0.305***	0.115	7.029	1.357
Constant	-1.264	1.090	1.346	0.282
Chi-square	65.610 (p = .000)			
Nagelkerke R^2	0.202			
Log-likelihood	488.547			
Accuracy	66%			

p < .1 = *; p < .05 = **; p < .01 = ***

4.5. Discussion

4.5.1. Influence of the predictors on the decision to adopt soil organic carbon sequestration practices

Twelve predictors out of twenty had a significant effect on the decision to adopt at least one SCS practice: age, independent winegrower, farm size, workforce hired, vine planting, HVE, AB, irrigation, subsidy, resources, attitude and confidence (Table 4.8). However, there were variations in the significance of the explanatory variables between SCS practices.

Table 4.8. Summary of how the significant factors influence the decision to adopt SCS practices.

Factors	OA	BC	PR	NT	CC	HG
Age			–			
Independent winegrower	+					
Farm size			+		–	
Workforce hired			–	–		
Vine planting	–				+	+
HVE			+			+
AB	+			–		+
Irrigation	–			–		
Subsidy						–
Resources				+	+	+
Attitude				+		
Confidence				+	+	+

Age had a significant, negative effect only on the decision to adopt PR. This confirms the results of previous studies analysing the role of farmer age in the adoption process of new practices (*e.g.*, Lambert et al., 2015; Sánchez et al., 2016; Paul et al., 2017). Several reasons explain why younger farmers are, in general, more likely to adopt management practices than older farmers. Younger farmers have a longer planning horizon than older farmers, which makes them more inclined to adopt new management practices, especially if they maintain or increase production on the farm (Knowler and Bradshaw, 2007). Younger farmers are also more exposed to information about new practices and are, therefore, more knowledgeable about innovations (Barnes et al., 2019). They are also more willing to face learning curves (Roberts et al., 2004). Long et al. (2016) observed in several European countries (the

Netherlands, France, Switzerland and Italy) that older farmers may be reluctant to change traditional agricultural practices, even if new practices are tried and tested. The difficulty in overcoming traditions makes it harder to incentivise training in new agricultural practices among older farmers.

Farm size had a significant effect on the decision to adopt PR and CC but was not significant for the other SCS practices; however, the effect of the variable was positive for PR but negative for CC, which means that winegrowers with larger vineyards are more likely to adopt PR but less likely to implement CC than winegrowers with smaller vineyards. Literature on the influence of farm size on the adoption of new management practices by farmers reports mixed effects of the variable. Lambert et al. (2015) and Barnes et al. (2019) both found that farmers with larger farms are more likely to be adopters of precision agriculture technologies. Goldberger and Lehrer (2016) also found that walnut growers with larger orchard farms were more likely to adopt biological control practices in the western USA, and Prager and Posthumus (2010) observed greater uptake of soil conservation practices in larger farms in Europe. This positive influence can be explained by the fact that, in larger farms, the costs of adopting a new practice are spread over more hectares (Lambert et al., 2015) and that when more land is being cultivated, farmers become less vulnerable to failure from the new practice (Mariano et al., 2012). Conversely, Despotović et al. (2019) showed that with increasing farm size, farmers become less willing to adopt integrated pest management practices, because they are less ready to take a risk by reducing pesticide use. This suggests that the effect of farm size on the adoption of new management practices is context-specific, and this applies to the adoption of SCS practices by French winegrowers.

The size of the workforce hired had a significant, negative effect on the decision to adopt PR and NT (but had no significant effect on the decision to adopt other SCS practices). This finding is consistent with that of Tey et al. (2014), who noticed that the number of hired workers was one of the most important factors in the adoption of conservation tillage and crop rotation in Malaysia and that its effect was negative. It could be explained in the case of French viticulture by the important costs associated with hiring workers on a full-time basis, which could reduce winegrowers' willingness to adopt PR and NT, due to the capital investment in new equipment necessary for both practices (Posthumus et al., 2015; Garcia et al., 2018). Conversely, as soil tillage requires more qualified workers, such as tractor drivers, than NT (especially when NT takes the form of chemical weeding), viticultural farms with a high number of workers are more likely to be associated with the use of tillage than with the use of NT. This goes against the results of other studies, which found a positive effect of hired (Barnes et al., 2019) or family (Paul et al., 2017) labour on the adoption of new management practices. The positive effect of family workforce observed by Paul et al. (2017) is, however, due to the fact that an increased number of family members working on the farm leads to a reduction in labour intensity, particularly in smaller farms where labour is more often manual than on larger farms, but at lower costs than when labour is hired outside of the household.

Being an independent winegrower had a significant effect on the decision to adopt OA but not any other SCS practice. This effect was positive, probably because independent winegrowers often have more capital and equipment than other winegrowers and would have a higher capability to adopt OA. The year of vine planting also significantly influenced the decision to adopt OA, CC and HG. The effect of the variable was negative for OA but positive for CC and HG.

Being certified HVE had a strong, positive effect on the decision to adopt PR and HG (by a factor of 7.29 and 4.39, respectively). This is coherent with the restrictions of the label, which require the use of practices that limit as much as possible inputs coming from outside the agricultural system and that help to increase biodiversity on the farm (IFV, 2019).

Being certified AB had a significant influence on the decision to adopt OA, NT and HG; however, this effect was positive in the case of OA and HG but negative for NT. The strong positive effect (by a factor of 3.02) obtained for the adoption of OA was anticipated since organic agriculture forbids the use of synthetic fertilisers, which are replaced by organic amendments (Council of the European Union, 2007). Under organic viticulture, winegrowers use OA to increase soil properties and quality and to ensure that grape yields are sufficient. However, organic fertilisers are used cautiously on viticultural land (often according to soil testing), as too much vine vigour could lead to a decrease in grape quality for winemaking. The positive effect of AB on the adoption of HG could be explained by the important role hedges play in agroecosystems under organic farming, mainly by providing shelter for beneficial organisms, which act as pest control in lieu of pesticides, and by improving soil quality and water infiltration (Holden et al., 2019). The negative effect of AB on NT can also be explained by the fact that, under organic certification (Council of the European Union, 2007), winegrowers cannot use herbicides treatments to control weed growth in vineyards; a majority uses tillage instead to ensure that weed does not compete too much with the vine.

The use of irrigation by winegrowers had a negative impact on the decision to adopt OA and NT. This could be due to the lower evapotranspiration associated with the use of NT, which may reduce the need for irrigation. It is also related to the bio-climatic conditions of the winegrowing regions where irrigation is used. Irrigation in viticulture is mostly practised in the southeast of France, where precipitations are low. Tillage is commonly used under such conditions as a way to mitigate the water and nitrogen competition between weed and vine. The negative effect of irrigation on the adoption of OA is surprising, however, as irrigation is often used on viticultural soils with low OM content, where the use of organic amendments could improve soil water retention and quality. It goes against the findings by Sánchez et al. (2016), who noted a positive effect of irrigation on the adoption of intercropping practices in Spain.

Receiving subsidies was, surprisingly, only significant in the decision to adopt HG and in a negative way. Previous studies observed, inversely, a positive effect of subsidies on the adoption of new management practices such as CC and intercropping (Sánchez et al., 2016) or precision agriculture technologies (Barnes et al., 2019). The negative effect of subsidies on the adoption of HG in viticulture might be due to the specific nature of subsidies that respondents were asked about: set up in the context of the vitivinicultural common market organisation and developed by FranceAgriMer[10], these subsidies aim at incentivising vineyard restructuration that would improve productivity, mainly by modifying vine row density, training the vine or implementing irrigation practices (FranceAgriMer, 2020), but they do not target non-productive investments such as hedgerows. Other types of financial incentives targeting more specifically the implementation or maintenance of hedgerows exist at the regional or *département* level, but respondents were not asked about them in the survey.

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[10] FranceAgriMer is a French agricultural agency whose aim is to implement the measures set up by the Common Agricultural Policy at the national level and to undertake actions to support the agriculture sector. It receives a fund of €280 million every year to support vineyard restructuration and conversion, investments in vitivinicultural businesses, wine promotion abroad, and the distillation of wine by-products (FranceAgriMer, 2020).

The variable resources had a significant and positive effect on the decision to adopt NT, CC and HG, which means that winegrowers who believe that they have the necessary resources (*i.e.* time and appropriate equipment) to adopt SCS practices are more likely to adopt NT, CC and HG than winegrowers who do not. This is in line with previous studies that analysed the effect of this variable on the adoption process of new agricultural practices (*e.g.*, Tey et al., 2014; Daxini et al., 2018; Barnes et al., 2019). These studies concluded that farmers who believed that their current machinery was able to support the new technology were more likely to adopt it. This finding is relevant to the fact that the implementation of SCS practices may require new tools and be time-consuming. Although the adoption of NT may reduce fuel and time costs associated with tillage, it is likely to require capital investment in new equipment (Posthumus et al., 2015) and to generate costs associated with weed control such as herbicides (Maillard et al., 2018). These costs, however, vary depending on the planting density of the vineyard: the costs of tillage are considerably higher than those of NT in vineyards with a high planting density but tend to be similar to those of NT in vineyards with a low planting density. The implementation of CC is associated with additional inputs and time costs (Sykes et al., 2020). Planting hedges requires capital investment for appropriate tools and increases time costs for maintenance (Lasco et al., 2014).

The variable attitude had a significant and positive effect on the decision to adopt NT, which is in line with the strong positive relationship between attitude and behaviour found by previous studies (*e.g.*, Wauters et al., 2010; van Dijk et al., 2016; Rezaei et al., 2018; Despotović et al., 2019). The positive effect of attitude on the decision to adopt was to be anticipated considering the important role attitude plays in behavioural modelling, and particularly in the theory of planned behaviour: it is generally admitted that the more favourable an attitude is towards a behaviour, the higher the possibility that an individual will perform the behaviour (Ajzen, 1991). For this reason, it was quite surprising that winegrowers' attitudes towards SCS practices did not have a significant effect on the adoption of the other SCS practices. This might be because the statements used to create the principal component 'attitude' considered SCS practices as a whole, but respondents may have answered with specific SCS practices in mind.

The variable confidence influenced significantly and positively the decision to adopt NT, CC and HG, suggesting that farmers who are confident in their capability to adopt SCS practices are more likely to adopt these practices. This is in line with the findings of Daxini et al. (2018) and Despotović et al. (2019), who noted a positive effect of the variable on farmers' intention to adopt specific management practices. It highlights the fact that if winegrowers do not adopt NT, CC and HG, it is not necessarily because they lack the motivation to do so but instead because they lack suitable levels of confidence in their understanding and skills to take action (Wilson et al., 2018).

It was surprising that the variable viticultural advisor was not significant for any of the practices. Most studies investigating the factors influencing the adoption of new agricultural practices reported a positive effect of being in contact with an agricultural advisor on adoption (*e.g.*, Ingram, 2008; Baumgart-Getz et al., 2012; Daxini et al., 2018; Barnes et al., 2019). Such a positive effect can be explained by the important support role of advisors, who provide knowledge and technical expertise, which encourages adoption (Busse et al., 2014). The effectiveness of this support role depends, however, on the advisors' knowledge and understanding of management practices, which, in the case of SCS practices, tends to be low at the European level (Ingram et al., 2014). SOC sequestration is not currently an objective in viticulture, which may explain why the variable viticultural advisor was not significant in this study. Nevertheless, SCS practices are in agreement with what is generally advised by viticultural advisors (*e.g.*, in the context of agroecology).

4.5.2. Uncertainty and further research

Although the simple random sample of French winegrowers created in this chapter was large (n = 400), a sampling error was detected in the fact that the adoption rate of some SCS practices in the sample was higher than at the national level as established by the latest national survey undertaken by the French Government (Agreste, 2017). The adoption rate of PR in the sample (91%) was similar to that estimated at the national level (87%), but this was not the case for the adoption rate of OA (73%), NT (50%) and CC (69%), which were considerably higher than at the national level (9%, 21% and 45%, respectively). This suggests that there is an overrepresentation of winegrowers who have adopted SCS practices in the sample, which may be because these winegrowers might have higher concerns about soil quality and climate change and would, therefore, be more inclined to answer the questionnaire. This overrepresentation may have skewed some of the results of the logistic regressions since adopters of SCS practices are more likely, on average, to have positive attitudes towards the practices than non-adopters. Furthermore, winegrowers whose viticultural farm is certified organic were overrepresented in this study: they represented 33% of the sample, while only 8% of the total viticulture at the national level is conducted under organic farming (Agreste, 2017). This could explain, for instance, the higher adoption rate of OA in the sample since the use of organic amendments is encouraged under organic agriculture as an alternative to synthetic fertilisers.

The adoption intensity in the sample averaged 3.3 practices, ranging from 0 (n = 1) to 6 (n = 1) practices adopted by a single respondent. Most respondents to the questionnaire implemented three or four practices (31% and 30%, respectively). 17% of respondents implemented two practices and 16% implemented five practices. Only 5% of the respondents implemented one practice, overall. This shows that winegrowers do not adopt just one SCS practice but, conversely, several at the vineyard level. The adoption intensity was not taken into account in this study; however, there is room for further research to investigate the factors having an influence on the adoption intensity of SCS practices and whether having already adopted one or several SCS practices incentivises winegrowers to implement more on their viticultural farm. This would be of great importance to better understand the role viticultural land could play in sequestering SOC since the adoption of several SCS practices at the vineyard level (*e.g.*, OA+NT) is associated with higher SOC sequestration rates than the adoption of a single SCS practice (*e.g.*, only OA or only NT), based on field experiments (see Chapter 2 and Chapter 3). Questions regarding the adoption intensity of SCS practices in French vineyards could be added to the surveys on viticultural practices conducted by Agreste at the national level, which rely on sample groups representative of each winegrowing region of France.

Another limitation stems from the fact that the binary logistic regression used in this chapter did not consider exhaustively the eventual influence of non-SCS practices on winegrowers' likelihood to adopt SCS practices. Although water management practices were included in the analysis (through the variable irrigation), other management practices relating to weed or pest control (*e.g.,* the use of herbicides or pesticides) were not. Integrating these non-SCS practices into the questionnaire and regression as explanatory variables would have made the analysis more comprehensive since such practices may interact with the use of SCS practices. For instance, because tillage is traditionally used in vineyards as weed control, winegrowers reluctant to use herbicides on their farm (due to their engagement in organic farming, for example) would be expected to be less likely to adopt NT.

4.6. Conclusions

This chapter adds to the existing literature relating to farmers' decision-making behaviour and adoption of new agricultural practices. It also addresses a gap in the literature, as vineyard agroecosystems have not been considered for analysis by any study dealing with the adoption process of SCS practices. The use of a binary logistic model proved to be adequate to evaluate the impact of the different variables tested in the study, except in the case of BC, whose adoption rate in the sample was too low for the model to be significant. Results show that socio-economic and behavioural characteristics are important factors in the decision to adopt SCS practices. Specific aspects of viticultural production (*e.g.*, vine age or being an independent winegrower) are also significant drivers of the decision to adopt the practices.

Findings from this chapter could help to improve policy targeted at the viticulture sector in France and potentially in the EU. The current subsidies received by French winegrowers do not incentivise effectively the adoption of agricultural practices with SOC sequestration elements, since subsidies did not play any significant role in the adoption of OA, PR, NT and CC in this study. The same could be said of AEMs: even though a relatively large number of winegrowers from the sample were involved in a measure directly incentivising the adoption of a SCS practice (mostly OA, CC and HG), being involved in an AEM did not have any significant effect on the adoption of these practices. This suggests that many winegrowers who implement SCS practices are not necessarily involved in the corresponding AEM, which represents a potential loss of earnings for these winegrowers. Further research would seek to understand the reasons behind this, and whether it is because payments are not high enough or winegrowers are not sufficiently aware of AEMs. Overall, results from this chapter provide insights into the decision-making behaviour of winegrowers, which could be useful in the context of the '4 per 1000' initiative, of which France is a founding member.

Chapter 5

Why do French winegrowers adopt soil carbon sequestration practices? Understanding motivations and barriers

5.1. Abstract

SCS practices on French agricultural land are part of the portfolio of actions available to policymakers in the field of climate change mitigation and are central to the success of the '4 per 1000' initiative, launched by France in 2015. To date, there has been limited research considering their applicability to vineyards. A survey was circulated to 506 French winegrowers to identify the adoption rate of six SCS practices in the viticulture sector (applying organic amendments, using biochar, returning pruning residues to the soil, no-tillage, cover cropping, and introducing or preserving hedges in the vineyard) and to explore motives and barriers to adoption. The survey also investigated ways of overcoming barriers to adoption and winegrowers' perception of AEMs. Differences in motivations and barriers between SCS practices were found, and winegrowers themselves suggested a need for improved communication of evidence about SCS practices and better-targeted policy incentives to support adoption.

5.2. Introduction

As is the case with many other developed nations, France has set ambitious GHG emission reduction targets for the coming decades: reducing GHG emissions by at least 55% compared to 1990 levels by 2030 and achieving carbon neutrality by 2050 (European Commission, 2021). To achieve these targets, the country will need to implement technologies leading to a net removal of GHGs from the atmosphere in addition to GHG emission reduction strategies (IPCC, 2018). In this context, in 2015, the French government launched the '4 per 1000' initiative (4p1000, 2018), which aims to achieve an annual growth rate of 0.4% in the global SOC stocks. SOC sequestration in agricultural soils has been identified as an effective mitigation technology, both at the global level (*e.g.*, Smith, 2016; Fuss et al., 2018; Sykes et al., 2020) and in France more specifically (*e.g.*, Pellerin et al., 2013; Pellerin et al., 2019). Several studies have evaluated the feasibility of the '4 per 1000' objective in French soils (*e.g.*, Minasny et al., 2017; Martin et al., 2021) and identified territories offering high SOC sequestration potential (Angers et al., 2011; Launay et al., 2021). Pellerin et al. (2019) showed that nine SCS practices were of interest for agricultural land in France: the use of no-tillage, cover cropping, the introduction of temporary pastures in crop rotations, the use of organic amendments, the introduction of agroforestry, planting hedges, implementing a moderate intensification of extensive pastures, transitioning from hay meadows to pastures, and the introduction of cover crops in vineyards. These practices have different sequestration potentials and are associated with varying implementation and maintenance costs.

Despite many SCS practices being associated with low or negative costs, their adoption by farmers is part of a complex decision-making process, including agronomic, environmental, sociological, economic and ethical dimensions (Chenu et al., 2019). Improving our understanding of the enabling environment for these practices in the agriculture sector is crucial to designing effective policies to incentivise their adoption. It is also important to consider the motives of different categories of land users and, to date, there has been little consideration of SOC sequestration in vineyards, which account for 3% of the agricultural territory in France. This study investigates the motivations underlying the adoption of SCS practices by farmers in France, as well as the eventual barriers that may hinder the adoption of these practices, via an online survey circulated nationally to winegrowers. Viticulture was chosen as a case study due to the importance of traditions and elements of national culture inherent to viticultural and winemaking know-how. This research also explores how motivations and barriers correlate to the way winegrowers view AEMs, which are commonly applied by the French government in the viticulture sector to support the adoption of some SCS practices (*e.g.*, cover cropping, no-tillage, maintenance of hedges, etc.).

The chapter is structured as follows. The next section provides background information on agricultural measure adoption and policy instruments to incentivise behavioural change. Section 5.4 covers data collection and methods. Section 5.5 provides results from the survey, categorised by motivations and barriers for each SCS practice considered. Section 5.6 discusses differences in motivations and barriers between SCS practices and puts the results of this study within the broader context of the literature on farmer motivations for adopting agricultural practices. Section 5.7 covers conclusions.

5.3. Agricultural practice adoption and agri-environment schemes

There is an extensive literature investigating, using mainly survey methods, the different factors (socio-economic, demographic, technical, etc.) associated with farmers and farms that influence the adoption of SCS practices on agricultural land (*e.g.*, Ingram et al., 2014;

Sánchez et al., 2016; see Chapter 4). However, psychological factors, such as farmers' motivations for undertaking various environmental activities, and constraints faced by farmers, whether they are structural or environmental, have received less attention. Motivations, more specifically, are important elements explaining farmer behaviour. Mills et al. (2013) identified a variety of extrinsic (*i.e.* financial incentives, risk minimisation, profit maximisation, capital investment, regulation, respect among peers and recognition in wider society) and intrinsic (*i.e.* personal sense of environmental responsibility, interest in the environment and personal sense of enjoyment) motivations involved in changes in farmer behaviour towards more environmentally-friendly practices. The strength of these motivations and the way they interact with each other can have a profound effect on farmer behaviour: changes in behaviour motivated by intrinsic reasons, for instance, tend to be more persistent than changes triggered by extrinsic motivations (Mills et al., 2018), while economic factors (*i.e.* household income, land tenure, family labour, and farm business structure) appear to be particularly influential determinants of participation (Lastra-Bravo et al., 2015). Additional studies are, thus, needed to refine our knowledge of the conditions that foster or perpetuate the use of SCS practices on agricultural land (Soussana et al., 2019).

A number of policy approaches can be used to incentivise behavioural change in the agriculture sector, including economic incentives, regulatory and control approaches, information schemes, and voluntary actions and agreements (IPCC, 2014). In the EU, AESs have been introduced as a key tool for the integration of environmental concerns into the Common Agricultural Policy (European Commission, 2017). AESs provide financial support for the Member States to implement AEMs. In France, as in many other Member States of the EU, AEMs serve as the main policy instrument to instigate a change toward more sustainable practices in the agriculture sector by providing payments to farmers who undertake specific agricultural practices aiming at protecting the environment on the farmland or reducing GHG emissions from agricultural activities. Each AEM has a specific environmental objective, such as climate change mitigation, climate change adaptation, biodiversity protection, soil quality improvement, etc. (European Commission, 2017). A core principle of AEMs is that participation is voluntary; farmers' willingness to participate in AEMs is, therefore, central to achieving policy objectives (Espinosa-Goded et al., 2010).

However, research (*e.g.*, Hammes et al., 2016) showed that AEMs have not been as effective as intended, which is illustrated by the insufficient participation of farmers in these measures.

This lack of success is due partly to a poor understanding of farmers' attitudes towards AEMs and individual reasons for participating or not (de Snoo et al., 2013; Schroeder et al., 2015). If AEMs are to be used to incentivise the uptake of SCS practices on agricultural land in France, a better knowledge of how French farmers perceive them would be central to the development of improved AEMs for SOC sequestration (Hammes et al., 2016). Farmers, like other people, may also not simply prioritise financial gain above all else; they can, on the contrary, gain equal or greater utility from actions benefiting society or the environment (Wynne-Jones, 2013). Increasing our understanding of what motivates farmers to adopt SCS practices may provide valuable insight to assess whether AEMs, under their current form, are the best policy instrument to incentivise the uptake of SCS practices.

5.4. Data collection

5.4.1. Soil organic carbon sequestration practices

Six SCS practices were included in this chapter: OA, BC, PR, NT, CC and HG. These practices have been identified as having the potential to participate in climate change mitigation via SOC sequestration on viticultural land (Demenois et al., 2020; see Chapter 2 and Chapter 3). Except for PR, the adoption rate of these practices at the national level of France is low (Agreste, 2017).

5.4.2. Mixed-methods approach

A survey was created to understand the drivers of and barriers to the adoption of SCS practices by winegrowers in France. It was developed using literature review and expert consultations and was piloted with a small group of winegrowers. The survey consisted of a combination of both close-ended and open-ended questions to gather a mix of quantitative and qualitative data. It was divided into four sections (Appendix F). Section one collected information used for classifying respondents according to their role in the viticultural farm (*e.g.*, farm manager, head of cultivation, etc.) and the geographical location of their vineyard (*département* and winegrowing region). The second section asked winegrowers, for each SCS practice, the reasons that motivated their adoption of the practice, in case they had adopted it, or the barriers that prevented them from adopting the practice, in case they had not adopted it.

It also investigated specific actions that the winegrowers believed could alleviate some of the identified barriers. These questions were open-ended to allow winegrowers to express what they felt were the most important motivations and barriers without leading their answers with pre-selected options. For each practice, winegrowers were free to mention as many motivations and barriers as they felt like; the aim was to grasp all the different types of motivations and barriers that would be mentioned by the respondents and to assess which would be more prevalent. Answers were analysed and categorised using thematic analysis, which is a particularly effective method to facilitate the organisation of qualitative data and determine common perspectives among respondents (Creswell and Guetterman, 2020). The third section was designed to collect data on winegrowers' received subsidies and participation in AEMs. The last section aimed at understanding winegrowers' attitudes towards AEMs: winegrowers were asked to evaluate four statements created to reveal their attitudes towards AEMs using a 5-point Likert scale.

An online survey was conducted between July 2020 and January 2021. It was administered via Google Form, using a random method. Responses were anonymous and handled in accordance with the General Data Protection Regulation. The survey targeted winegrowers who had an active decision-making role regarding how to conduct viticultural activities on their vineyard; only the responses of farm managers, co-managers, heads of cultivation (*chefs de culture*) and technical directors (*directeurs techniques*) were accepted. 1,635 winegrowers were contacted by email using personal contacts, viticultural databases and wine shops. The French Institute of Vine and Wine and several regional inter-professional councils of wine (*e.g.*, the *Syndicat des vignerons des Côtes du Rhône*) were contacted and circulated the questionnaire to their members. A total of 506 full responses were received from across France, giving a return rate of 31%. Most winegrowers who responded were farm managers (84%), with the remainder being either co-managers (10%), heads of cultivation (5%) or technician directors (1%). Responses covered each of the fourteen French winegrowing regions, though a higher number of responses was received from regions with a larger viticultural land (*e.g.*, Languedoc-Roussillon and the Rhône Valley).

5.5. Results

5.5.1. Viticultural practices and participation in agri-environment measures

The adoption rate of SCS practices among French winegrowers was high, overall: almost all winegrowers surveyed (99.6%) have adopted at least one SCS practice; only two respondents out of the 506 have not adopted any SCS practice at all. Most winegrowers (91%) return pruning residues to the soil, either simply leaving them on the ground or crushing them with a woodchipper to facilitate their incorporation into the soil. The use of organic amendments and cover cropping is practised by a high number of surveyed winegrowers (73% for both). More than half the respondents (57%) maintain hedges in their vineyard, while a bit less than half (48%) practise no-till viticulture. Only very few winegrowers (2%) use biochar amendments in their vineyard.

Winegrowers' participation in AEMs was low, with around 24% of respondents stating that they were involved in an AEM. Not all respondents indicated which AEM they were participating in, but the most commonly cited were COUVER_06 (Creation and management of a grass cover or strip), COUVER_11 (Creation of a soil cover on the inter-rows of grapevines), PHYTO_02 (No use of herbicides) and PHYTO_10 (No use of herbicides on the inter-rows of perennial crops). COUVER_11 targets viticultural systems specifically, whereas the other AEMs were developed more broadly for perennial systems (PHYTO_10) or all types of agricultural systems in France (COUVER_06 and PHYTO_02). 47% of the winegrowers surveyed received subsidies as part of the National Programme of Support to the Viticultural and Wine Sector.

5.5.2. Motivations for and barriers to the adoption of SCS practices

5.5.2.1. Organic amendments

Out of 506 respondents to the survey, 341 indicated one or several drivers that motivated the use of OA in their vineyard. Motivations behind the adoption of OA were mostly to achieve biophysical and economic outcomes (Fig. 5.1). The most commonly given motivation was the wish to return OM to the soil to improve SOM and enhance soil quality, which corresponded to 58% of all identified motivations for OA and was given by 276 respondents out of the 341 who answered this question. Fertilising grapevines to increase vine vigour and maintain yields was also an important motivation for using OA in vineyards (19% of all identified motivations). Several other motivations were mentioned by winegrowers, but their frequency was considerably lower.

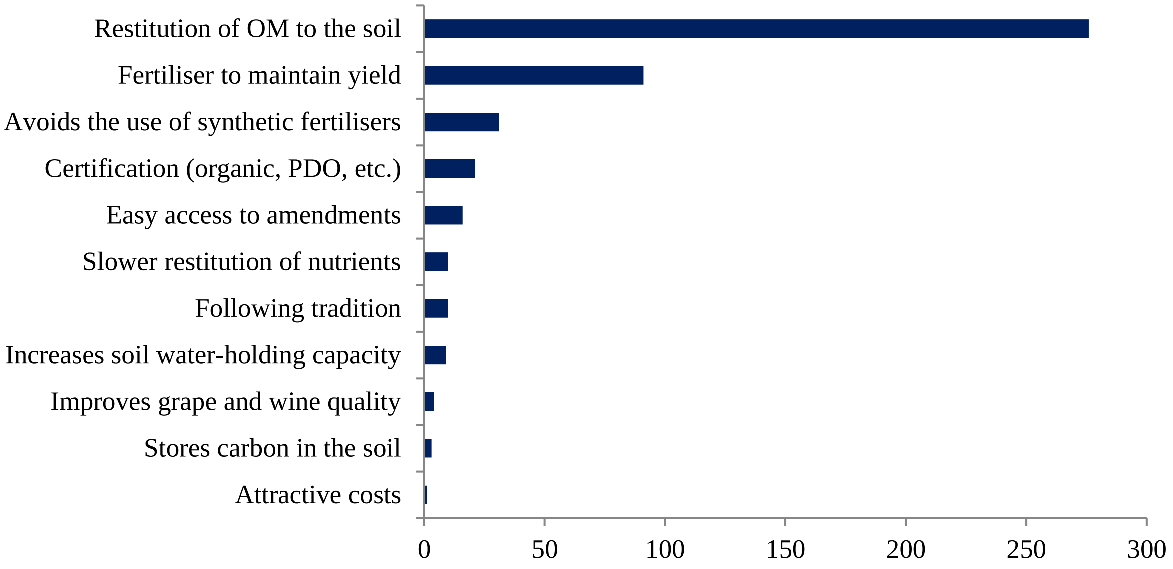


Fig. 5.1. Motivations for the adoption of OA in viticulture in France (n = 341). Several responses were possible for each respondent.

The number of respondents who identified eventual barriers that prevented them from using OA in their viticultural farm was lower than for motivations (n = 107). This was to be expected based on the adoption rate of OA, which was high. Barriers to the adoption of OA were mainly economic, biophysical and technical (Fig. 5.2). The total count was more homogeneously distributed between each barrier, which suggests that the reasons behind the non-adoption of OA were context-specific. Two barriers, in particular, were very often given by winegrowers: the fact that costs associated with the use of OA (mainly the costs of purchasing organic amendments) were too high (31%) and that the use of OA was not needed in the vineyard, since winegrowers achieved expected yields without them, there was a good C/N balance in the soil without them, or there were risks of disrupting grape quality by increasing yields too much (26%). The rest of the barriers mentioned by winegrowers were less commonly observed in the sample.

Fig. 5.2. Barriers to the adoption of OA in viticulture in France (n = 107). Several responses were possible for each respondent.

5.5.2.2. Biochar amendments

As the adoption rate of BC was very low in the sample, only a very small number of respondents indicated motivations for the adoption of this practice (n = 6). However, because the use of BC is still more experimental in viticulture than the other SCS practices considered in this study, statements from these winegrowers were very valuable in understanding the rationale behind the use of BC in viticulture. The main motivation behind the use of BC was the restitution of OM to the soil to improve SOM and soil fertility (43%) (Fig. 5.3). One winegrower stated that they were using BC specifically to capture and store CO_2 into the soil to help to mitigate climate change, and for no other reason.

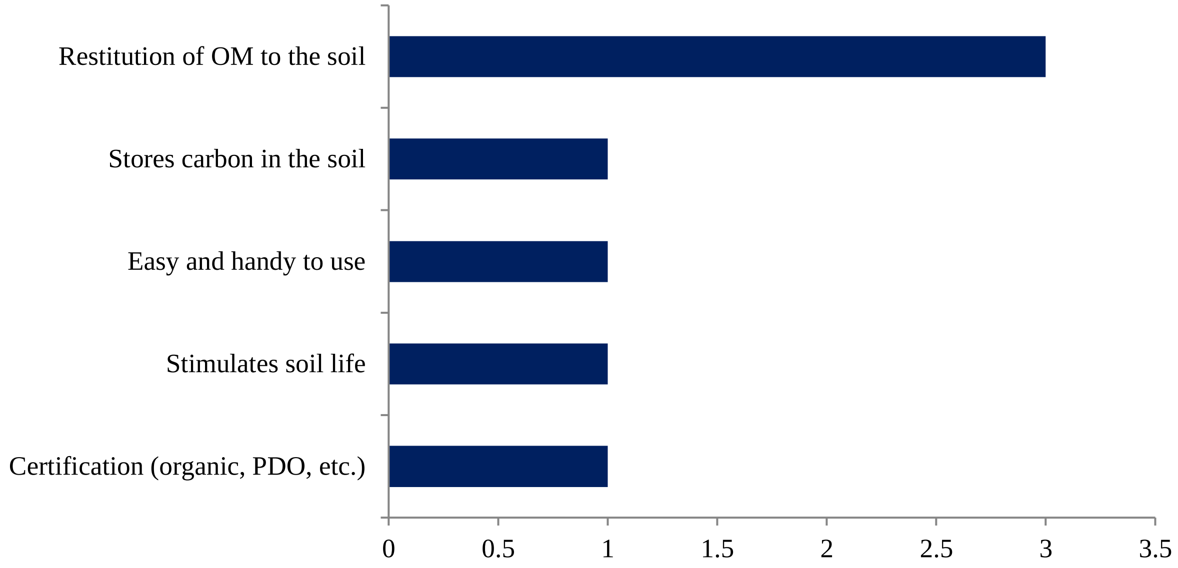


Fig. 5.3. Motivations for the adoption of BC in viticulture in France (n = 6). Several responses were possible for each respondent.

Despite the non-adoption of BC by nearly all the respondents, almost half of them decided not to answer this question (n = 221), perhaps because they were unfamiliar with the practice. Barriers to the use of BC in vineyards were mostly capacity-building barriers (Fig. 5.4). The main barrier to the adoption of BC comes from the fact that most winegrowers are unaware that this practice exists: this barrier corresponded to 66% of all barriers identified and was given by 201 respondents out of the 279 who answered this question. Even among winegrowers who are aware of BC, the practice is not well-understood, because not enough information about it is available to winegrowers, especially information on the benefits of using BC, how to implement the practice, and the long-term effects of the practice on the soil (8%).

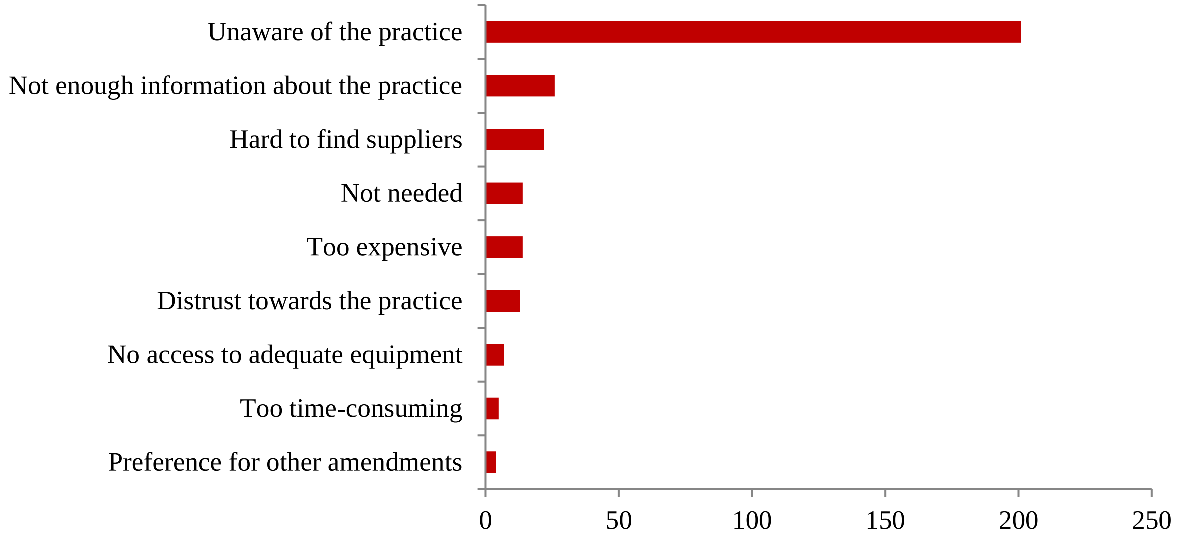


Fig. 5.4. Barriers to the adoption of BC in viticulture in France (n = 279). Several responses were possible for each respondent.

5.5.2.3. Returning pruning residues to the soil

Contrary to BC, the adoption rate of PR was very high; as a result, a substantial number of respondents identified motivations behind the use of PR in their vineyard (n = 421). Motivations for the adoption of PR in viticulture were mainly to reach biophysical outcomes and technical reasons (Fig. 5.5). As for OA, the most important motivation for using PR was the wish to return OM to the soil to improve SOM and soil quality (48%). 283 respondents out of 421 mentioned the restitution of OM as one of the main drivers for the use of PR. The second two most important motivations for PR were that the practice is particularly easy and handy to conduct (20%) and leads to a gain of time for the winegrower (7%) since gathering and exporting residues out of the vineyard requires specific equipment and techniques and is quite time-consuming. The other motivations given by respondents were technical and environmental.

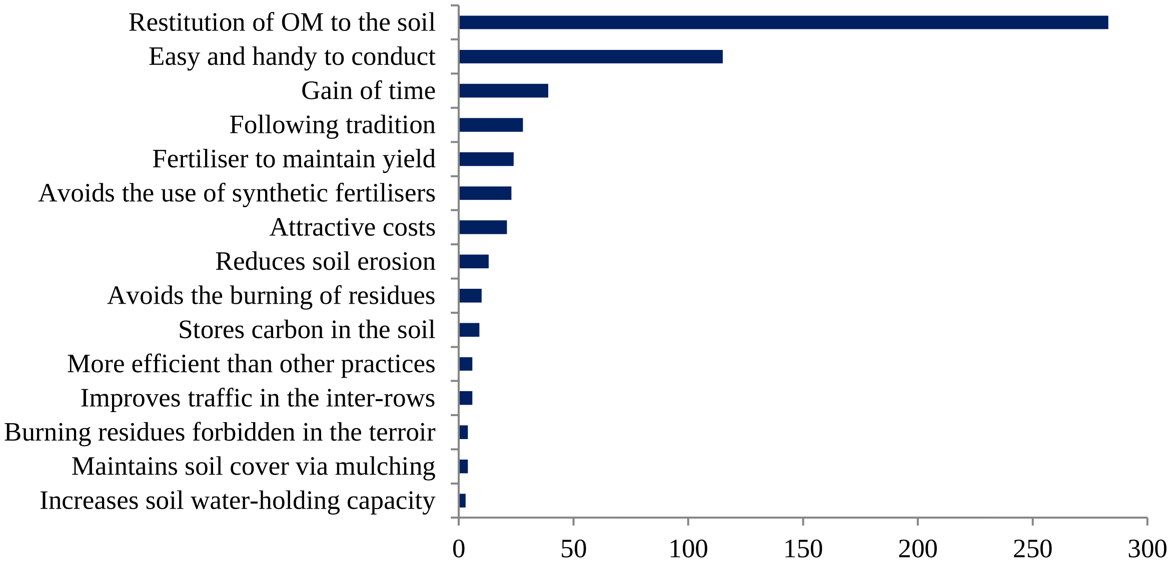


Fig. 5.5. Motivations for the adoption of PR in viticulture in France (n = 421). Several responses were possible for each respondent.

Only 42 out of the 506 winegrowers in the sample responded to the question about barriers to the adoption of PR, which was predicted due to the high adoption rate of PR. Barriers to the adoption of PR were mainly technical and biophysical (Fig. 5.6). Though several barriers were identified by winegrowers, one was prevalent: the fact that returning pruning residues to the soil could facilitate the propagation of wood diseases, such as mildew, to the soil (49% of all identified barriers). Other barriers were more sporadically given. An interesting barrier from a social perspective is the cultural aspect associated with the use of PR by some winegrowers, who have been using them traditionally for heating or cooking purposes.

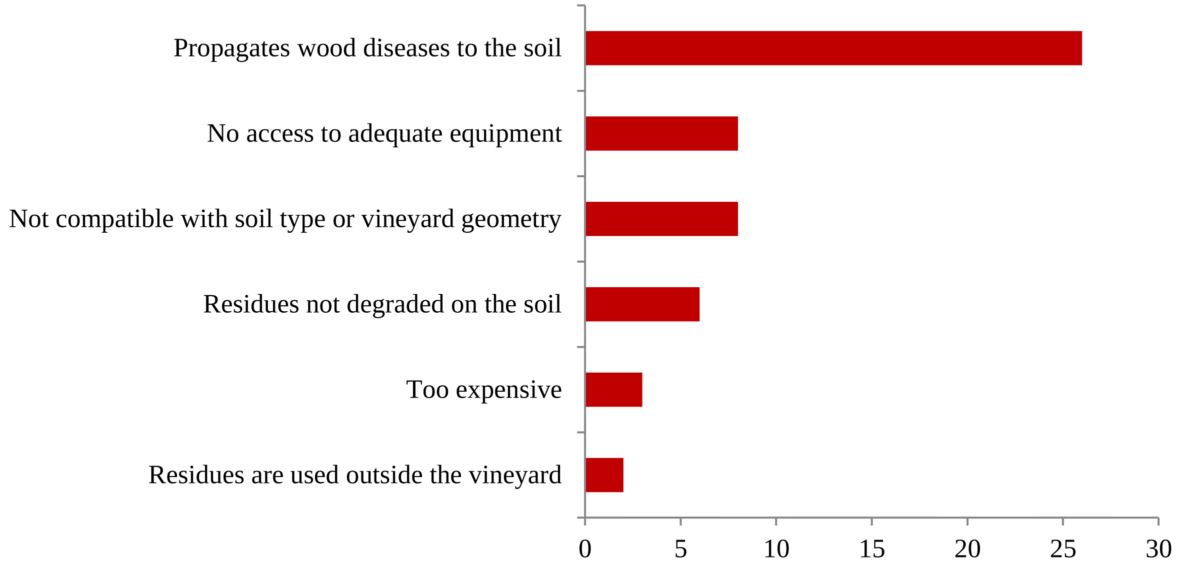


Fig. 5.6. Barriers to the adoption of PR in viticulture in France (n = 42). Several responses were possible for each respondent.

5.5.2.4. No-tillage

The adoption rate of NT was more balanced between adopters and non-adopters than it was for other SCS practices. The number of respondents who provided motivations behind the adoption of NT in their vineyard (n = 201) was consistent with the number of winegrowers using the practice in the sample (245 out of 506). Motivations for the adoption of NT in viticulture were predominantly to reach specific biophysical outcomes (Fig. 5.7). Three important biophysical outcomes were mentioned by winegrowers: to preserve soil life (*i.e.* microorganism and earthworm activity), which may be disturbed and negatively impacted by tillage (19% of all identified motivations); to maintain soil structure and avoid mixing soils horizons (14%); and to reduce soil erosion, which may be aggravated by a deep and regular ploughing of the soil, especially if left bare afterwards (13%). Other motivations were environmental and cultural; their frequency was lower than that of the motivations previously presented.

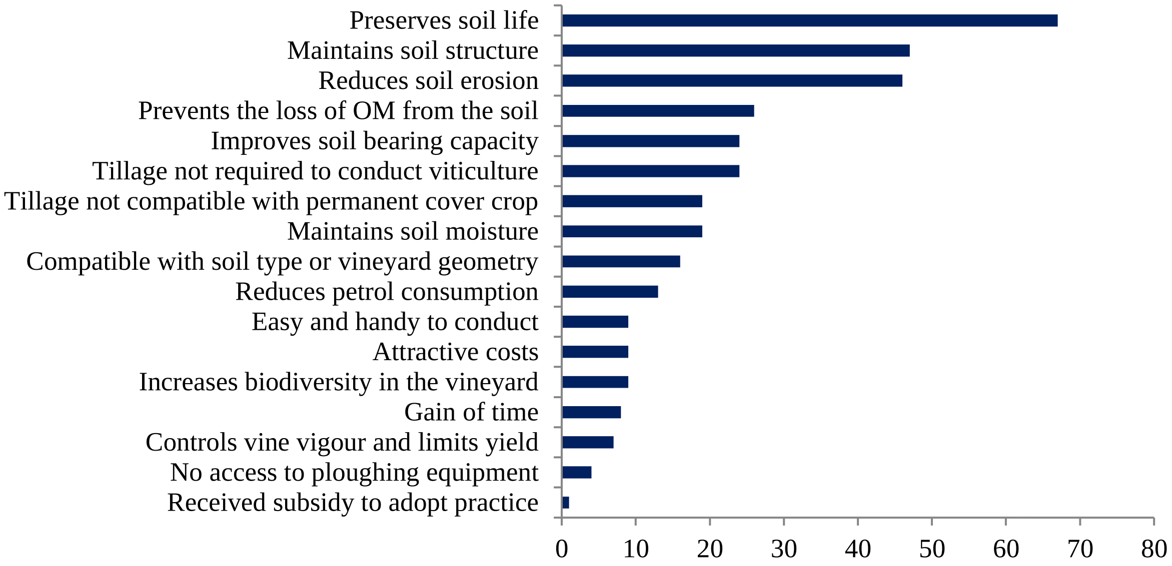


Fig. 5.7. Motivations for the adoption of NT in viticulture in France (n = 201). Several responses were possible for each respondent.

A similar number of respondents provided insights on barriers to the adoption of NT (n = 186). Barriers preventing the use of NT in viticulture were diverse, ranging from biophysical and technical to environmental and economic barriers (Fig. 5.8). Despite this diversity, two barriers were referred to more frequently than others: the fact that the use of NT is not successful in reducing the competition for water and nutrients between grapevines and plant activity in the soil enough for grapevines to thrive (24%) and that, in some vineyards, the use of tillage is required to control vegetation growth adequately – herbicides or reduced tillage not being effective enough (18%). A distinguishing result observed for NT was that the soil bearing capacity was mentioned both as a motivation and a barrier: this highlights the fact that the effect of NT on the soil varies depending on the context, improving soil bearing capacity in some places, but damaging it in other places. Another distinctive observation for NT was the strong influence of cultural habits and traditions on how winegrowers relate to the practice: some respondents felt strongly that viticulture did not require tillage at all, whereas others saw tillage as an obvious way to control vegetation growth and considered that their vineyard looked “dirty” if not tilled.

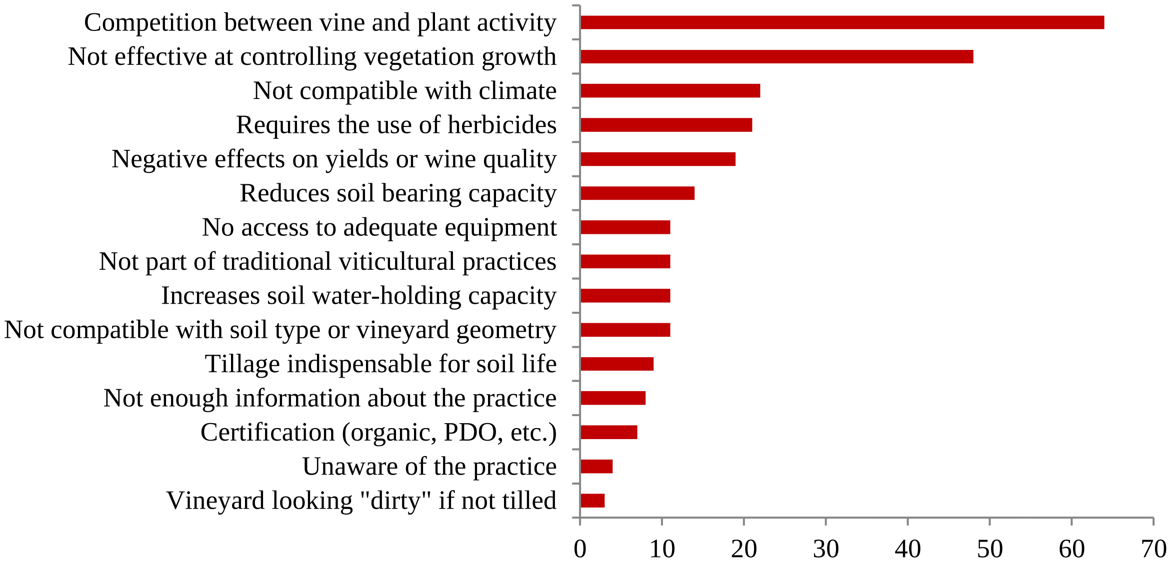


Fig. 5.8. Barriers to the adoption of NT in viticulture in France (n = 186). Several responses were possible for each respondent.

5.5.2.5. Cover cropping

Out of the 506 winegrowers in the sample, 341 provided motivations that played a positive role in their adoption of CC, which is in line with the adoption rate of this practice. A surprisingly high number of motivations were given by winegrowers, many of them being to achieve biophysical and environmental outcomes (Fig. 5.9). The three most frequent biophysical outcomes identified by winegrowers were: to return OM to the soil to improve SOM and soil quality (23%); to reduce soil erosion by ensuring that soils are not left bare, especially in the inter-rows (20%); and to improve the soil bearing capacity, which in turn facilitates the passage of tractors in the vineyard, particularly after a heavy rainfall event, and reduce soil compaction (12%). The use of CC was also motivated by the will to increase biodiversity in the vineyard, both via the cover crop and by attracting insects and birds into the vineyard (10%).

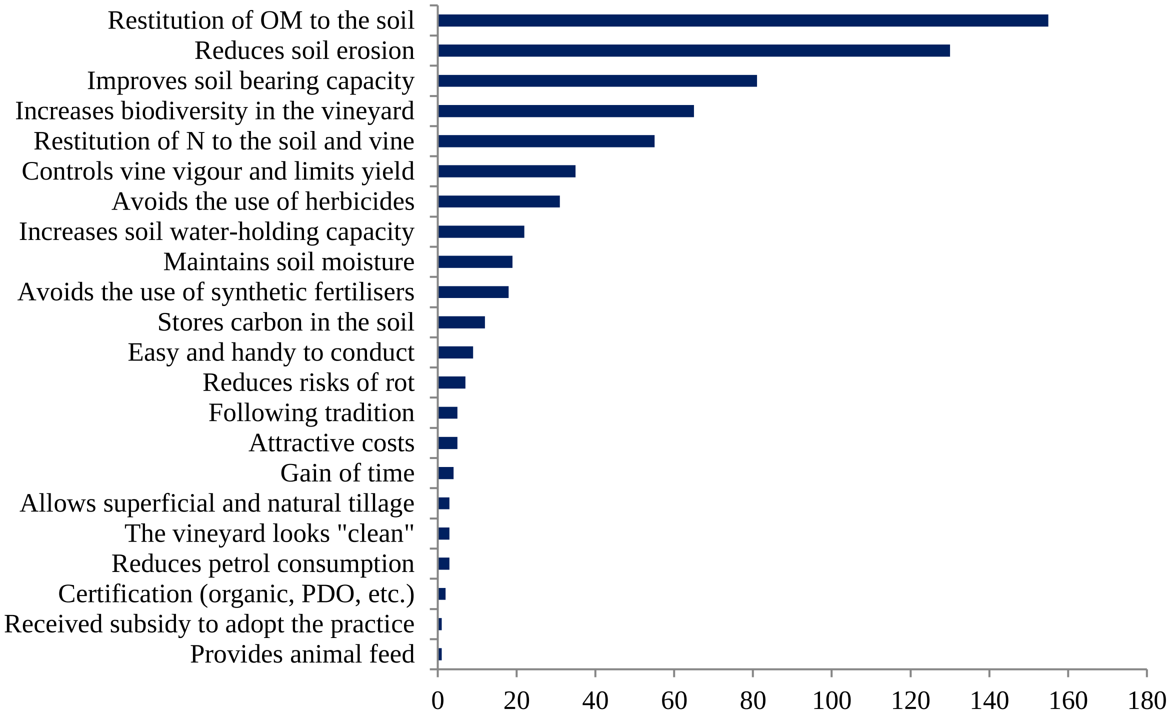


Fig. 5.9. Motivations for the adoption of CC in viticulture in France (n = 341). Several responses were possible for each respondent.

The number of respondents who discussed barriers to the adoption of CC (n = 108) was expected based on the adoption rate of the practice in the sample. Most barriers to the adoption of CC in vineyards were biophysical, though technical and economic barriers were not negligible (Fig. 5.10). The too-high competition for water and nutrients between the grapevines and the cover crop was one of the most important obstacles for winegrowers in using CC in their vineyard (42% of all identified barriers). In winegrowing regions with water scarcity during the summer (*e.g.*, the Mediterranean coast) or with poor soils, the use of CC was completely impossible as the negative impacts on grapevines were too important (16%). The use of CC was also impossible in vineyards with too stony or too sandy soil types or with peculiar geometries, such as vineyards with high density or located on steep slopes (13%).

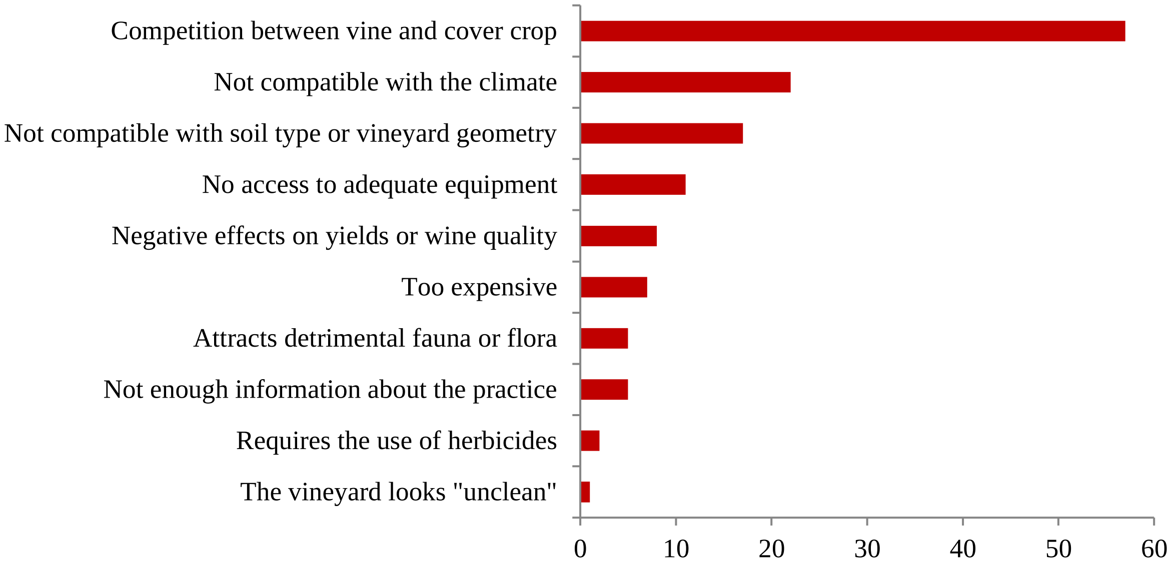


Fig. 5.10. Barriers to the adoption of CC in viticulture in France (n = 108). Several responses were possible for each respondent.

5.5.2.6. Hedges

220 respondents out of 506 provided elements of response to the question about drivers that motivated the implementation of HG in their vineyard. Motivations for the adoption of HG in viticulture were mainly environmental and to achieve specific biophysical outcomes (Fig. 5.11). The most frequently given motivation for the adoption of HG was to increase biodiversity in the vineyard (52% of all identified motivations). 171 winegrowers out of the 220 who answered this question wrote that biodiversity was the primary reason why they decided to plant hedges on their viticultural farm. Their responses took into account biodiversity via the species of hedges planted, but also how hedges attract auxiliary fauna (*e.g.*, birds or insects) that interact positively with grapevines by fulfilling roles of predators against harmful species or by helping to pollinate grapevines (10%). Other motivations related to the ecosystem services provided by hedges, namely protecting vines from wind (*e.g.*, mistral) and bad weather (9%), preserving the aesthetic value of the landscape (9%), and acting as buffer zones with neighbouring lands, avoiding, for instance, the run-off of phytosanitary products (8%).

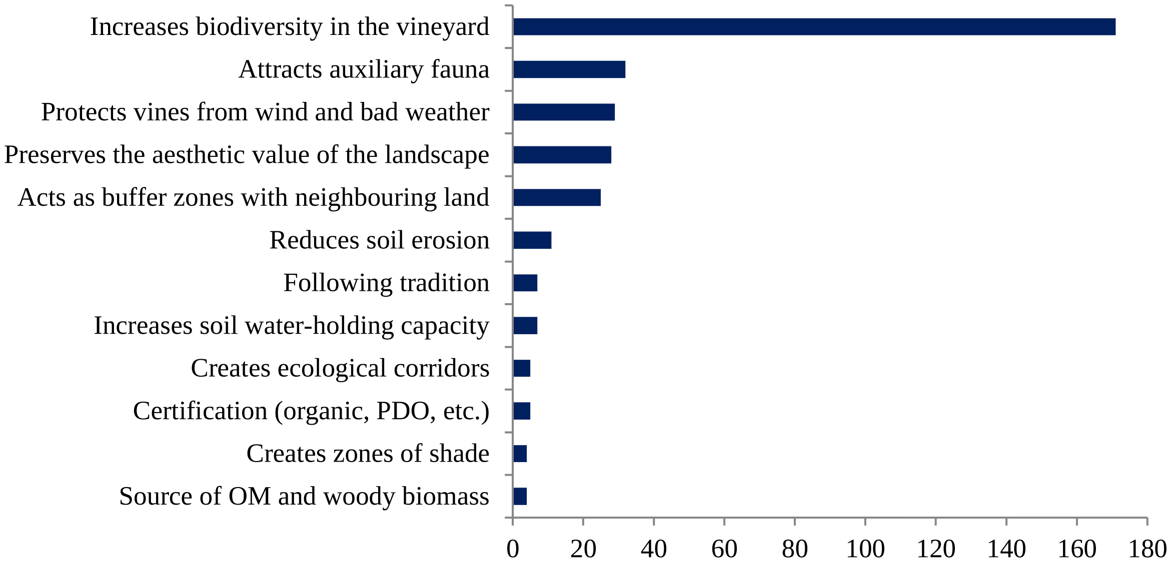


Fig. 5.11. Motivations for the adoption of HG in viticulture in France (n = 220). Several responses were possible for each respondent.

The number of respondents who answered the question about barriers against the adoption of HG in their vineyards was lower (n = 136), which aligns with the number of non-adopters of HG in the sample. The types of barriers named by winegrowers were heterogeneous, with biophysical, environmental, technical and economic barriers being discussed by respondents (Fig. 5.12). The three most important obstacles to the adoption of HG in viticulture were the incompatibility of the practice with the geometry of the vineyard, which was either too dense, lacking enough space to set up hedges (which would hinder the use of tractors) or split into lots of small, unconnected parcels (28%); the proximity of the vineyard to woodland or scrubland (20%); and the fact that the practice is too time-consuming to set up or maintain (16%). An interesting barrier mentioned by a few winegrowers is the belief that hedges are not compatible with viticulture and are more relevant for grasslands or annual croplands (2%).

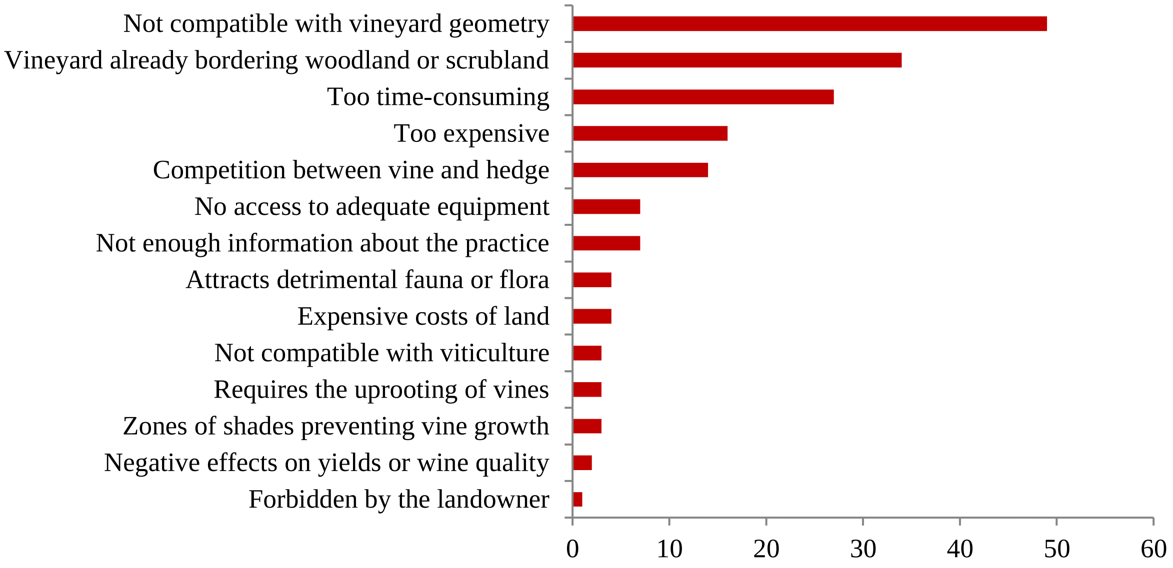


Fig. 5.12. Barriers to the adoption of HG in viticulture in France (n = 136). Several responses were possible for each respondent.

5.5.3. Actions to overcome the barriers to the adoption of SCS practices

The question asking respondents about potential actions they believe could help to alleviate some of the barriers to the adoption of SCS practices that they had identified throughout the survey was optional to not overwhelm them after a long series of open-ended questions; as a consequence, only a few respondents (n = 30) answered the question. However, those who answered provided a high and diversified number of strategies that could overcome some of the barriers they identified. Most of these actions were economic (46%), political (35%) and communication-based (30%) (Table 5.1). They included developing marketing strategies on SCS practices particularly in viticulture to increase their profitability and added value; increasing subsidies to allow for the purchase of the appropriate equipment and techniques required to conduct SCS practices efficiently; and improving the communication of evidence and information about the effectiveness of SCS practices to winegrowers. The majority of responses presented in Table 5.1 reflected on SCS practices as a whole and did not target specific practices, except for a few of them, which mentioned BC as an example of practice for which winegrowers were lacking proper information and adequate equipment.

Table 5.1. Actions proposed by winegrowers to overcome the barriers to the adoption of SCS practices (n = 30). Several responses were possible for each respondent.

Actions to overcome barriers	Count	Category of action
Improve the communication of information on SCS practices in viticulture	11	Communication
Increase subsidies for the purchase of adequate equipment	9	Political; economic
Develop marketing strategies for SCS practices in viticulture	4	Economic
Set up additional payment schemes for the adoption of SCS practices	4	Political; economic
Accompany the search for qualified workers at the local level	3	Social
Replant vines to increase vineyard compatibility with SCS practices	3	Technical
Develop training on SCS practices	2	Capacity building
Accompany the change of opinions about winemaking practices and culture	1	Social

5.5.4. Winegrowers’ attitudes towards agri-environment measures

The statements on AEMs were answered by a fifth of the respondents (n = 106). Responses to these statements provided insight into the attitudes of French winegrowers towards such measures (Fig. 5.13). Overall, winegrowers’ attitude toward AEMs was positive: most winegrowers stated that they were interested in AEMs (63%) and agreed with the fact that they were important elements to fight against climate change (56%). This is reflected in the fact that 70% of the respondents try to participate in AEMs as much as possible, while only 5% of them do not; the rest have a neutral opinion towards this statement.

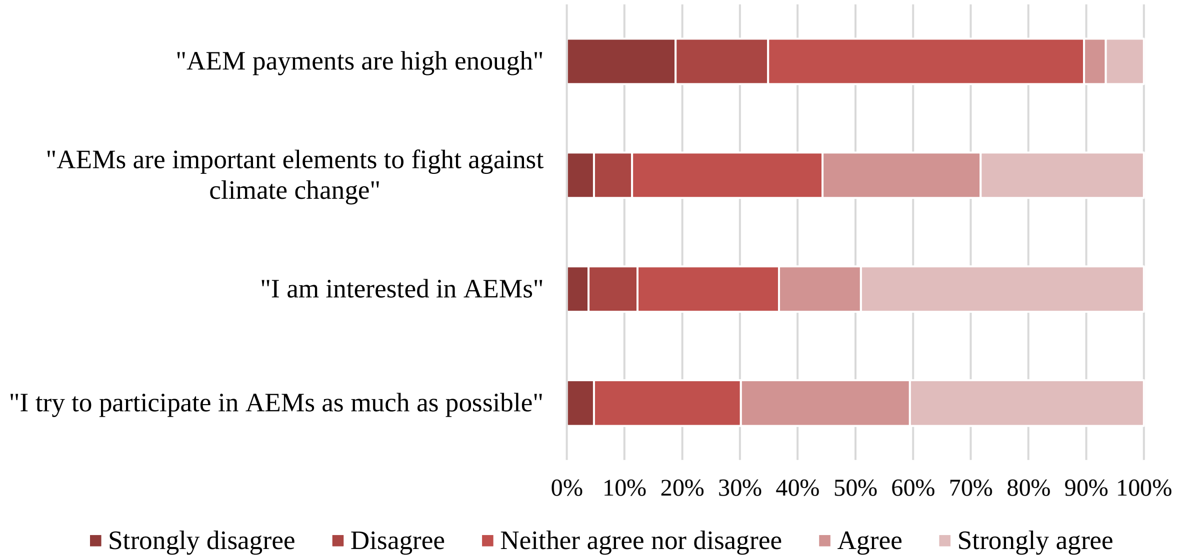
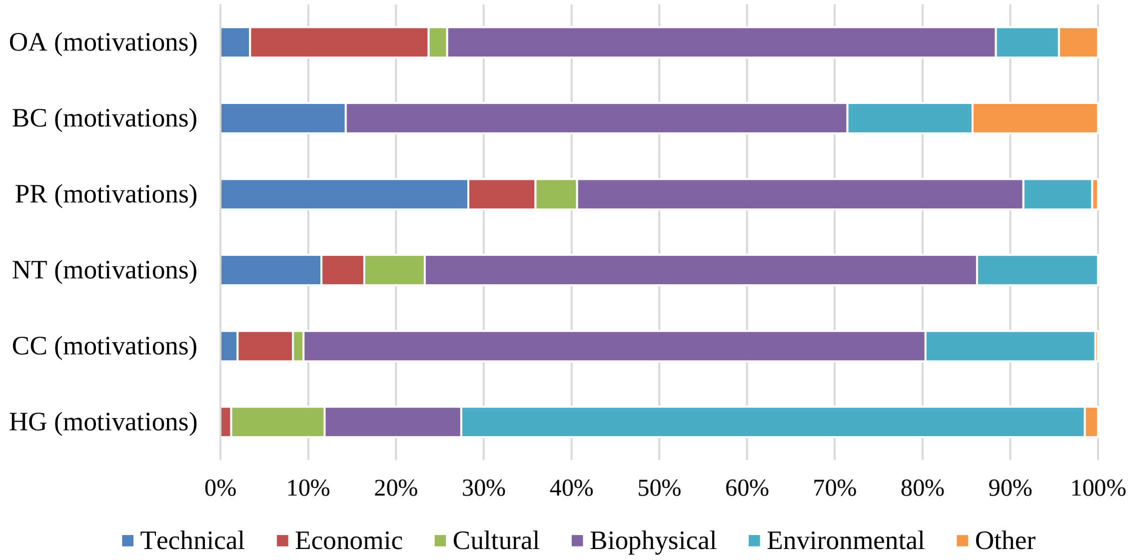


Fig. 5.13. Agreement of surveyed winegrowers to statements on agri-environment measures (n = 106). Five-point Likert scale: –2 = strongly disagree, 2 = strongly agree.

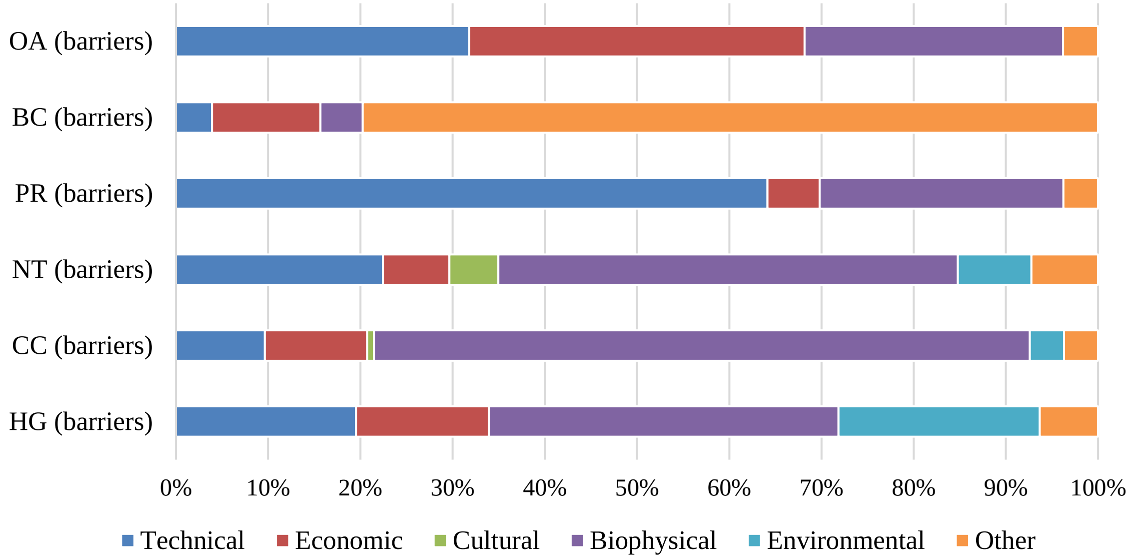
5.6. Discussion

5.6.1. Differences in motivations and barriers between SCS practices

Findings from this study highlighted the role played by extrinsic and intrinsic motivations in undertaking SCS practices in viticulture, showing that motivations were heterogeneous and overlapping (Fig. 5.1, 5.3, 5.5, 5.7, 5.9 and 5.11). Despite this heterogeneity, winegrowers were mainly motivated to undertake SCS practices to achieve biophysical outcomes, *i.e.* to overcome the biophysical degradation of the soil caused by conventional management, which negatively affects the agronomic soil characteristics required to conduct viticulture and produce high-quality grapes for winemaking. For all SCS practices (except HG), achieving biophysical outcomes represented more than 50% of all motivations mentioned for the practice (Fig. 5.14 (a)). HG was the exception to this trend, for which motivations were predominantly of environmental nature (71%).



(a)



(b)

Fig. 5.14. Categories of motivations for (a) and barriers to (b) the adoption of SCS practices by winegrowers in France.

There were economic motivations at play for each practice, though they were second to other categories of motivations (*e.g.*, to achieve biophysical or environmental outcomes). Only in the case of OA were economic reasons important motivations in the adoption of the practice (20%), due mainly to the use of organic amendments as fertilisers to increase yields (Fig. 5.14 (a)). This shows that winegrowers do not simply react to financial opportunities and imperatives but, conversely, make decisions within a care-based ethic and have a strong sense of stewardship over the land and the soil. This stewardship ethic has also been observed by

Greiner and Gregg (2011) in their study on the adoption of conservation practices by farmers in northern Australia. They found that environmental and lifestyle motivations (*e.g.*, the will to look after the environment or to live and work on a grazing property) were more important than economic and social motivations (*e.g.*, the wish to maximise company profit or to be appreciated by colleagues or society) in the adoption process of graziers, suggesting a strong altruistic motive. In addition, Mills et al. (2018) highlighted the greater importance of agronomic and environmental motivations over financial ones in the adoption of sustainable practices by English farmers. However, this was only true for unsubsidised activities; financial drivers were of greater importance in the adoption process for subsidised actions.

Barriers to the adoption of SCS practices were diverse and varied depending on the practice (Fig. 5.2, 5.4, 5.6, 5.8, 5.10 and 5.12). Overall, winegrowers were mainly constrained from adopting SCS practices by biophysical and technical barriers, *i.e.* by the incompatibility of the practice with specific biophysical features of the vineyard (such as soil type, vineyard slope, and climate) or farm characteristics (such as vine density, vineyard size, and vine age) and by a lack of technical resources required to conduct the practice (*e.g.*, access to adequate equipment, not enough additional time, etc.). Biophysical barriers accounted for 71% and 50% of all barriers against the adoption of CC and NT, respectively, and technical barriers represented 64% of all barriers against the use of PR (Fig. 5.14 (b)).

A few practices were an exception to these observations, however. The main barriers preventing the use of OA by winegrowers in France were economic (36%), relating to the high costs associated with the purchase of organic amendments and the difficulty to find suppliers at the regional scale. The most important barriers to the adoption of BC were capacity-building barriers (74%), linked to the low or non-awareness of biochar as a potential amendment for viticultural soils among winegrowers and to the lack of experiments and trials on biochar conducted in viticulture, making the effects of biochar on soil, vine and grape quality uncertain (though some evidence is starting to emerge). For these practices, barriers preventing their adoption were more related to the winegrowers' enabling environment (*i.e.* lack of economic incentive, lack of training and proper information, governance) than to technical issues. Therefore, overcoming these barriers is not really under the control of winegrowers themselves, or at least not only, and more holistic actions would be needed to target other stakeholders from the agriculture sector (*e.g.*, viticultural advisors) beyond winegrowers (Demenois et al., 2020).

Based on these observations, it seems that AEMs are a useful policy instrument to incentivise the uptake of SCS practices in the viticulture sector. AEMs may help winegrowers to overcome economic barriers (such as the high costs or the decrease in yields associated with some SCS practices) by providing them with financial compensation for adopting SCS practices. They may also play a role in surmounting biophysical and technical barriers by giving winegrowers more resources to undertake restructuring operations in the vineyard to make it more compatible with the use of SCS practices (*e.g.*, pulling grapevines up and replanting them with a lower density or on a more adapted soil) and to invest in new equipment or hire more workforce. However, considering the suggestions made by winegrowers to increase subsidies for the purchase of adequate equipment and to set up supplementary payment schemes (Table 5.1), it seems that the amount of money given to winegrowers participating in AEMs has not been sufficient over the 2014-2020 period. The budget allocated to AESs post-2020 may need to be increased to provide financial incentives suitable to farmers' needs.

The current design of AEMs also does not encompass all the barriers at play in restricting the adoption of SCS practices by French winegrowers. In addition, because winegrowers' desire to achieve biophysical and environmental outcomes is more important than economic motivations for adopting SCS practices, providing financial incentives may not be enough to trigger winegrowers' participation in AEMs. Further policy mechanisms would be needed as complementary approaches to AEMs to tackle the other types of barriers refraining action in the viticulture sector, mainly barriers relating to capacity building and cultural norms, and to appeal to the sense of stewardship expressed by winegrowers. Information and education schemes, such as government-provided information and reporting, could improve the communication of proper evidence supporting the feasibility, benefits and impacts of using SCS practices in vineyards to French winegrowers. This may better winegrowers' understanding of the effects of SCS practices on soil characteristics (*e.g.*, OM, structure, bearing capacity, water-holding capacity, agronomic potential, etc.) and promote the environmental dimensions associated with SCS practices (*e.g.*, climate change mitigation, biodiversity increase, landscape improvement, etc.). Information and education schemes could also help to attenuate the weight of tradition and cultural habits, which may lead winegrowers to develop negative attitudes towards practices or strong beliefs that they are incompatible with the art of winemaking, in preventing the adoption of SCS practices.

5.6.2. Motivations and barriers in the literature

Studies analysing what drives and prevents the adoption of SCS practices are few in the context of France and viticulture, though this research topic is gaining increasing attention. Reasons behind the adoption of CC, along with obstacles preventing adoption, were studied specifically in vineyards located in the Languedoc-Roussillon winegrowing region by Frey et al. (2017), who surveyed 334 winegrowers. The similarities in the findings observed for motivations comparatively to this study were striking, both in terms of motivations given by winegrowers overall and the importance of each motivation in the sample. The four most frequent motivations mentioned by winegrowers in Frey et al. (2017) were identical to these given by winegrowers in this chapter: to increase biodiversity, to return OM to the soil, to help to prevent soil erosion, and to improve soil bearing capacity, with the slight difference being the order of importance of each motivation. Barriers to the adoption of CC were also similar in both studies, though to a lesser extent than for motivations. Water and nutrient competition, a decrease in yields and the lack of adequate equipment were the three most important barriers mentioned by respondents in Frey et al. (2017); in this study, competition for water and nutrients between vines and cover crops were also the most frequent barriers given, but the incompatibility of the practice with the climate and the soil type or vineyard geometry came second and third, before concerns for yields and a lack of adequate equipment. These similarities may be due to the high representation of winegrowers from Languedoc-Roussillon in the sample (29%), which is in line with the fact that the viticultural land of Languedoc-Roussillon represents 30% of the total viticultural land in France (MEF, 2018). Findings from this chapter confirm previous analyses observed in French vineyards regarding CC; they also broaden the understanding of the factors at play in the adoption process of winegrowers to the national scale and for a more comprehensive set of SCS practices.

Barriers to the adoption of SCS practices were investigated by Demenois et al. (2020) in France for different agricultural systems, including vineyards located in Beaujolais. In their study, the barriers were not categorised per SCS practice but given as a whole for the entirety of the SCS practices considered by the stakeholders participating in the workshops. Out of the seven SCS practices identified by these stakeholders, four were similar to those considered in this study: OA, CC (in the form of grass cover or legume crop) and agroforestry (via hedges). There were strong similarities in the barriers identified by Demenois et al. (2020) and this study in the fact that biophysical and technical barriers were two of the most important categories of barriers preventing the adoption of SCS practices in both studies. More particularly, the biophysical barriers reported by Demenois et al. (2020) correspond to some of the main barriers mentioned in this chapter, namely the poor quality of viticultural soils and the competition for water between vines and cover crops or trees/hedges. One point of divergence, however, was social barriers, which were few in this chapter, but prevalent in Demenois et al. (2020). Increased difficulty of work and workload was mentioned in Demenois et al. (2020) as one of the key barriers by participants, which is in opposition to the fact that winegrowers in this chapter mostly mentioned the easiness and handiness of implementing SCS practices as a reason that motivated them to use the practices. This highlights how the reality of adopting SCS practices may vary at the regional or local level (winegrowers from Beaujolais represented only 5% of the respondents in the sample) or depending on the practices considered. The eventual complexity of implementing SCS practices is linked to the way viticulture is conducted (*e.g.*, planting density, vineyard slope, soil characteristics, vine pruning, etc.); for instance, specific vineyards may prevent the mechanisation of viticultural practices (due to a high planting density or a too steep terrain), which may, in turn, increase the difficulty of implementing SCS practices. Adopting a more territorial approach, based on the specificities of winegrowing regions and *terroirs*, could be more relevant to discussing and planning the dissemination of SCS practices in viticultural land in France.

Claessens et al. (2019) conducted a global survey to understand how barriers to the adoption of SCS practices vary at the global level and, more particularly, at the EU level. They also reflected on potential solutions that could be implemented to alleviate some of these barriers. Though their study was conducted for all types of agricultural systems, it allows for the findings from this chapter to be put within the broader context of EU agriculture and to assess how viticulture in France may differ from other agricultural systems in the EU. EU farmers in Claessens et al. (2019) ranked the fact that SOC sequestration is not rewarded financially (no subsidies nor carbon credits available) as their primary barrier to the adoption of SCS practices, followed by the fact that SOC management is not a political priority and that farm extension services do not have the knowledge nor the capacity to train farmers on technical solutions. This shows that, overall, economic barriers play a much more important role in preventing the adoption of SCS practices on agricultural land at the EU level than they do more specifically in the context of viticulture in France, reflecting the fundamental difference in commodities and supply chains between viticulture, where grapes are not the final product, and other types of cropping systems (*e.g.*, wheat). Furthermore, the solutions discussed by EU farmers in Claessens et al. (2019) had similar implications to those mentioned by French winegrowers in this chapter in the fact that the majority of solutions ranked as most important by EU farmers dealt with improving the capacity building to allow for better communication on how to increase SOC stocks on farmland and improved awareness among the public about SCS practices. Economic solutions were also identified as central in facilitating the adoption of SCS practices by EU farmers in Claessens et al. (2019) and by French winegrowers in this chapter. This shows that solutions focusing on improved capacity building coupled with economic actions (*e.g.*, increasing subsidies for the purchase of adequate equipment or setting up additional payment schemes to reward the adoption of SCS practices) would be effective approaches to policy design for the EU agriculture sector and more specifically for the French viticulture sector.

5.6.3. Attitudes towards agri-environment measures and winegrower participation

Despite the overall positive attitude of French winegrowers towards AEMs highlighted by this study (Fig. 5.13), respondents' participation in AEMs was low. This discrepancy may be because only 106 respondents out of the total 506 that composed the sample answered the statements on attitude towards AEMs. Among those who answered the statements, the participation rate was much higher (52%; n = 106) than among the whole sample (24%; n = 506). This suggests that the observations on attitudes towards AEMs made in this chapter may be skewed by an overrepresentation of participants within the respondents, even though a positive attitude towards AEMs does not automatically lead to participation in AEMs (Hammes et al., 2016).

However, conclusions based only on respondents who answered the statements on attitude (n = 106) can still be drawn and inform winegrowers' participation in AEMs. As shown by Fig. 5.13, the proportion of winegrowers who try to participate in AEMs as much as possible was higher than that of winegrowers who believe that AEMs are important in climate change mitigation; this tends to suggest that there would be other reasons behind the involvement of winegrowers in AEMs than only climate-related ones. This is coherent with the fact that AEMs are not only designed as mitigation strategies but can also aim at improving other ecosystem services such as biodiversity, water quality, landscape quality, etc. (European Commission, 2017).

It is also interesting to notice that only 10% of the respondents (n = 106) thought that the payments that they would receive if they participated in AEMs would be high enough. Hammes et al. (2016) found similar results in northern Germany, where 30% of the surveyed farmers stated that AEM payments were too low. Too low financial incentives provided by AEMs may be one of the reasons why only 52% of the respondents (n = 106) participated in AEMs, though 70% stated that they try to participate in AEMs as much as possible. This is in line with Mills et al. (2018), who showed in their study that the primary motivation of farmers for participating in subsidised AEMs was financial.

5.6.4. Gaps and uncertainty

The way questions were asked in the survey made it so respondents would have the opportunity to identify motivations behind the adoption of a SCS practice if they have adopted it and to mention barriers that may have prevented them from adopting a SCS practice if they have not adopted it. As a result, the number of respondents providing answers for motivations and barriers was correlated to the adoption rate of each practice in the sample: for example, because the adoption rate of PR was very high in the sample (91%), most respondents discussed the reasons that motivated them to use PR in their vineyard and a few only mentioned the barriers against the use of PR. The adoption rate of SCS practices in the sample was, overall, higher than that at the national level, with the exception of BC and PR: for instance, at the national level, OA is used on only 9% of the viticultural land (Agreste, 2017), while in the sample 73% of winegrowers used OA yearly; CC is used in the inter-rows of vineyards on 46% of the viticultural land at the national level and under the rows on 8% (Agreste, 2017), whereas the adoption rate of CC reached 73% in the sample. This suggests that there was an overrepresentation of adopters in the sample and, due to the way the survey was designed, motivations were more frequently mentioned by respondents than were barriers. If the results from this chapter provided a strong overview of the barriers at play in the viticulture sector, further research should be led to understand why non-adopters participated less, on average, in the survey and to investigate more in detail the barriers that prevent them from adopting SCS practices.

This chapter took viticulture in France as a case study; therefore, respondents to the survey were all winegrowers. Though it provides insights into the reasons motivating winegrowers to adopt SCS practices and the obstacles preventing them from doing so, it does not consider other types of agricultural land (*e.g.*, arable land, pastures, other perennial croplands, etc.), which represent a substantial share of the total agricultural land in France. Viticultural land accounts for only 3% of the French total agricultural land; most agricultural land in France (63%) is classified as arable land (FAO, 2019). Understanding the enabling environment for SCS practices in different agricultural systems is paramount if SOC sequestration is to be used effectively as a CO_2 removal technology in France and to reach the target of the '4 per 1000' initiative. Further research into the motivations for and barriers to the uptake of SCS practices in arable land, pastures and perennial croplands is needed to make our understanding of the factors influencing the adoption of SCS practices by farmers exhaustive.

5.7. Conclusions

A survey of French winegrowers on SCS practices provided valuable inputs on the adoption of these practices in the viticulture sector. Results showed that most SCS practices were adopted to achieve biophysical outcomes, while barriers to their adoption were mainly biophysical and technical. Economic motivations and barriers tended to be secondary to these factors, though they did play an important role in motivating or preventing the adoption of SCS practices by winegrowers in France. This may explain why the rate of adoption of some SCS practices (*e.g.*, OA and NT) in the viticulture sector in France is limited at the national level, even though the adoption of these practices is estimated to have a low cost or even generate benefits for farmers (Pellerin et al., 2017). However, the costs estimated by Pellerin et al. (2017) need to be taken with care for viticultural land, as their calculations were based on low planting density; costs of implementing SCS practices are expected to be higher in cases of high planting density.

A few winegrowers in the sample reflected on possible actions that could be undertaken to facilitate the adoption of SCS practices in their vineyard: the majority of their recommendations suggested increasing the communication of adequate and quantified information on the benefits of SCS practices at the local level and setting up further financial incentives (such as subsidies or payment schemes) to facilitate or reward the adoption of SCS practices in vineyards. These propositions indicated that the current AEMs used by the EU to incentivise the uptake of SCS practices by farmers, though useful in providing financial compensations, may have to be complemented by information and education schemes. Such schemes would need to underline the GHG mitigation potential of SCS practices, which are not seen by French winegrowers as mitigation strategies, but rather as practices allowing for an improvement in soil quality or an enhancement of biodiversity in the vineyard. In addition, France has recently launched the Low Carbon Label (*Label bas-carbone*), which provides funding from public bodies, companies and private individuals to projects aiming at reducing or offsetting GHG emissions (MTE, 2021). The methodology for applying the label to viticulture is currently being developed. It will be of interest to investigate whether these additional financial incentives facilitate the adoption of SCS practices in vineyards in the future.

Chapter 6

Conclusions and recommendations

This thesis has aimed to quantify the C sink potential of viticultural soils under several SCS practices, with a focus on how the capacity of these soils to sequester C may vary at the regional and local levels based on soil and climatic specificities. It has also assessed the extent to which SCS practices were already used by winegrowers in vineyards, taking France as a case study, and analysed the different factors that could explain why winegrowers decided to implement these practices or were unable to. This final chapter critically discusses how the main findings of the thesis contribute to strengthening the broader literature on SOC sequestration and their relevance for policymaking in the field of climate change mitigation and the agriculture sector. It finally outlines limitations and potential for further work.

6.1. Main findings and key contributions to the literature

This thesis addresses some gaps in the existing literature on SOC sequestration, mainly relating to vineyard agroecosystems, where previous evidence has been limited. By drawing together biophysical and socio-economic elements linked to the adoption and success of SCS practices in vineyards, this research has furthered our understanding of the extent to which SCS practices are suitable for encouraging SOC sequestration in vineyard agroecosystems to help to mitigate climate change. Some of the findings dealing with the barriers to the adoption of SCS practices, though based on analyses and modelling conducted for viticultural soils, may be of use for broader agricultural land and SOC sequestration research.

Chapter 2 compared the response of SOC stocks in vineyards between SCS management and conventional management. The meta-analysis indicated that vineyard agroecosystems may sequester substantial amounts of SOC under SCS management and can, therefore, play an important role in the global efforts to mitigate climate change via SOC sequestration, especially in countries with a large viticultural land area. Results also showed that, under the same management practices, vineyards may sequester similar or larger amounts of SOC compared to other types of agricultural land (mainly other woody perennial croplands and arable land), which suggested that deploying SCS practices in vineyards should not be overlooked in the favour of other land uses. Implementing SCS practices in vineyards may also make the viticultural phase of winemaking carbon-negative and help to reduce the carbon footprint of the wine sector at the global level.

In Chapter 3, the dataset created in Chapter 2 was used to develop a machine-learning model to estimate the SOC sequestration rates in vineyards under specific SCS practices. A random forest regression was chosen as the modelling approach due to its numerous advantages (such as the possibility to include categorical along with continuous explanatory variables). The final model can predict, using input data relating to soil (*e.g.*, initial SOC stock, percentage of clay and sand in the soil, PET, etc.) and climatic characteristics and for a specific SCS practice or combination of SCS practices, the change in SOC stocks in vineyards after a given number of years under this SCS management. Modelled values of SOC stocks can be used to calculate how much SOC can be sequestered per hectare annually in vineyards under specific SCS management. Results showed that the abatement rate varied greatly depending on the winegrowing regions and practices considered. Certain winegrowing regions (*e.g.*, the Canary Islands and Ahr) proved to be hotspots for SOC sequestration, holding the potential to sequester substantial amounts of SOC (17.53 Mg CO_2-eq. ha^{-1} yr^{-1} in the former and 15.31 Mg CO_2-eq. ha^{-1} yr^{-1} in the latter under OA+NT+CC), while others were associated with low abatement rates under most SCS practices (*e.g.*, between 3.73 and 4.58 Mg CO_2-eq. ha^{-1} yr^{-1} in Extremadura).

Chapters 2 and 3 have shown that the use of SCS practices in vineyards had the potential to sequester large amounts of SOC. However, this potential will only be realised if SCS practices are adopted by winegrowers. So far, the uptake of most SCS practices on viticultural land is low. This is why Chapters 4 and 5 investigated why winegrowers adopt SCS practices and, if they do not, what prevents them from doing so. Better understanding the motives and barriers to the adoption of SCS practices in vineyards will be crucial in designing appropriate policies and policy instruments to further incentivise the uptake of SCS practices in the viticulture sector and ensuring that vineyards can fulfil their C sink potential.

Chapter 4 investigated the decision-making process associated with the adoption of SCS practices by winegrowers. France was chosen as a case study and a questionnaire was circulated to 400 winegrowers. The survey was used to gather quantitative data on the adoption rate of SCS practices in French vineyards and on different aspects of winegrowers' socio-economic characteristics, farm attributes, viticultural activities and involvement in policy instruments. Findings indicated that socio-economic and behavioural characteristics were important factors in winegrowers' likelihood to adopt SCS practices in France. Specific aspects of viticultural production (*e.g.*, the vine's age or being an independent winegrower) were also significant drivers of the decision to adopt the practices. Results from Chapter 4 could help to improve policy targeted at the viticulture sector in France in the sphere of climate change mitigation and can potentially be useful at the European level for other wine-producing countries such as Spain or Italy.

In Chapter 5, the motives and barriers to the adoption of SCS practices by winegrowers were explored in France. A survey with a mix of open- and close-ended questions was circulated to 506 winegrowers. For each SCS practice, winegrowers were asked, if they had adopted the practice, to describe the reasons that motivated them to adopt it or, if they had not adopted the practice, to detail the perceived barriers that prevented them from doing so. Though there were differences between SCS practices, the wish to achieve biophysical outcomes in the vineyard, and more specifically the desire to return OM to the soil to improve SOM and enhance soil quality, was the main motivation behind the adoption of SCS practices. Winegrowers cited biophysical barriers (*e.g.*, the incompatibility of the practice with specific biophysical features of the vineyard) and technical barriers (*e.g.*, a lack of the main resources required to conduct the practice) as the main barriers hindering the adoption of SCS practices on their farm. The survey also asked winegrowers about the possible actions that could be implemented to alleviate some of the barriers they had identified. Their responses suggested that the current policy instruments in place in the viticulture sector in France may have to be complemented with further information and education schemes.

6.2. Recommendations and implications for policymakers

Vineyards should be considered as key agroecosystems to reach the target of the '4 per 1000' initiative, particularly in countries and regions with a large viticultural land area. Findings from this thesis have shown that the use of SCS practices may lead to an increase in SOC stocks by +5.8% annually to a 30-cm depth, which is considerably higher than the '4 per 1000' target of +0.4% to a 40-cm depth. This value is, however, based on field experiments whose duration averaged 8.5 years; the estimated rate of increase is likely to be lower 10 years after the adoption of a SCS practice and can be considered negligible 20 years after, though changes in SOC stocks may take up to 100 years to reach a new equilibrium (Poeplau and Don, 2015). The abatement potential of the total viticultural land in several European countries, *i.e.* the total amount of SOC that could be sequestered per year on viticultural land using one or several SCS practices, has also been quantified. In France, more specifically, viticultural land under SCS management may sequester 11% of the total amount of SOC needed to reach the annual target of the initiative, while vineyards only account for about 3% of the total agricultural land in France. However, this value assumes that SCS practices are implemented in all vineyards and does not take into account the current adoption rate of SCS practices on viticultural land. Nonetheless, the results presented in this thesis may be of value for estimating, at the regional or national levels, the feasibility of the ‘4 per 1000’ target, especially in countries such as France where vineyards have been identified as areas of high SOC sequestration potential (Angers et al., 2011). They expand the state of scientific evidence on SCS practices and their implementation, which may be of particular interest to all partners and members of the initiative (*e.g.*, France, Spain, Germany, Canada, the UK, etc.). The results of this thesis also suggest, based on the low awareness of the initiative by winegrowers in France (see Chapter 4), that the initiative needs to be further communicated to the appropriate stakeholders of the agriculture sector. It is, indeed, very unlikely that the target of the initiative will be met if the stakeholders who are meant to take action to increase SOC stocks are unaware that it exists. Though negative criticisms of the initiative have emerged[11], it remains an important lever of action that could help to reduce GHG concentrations in the atmosphere via SOC sequestration.

In the EU, applying organic amendments in vineyards and cover cropping should be opted for as a priority to ensure climate change mitigation on viticultural land via SOC sequestration. Analyses conducted throughout the thesis have identified these two practices as having a high potential for SOC sequestration in vineyards in European countries and their uptake should be encouraged on viticultural land. Table 3.2 in Chapter 3 and the series of maps available in Appendix D are valuable outcomes that can be used as a roadmap to prioritise further policymaking in the viticulture sector at the EU level. They provide guidance for policymakers to identify hotspots for SOC sequestration at the regional and local levels under specific SCS practices and can help the EU Member States to decide where to start to achieve their mitigation targets. Winegrowing regions that are SOC sequestration hotspots include the Canary Islands, the Basque Country and Galicia in Spain; Bugey, Jura

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[11] Criticisms of the ‘4 per 1000’ initiative mention the risk of a political delay in the transition to renewable energies and net negative emissions as well as the uncertainty of the target calculation, based on certain assumptions that are highly debatable, such as the soil depth to consider (Basile-Doelsch et al., 2020).

and Savoy in France; the Aosta Valley, Trentino-South Tyrol and Liguria in Italy; Madeira, Minho and Dão in Portugal; Ahr, Baden and Saxony in Germany; and Styria, Lower Austria and Vienna in Austria (though Austria only totals four winegrowing regions overall). Ensuring that the uptake of OA and CC is maximised in these winegrowing regions should be put first in these countries.

Further policy instruments are needed in the viticulture sector to incentivise the uptake of SCS practices by winegrowers. Findings from a case study on France have suggested that payments received by farmers in the form of subsidies or as part of their participation in AEMs, though they may help to alleviate some of the economic barriers to the adoption of SCS practices by providing financial compensation, are not enough. Winegrowers are facing important technical and biophysical barriers that may require the purchase of new equipment or the restructuring of their vineyard to be compatible with the use of SCS practices. These obstacles are currently not being compensated enough by the available schemes, so winegrowers are discouraged from swapping to different soil management practices. Furthermore, schemes that are not based on providing financial incentives may be necessary to complement those that are. Developing information and education schemes focusing specifically on SCS practices could help to disseminate information and evidence on SCS practices, with an emphasis on their benefits for climate change mitigation and soil quality. At the moment, many winegrowers in France are either not convinced by the legitimacy and validity of SCS practices or uncertain about the possible repercussions SCS practices may have on soil and grape quality. Such schemes may also build winegrowers' confidence in their ability in implementing SCS practices on their farm as well as their attitudes towards the practices, which are significant factors involved in the adoption process of the practices by winegrowers in France.

The adoption of SCS practices in the viticulture sector will have positive externalities in terms of climate change adaptation. This thesis focused on the climate change mitigation potential of vineyards; however, one of the main challenges that viticulture will face throughout the 21st century is climate change due to the high sensitivity of vines to weather patterns. High-quality wine production is limited to a very narrow climatic window, *i.e.* specific climatic conditions that need to be met during particular stages of the vine cycle (Jones et al., 2005). Vines producing high-quality wine are located in regions where the average temperature during the growing season (*i.e.* between April and October in the

Northern Hemisphere and between October and April in the Southern Hemisphere) ranges from 13 to 21 °C (Jones, 2006). With increasing average temperatures and higher occurrences and intensity of extreme weather events due to climate change, many winegrowing regions are at risk of no longer providing suitable conditions for high-quality wine production. Furthermore, vine sensitivity to temperature varies among grapevine varieties, with some varieties (such as pinot noir) being more sensitive than others (such as chardonnay) (Jones et al., 2012). Winegrowing regions whose wine production is based on the most sensitive grapevine varieties (*e.g.*, Burgundy in France for red wine production, which is based mostly on pinot noir) are even more at risk of failing to keep producing high-quality wine in the future. The adoption of SCS practices may, however, have beneficial effects regarding vineyard vulnerability to climate change and create synergies between climate change mitigation and adaptation. For instance, the introduction of cover cropping in vineyards may have positive impacts on counterbalancing canopy microclimates through their cooling effect. Cover crops reduce soil evaporation by increasing soil moisture in the soil's upper layer during the crucial stages of the vine (Monteiro and Lopes, 2007). Cover crops may also improve soil quality by reducing soil erosion (Fraga et al., 2012). These positive externalities may help vineyards to become more resilient to climate changes, particularly to the impacts of increased temperatures, in addition to enhancing SOC sequestration.

6.3. Limitations and opportunities for further research

In this thesis, the focus was put on investigating the biophysical and socio-economic barriers to the adoption of SCS practices in vineyards, but the scope of the thesis did not include a thorough evaluation of the costs associated with the implementation and maintenance of SCS practices in vineyards. As stated in Chapter 1 (see section 1.3.5), it has been estimated that the implementation of SCS practices at the global level and including all agricultural land can be done at negative or low costs (Smith, 2016). However, these costs vary based on the practice considered, the agricultural system, the country, etc. and the cost-effectiveness of SCS practices has not been assessed specifically for vineyards. There is an opportunity for further research to conduct a cost-effectiveness analysis of SCS practices in vineyards and develop marginal abatement cost curves (MACCs) of all the mitigation measures that could be applied to the viticulture sector in a given country. MACCs are detailed technology-rich models, based on a bottom-up engineering approach, that are used for modelling the abatement potential and costs of individual technologies and measures (MacLeod et al., 2010). They illustrate the costs of implementing emission mitigation measures compared to 'business as usual' scenarios (Moran et al., 2011) and provide a visualisation of which mitigation measures are currently worth investing in and which are not economically favourable for a given country (MacLeod et al., 2010). Several MACCs have been developed for the agriculture sector in different countries, *e.g.*, in France (Pellerin et al., 2017) and Spain (Baccour et al., 2021). SCS practices applicable to viticulture have been evaluated in these MACCs, but for croplands in general and not specifically for vineyards (except for the use of CC) and only at the regional level of Aragon for Spain. Because the modalities of implementing each SCS practice vary in vineyard agroecosystems compared to other cropping systems (and so do the mitigation potential and associated costs of each practice), the results of existing MACCs for each SCS practice cannot be applied as such for vineyards.

Though this thesis aimed to quantify the SOC sequestration potential of vineyards under all SCS practices suitable for viticultural soils, the literature search conducted for the meta-analysis only found data on five SCS practices (OA, BC, PR, NT and CC) used individually or combined in vineyards at the global level. Even though no data on HG from field experiments were used in Chapters 2 and 3, HG was included in the case study on France (in Chapters 4 and 5) because the SOC sequestration potential of maintaining or planting hedges on all agricultural land had been evaluated by Pellerin et al. (2019) for France specifically. This potential (0.061 Mg CO_2-eq. ha^{-1} yr^{-1}) does not depend on the type of agricultural land considered but more on the land area available to accommodate hedges and could, therefore, be applied to viticultural land. However, all the other SCS practices that could be applied to viticultural land (Table 1.3) had to be excluded from the analysis. There is, thus, a need for further field experiments to be conducted to assess the effect of using these practices in vineyards on SOC stocks and compare it to conventional management. Undertaking this work would allow for a more exhaustive estimate of the SOC sequestration potential of vineyards under SCS management to be formulated and to further our understanding of how SOC stocks react to specific management practices in different agroecosystems.

Though the geographic scale of Chapter 2 was global, important winegrowing countries in terms of land area dedicated to viticulture were not included in the meta-analysis because no field experiment carried out in these countries was found. For instance, no study in China was found, though it is the country with the second-largest viticultural land (OIV, 2019).

Similarly, only one study located in Turkey was gathered by the literature search, although Turkey has the fifth largest viticultural land area in the world (OIV, 2019). As a result, the SOC sequestration potential calculated in Chapter 2 may not be fully representative of global vineyards but vineyards from specific areas of the world instead. Spain, Italy and France were the three most represented countries in the dataset; they embody traditional European viticulture, based on *terroirs* and under a strict system of geographical indications. More field experiments taking place in countries with large viticultural land are needed to have a more precise picture of how SOC stocks react to SCS practices based on different soil characteristics, climates and management practices in different parts of the world. Further research should also be conducted in countries where viticultural land is increasing rapidly (*e.g.*, Peru, Mexico, Georgia or even the UK) or shifting due to climate change. In these countries, the creation of new vineyards implies land-use changes that may have negative repercussions on SOC stocks, especially if land uses with SOC stocks that are on average higher than that of vineyards are converted (*e.g.*, from grasslands to vineyards). To ensure that SOC stocks in newly-created vineyards do not deplete due to conventional management, SCS practices need to be implemented by winegrowers. Because some SCS practices may be incompatible with specific geometry features and structural aspects of vineyards, it is better if their implementation is planned and implemented within the design of the viticultural farm before setting it up. Besides, there is a lack of knowledge regarding what practices are used in these countries. Further work could be done to investigate which soil management practices are adopted by winegrowers in newly-established vineyards and why. It could be interesting to compare this with countries where viticulture has been conducted traditionally for centuries, as a way to identify possible differences in what informs the decision making of winegrowers in varying socio-cultural environments.

Using field experiments to estimate the SOC sequestration potential of vineyards comes with strengths, as results are calculated from measured values. However, there are also limitations to using field experiments. In this study, only field experiments conducted in the short or medium term were gathered (very few studies had an experiment duration higher than 20 years). Furthermore, due to a lack of data in published studies, the old IPCC (2006) guidelines (based on fixed depth) had to be used for SOC stock calculations instead of the new ones (IPCC, 2019). Within the IPCC (2006) guidelines, crucial data to calculate SOC stocks (*i.e.* bulk density) was missing and had to be extrapolated using quadratic functions, which have high uncertainty. As a result, the SOC sequestration rates estimated in Chapter 2 are best applied to the short and medium term and need to be qualified due to the inherent uncertainty of the calculated values. To overcome some of these limitations, further research could use modelling approaches to estimate the SOC sequestration potential of SCS practices in vineyards. Using models that were designed to simulate changes in SOC stocks based on different initial conditions (*e.g.*, soil characteristics, climate, soil management practices, etc.) such as RothC (Coleman and Jenkinson, 1996) or ECOSSE (Smith et al., 2010) could complement the findings of this thesis, particularly by giving a more accurate picture of the changes in SOC stocks under SCS practices in the long term (> 20 years). It would also help to identify the areas of viticultural land within each winegrowing region that may not participate in SOC sequestration efforts due to limited C availability at the local level under current management practices or because of SOC saturation resulting from physicochemical limitations to SOC storage in the fine mineral fractions of the soil (Martin et al., 2021).

6.4. Concluding remarks

The overarching findings of the thesis prove that there is an unexploited potential for SOC sequestration within vineyard agroecosystems. If managed using SCS practices, vineyards across the globe could participate in international efforts to mitigate climate change. More particularly, increasing SOC sequestration on viticultural land will be crucial to meet the target of the ‘4 per 1000’ initiative for the countries and regions with a large viticultural land area that are members of the initiative. The adoption of SCS practices could also, on a smaller scale, help to reduce the carbon footprint of winemaking and contribute to making the wine sector carbon-neutral. However, important factors are currently obstacles to the adoption of SCS practices by winegrowers and hinder the realisation of the SOC sequestration potential on viticultural land. A case study of the French viticulture sector showed that additional policy instruments at the local, regional, national and European levels may help to incentivise the uptake of SCS practices by winegrowers.

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Appendix A

The full references of the papers published from Chapter 2 (Payen et al., 2021a), Chapter 3 (Payen et al., 2021b) and Chapter 4 (Payen et al., 2022) can be found below, along with the DOI links to the online publications:

Payen, F. T., Sykes, A., Aitkenhead, M., Alexander, P., Moran, D., & MacLeod, M. (2021a). Soil organic carbon sequestration rates in vineyard agroecosystems under different soil management practices: A meta-analysis. *Journal of Cleaner Production*, *290*, 1–13. https://doi.org/10.1016/j.jclepro.2020.125736

Payen, F. T., Sykes, A., Aitkenhead, M., Alexander, P., Moran, D., & MacLeod, M. (2021b). Predicting the abatement rates of soil organic carbon sequestration management in Western European vineyards using random forest regression. *Cleaner Environmental Systems*, *2*, 1–11. https://doi.org/10.1016/j.cesys.2021.100024

Payen, F. T., Moran, D., Cahurel, J.-Y., Aitkenhead, M., Alexander, P., & MacLeod, M. (2022). Factors influencing winegrowers' adoption of soil organic carbon sequestration practices in France. *Environmental Science and Policy*, *128*, 45–55. https://doi.org/10.1016/j.envsci.2021.11.011

Appendix B

Additional table showing reference, country, sub-climate, SCS practice, study duration, initial SOC stock and final SOC stock for each pairwise comparison used in the meta-analysis. Köppen-Geiger sub-climates: BSk, cold semi-arid climate; BWh, hot desert climate; Cfa, humid subtropical climate; Cfb, temperate oceanic climate; Csa, hot-summer Mediterranean climate; Csb, warm-summer Mediterranean climate; Csc, cold-summer Mediterranean climate; Dfa, hot-summer humid continental climate. SCS practices: OA, organic amendments; BC, biochar; PR, incorporating pruning residues into the soil; NT, no-tillage; CC, cover cropping.

Reference	Country	Sub-climate	SCS practice	Duration	Initial SOC stock	Final SOC stock
Agnelli et al. (2014)	Italy	Cfa	NT+CC	7	59.03	66.70
Bartoli and Dousset (2011)	France	Cfb	OA+NT	10	38.64	58.01
Bartoli and Dousset (2011)	France	Cfb	NT+CC	10	38.64	73.36
Belmonte et al. (2018)	USA	Csc	CC	22	69.10	64.42
Belmonte et al. (2018)	USA	Csc	NT+CC	22	69.10	90.81
Belmonte et al. (2016)	Italy	Csb	NT+CC	19	24.53	71.32
Besnard et al. (2001)	France	Cfb	PR+NT	12	54.31	102.82
Besnard et al. (2001)	France	Cfb	OA+NT	12	54.31	195.03
Blavet et al. (2009)	France	Csa	PR	21	20.73	33.16
Bravo-Martin-Consuegra et al. (2016)	Spain	BSk	OA	8	12.76	46.54
Calleja-Cervantes et al. (2015)	Spain	Cfb	OA	13	25.35	36.05
Capo-Bauca et al. (2019)	Spain	BSk	NT+CC	7	90.95	106.47
Celette et al. (2009)	France	Csa	NT	3	34.75	40.75
Celette et al. (2009)	France	Csa	NT+CC	3	36.31	37.07
Celette et al. (2009)	France	Csa	CC	3	36.19	40.76
Coll et al. (2011)	France	Csa	OA	11	35.31	50.02
Coll et al. (2011)	France	Csa	OA	10	40.48	49.83

Conradie (2001)	South Africa	Csb	OA+NT+CC	9	16.12	24.63
Conradie (2001)	South Africa	Csb	NT+CC	9	16.12	21.20
Costantini et al. (2015)	Italy	Csa	OA	5	19.34	25.86
Costantini et al. (2015)	Italy	Csa	OA+NT+CC	5	27.67	35.03
DeVetter et al. (2015)	USA	Dfa	NT	7	43.82	46.21
DeVetter et al. (2015)	USA	Dfa	NT+CC	7	41.41	62.45
DeVetter et al. (2015)	USA	Dfa	OA+NT	7	41.41	64.70
Ferrero et al. (2007)	Italy	Cfb	NT+CC	7	38.25	69.44
Fourie et al. (2012)	South Africa	BSk	NT	10	21.16	35.57
Fourie et al. (2012)	South Africa	BSk	OA+NT	10	21.04	38.24
Fourie et al. (2012)	South Africa	BSk	NT+CC	10	23.69	39.07
Fourie et al. (2012)	South Africa	BSk	NT+CC	10	26.11	44.95
Fourie et al. (2012)	South Africa	BSk	NT+CC	10	25.84	38.52
Fourie et al. (2012)	South Africa	BSk	NT+CC	10	22.02	38.19
Fourie et al. (2012)	South Africa	BSk	NT+CC	10	23.77	40.95
Fourie et al. (2012)	South Africa	BSk	NT+CC	10	25.46	41.88
Fourie et al. (2012)	South Africa	BSk	NT+CC	10	24.18	44.15
Fourie et al. (2012)	South Africa	BSk	NT+CC	10	25.45	36.37
Fourie et al. (2007a)	South Africa	BWh	NT	10	6.01	5.01
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	5.77	9.31
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	6.01	6.48
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	5.77	7.10
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	5.27	6.62

Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	4.77	7.81
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	5.27	8.01
Fourie et al. (2007a)	South Africa	BWh	CC	10	4.77	6.25
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	5.77	7.57
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	5.27	7.10
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	6.01	6.49
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	4.77	6.49
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	5.27	8.27
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	6.01	9.07
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	5.77	9.32
Fourie et al. (2007a)	South Africa	BWh	NT+CC	10	4.77	12.24
Fourie et al. (2007a)	South Africa	BWh	CC	10	4.77	5.59
Fourie et al. (2007b)	South Africa	Csb	NT	10	21.75	26.52
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	21.75	43.87
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	21.14	35.75
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	21.14	32.76
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	20.12	31.14
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	21.75	33.50
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	21.75	33.11
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	21.55	31.38

Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	21.55	30.34
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	17.63	38.18
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	20.53	40.15
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	20.53	33.86
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	20.73	33.19
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	17.63	34.86
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	21.55	41.44
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	19.09	33.76
Fourie et al. (2007b)	South Africa	Csb	NT+CC	10	21.55	34.21
Gaiotti et al. (2017)	Italy	Cfa	OA	5	52.43	58.49
Gaiotti et al. (2017)	Italy	Cfa	OA	5	52.83	63.87
Garcia et al. (2018)	France	Csa	NT+CC	5	30.28	46.91
Garcia-Diaz et al. (2018)	Spain	Csa	NT+CC	3	28.64	36.81
Garcia-Diaz et al. (2018)	Spain	Csa	NT+CC	3	32.21	41.30
Garcia-Orenes et al. (2016)	Spain	BSk	OA+PR+NT	10	37.55	59.19
Garcia-Orenes et al. (2016)	Spain	Bsk	PR+NT+CC	10	35.10	61.42
Goulet et al. (2004)	France	Cfb	NT+CC	9	40.19	50.99
Goulet et al. (2004)	France	Cfb	OA+NT	9	40.19	54.09
Gristina et al. (2005)	Italy	Csb	NT+CC	3	34.09	38.04
Gristina et al. (2005)	Italy	Csb	NT+CC	3	32.21	35.80
Herrero-Hernandez et al. (2012)	Spain	Cfa	OA	3	21.79	27.93
Herrero-Hernandez et al. (2012)	Spain	Cfa	OA	3	26.36	30.62
Herrero-Hernandez et al. (2012)	Spain	Cfb	OA	3	41.13	44.49
Herrero-Hernandez et al. (2012)	Spain	Cfb	OA	3	40.38	44.41
Herrero-Hernandez et al.	Spain	Cfb	OA	3	51.71	61.43

(2012)						
Herrero-Hernandez et al. (2012)	Spain	Cfb	OA	3	48.60	53.64
Laudicina et al. (2017)	Italy	Csa	NT+CC	5	54.56	57.27
Lejon et al. (2007)	France	Cfb	NT+CC	13	29.10	39.26
Lejon et al. (2007)	France	Cfb	OA+NT	13	29.10	42.30
Lejon et al. (2007)	France	Cfb	PR	27	17.44	23.54
Lejon et al. (2007)	France	Cfb	OA	27	17.44	31.74
Linares et al. (2014)	Spain	Csa	NT	8	18.47	32.99
Linares et al. (2014)	Spain	Csa	NT+CC	8	18.47	49.37
López-Piñeiro et al. (2013)	Spain	Csa	NT+CC	6	8.29	51.93
López-Piñeiro et al. (2013)	Spain	Csa	NT+CC	6	8.51	31.36
Morlat and Chaussod (2008)	France	Cfb	PR	28	30.61	33.88
Morlat and Chaussod (2008)	France	Cfb	OA	28	22.99	39.51
Morlat and Chaussod (2008)	France	Cfb	OA	28	22.46	39.15
Morlat and Chaussod (2008)	France	Cfb	OA	28	25.49	48.23
Morlat and Chaussod (2008)	France	Cfb	OA	28	24.85	54.57
Morlat and Jacquet (2003)	France	Cfb	NT+CC	17	24.80	27.24
Morlat and Jacquet (2003)	France	Cfb	NT+CC	17	25.60	28.90
Mugnai et al. (2012)	Italy	Cfb	NT+CC	9	59.71	81.58
Mugnai et al. (2012)	Italy	Cfb	OA+NT+CC	9	59.71	149.34
Novara et al. (2019)	Italy	Csa	CC	5	37.32	38.75
Novara et al. (2019)	Italy	Csa	CC	5	38.05	40.90
Novara et al. (2019)	Italy	Csa	CC	5	36.61	40.90
Novara et al. (2019)	Italy	Csa	CC	5	41.48	43.61
Okur et al. (2009)	Turkey	Csa	OA+NT+CC	3	33.38	39.78
Okur et al. (2009)	Turkey	Csa	OA+NT+CC	3	32.65	39.08
Okur et al. (2009)	Turkey	Csa	OA+NT+CC	3	31.56	36.96
Olego et al. (2015)	Spain	Csb	OA	3	24.76	31.17
Olego et al. (2015)	Spain	Csb	OA	3	24.95	32.50
Peregrina et al. (2014a)	Spain	Cfb	NT+CC	3	26.85	40.72

Peregrina et al. (2014b)	Spain	Cfb	NT+CC	5	29.67	36.27
Peregrina et al. (2012)	Spain	Cfb	OA	4	26.48	45.86
Peregrina et al. (2010)	Spain	Cfb	NT+CC	4	26.51	32.01
Perez-Bermudez et al. (2016)	Spain	Cfb	PR	4	41.70	48.44
Perez-Bermudez et al. (2016)	Spain	Cfb	PR+CC	4	41.70	58.23
Perez-Bermudez et al. (2016)	Spain	Cfb	PR	4	43.40	49.76
Perez-Bermudez et al. (2016)	Spain	Cfb	PR+CC	4	43.40	63.63
Rahman et al. (2009)	Australia	Cfa	NT+CC	3	30.89	31.96
Rahman et al. (2009)	Australia	Cfb	NT+CC	3	61.81	69.54
Ramos (2017)	Spain	Cfa	OA	4	45.64	70.09
Ramos (2017)	Spain	Cfa	OA	4	21.54	33.44
Reuter and Kubiak (2003)	Germany	Cfb	NT	8	36.96	49.17
Reuter and Kubiak (2003)	Germany	Cfb	NT+CC	8	36.96	60.90
Rombola et al. (2019)	Italy	Cfb	BC	5	35.69	66.39
Ruiz-Colmenero et al. (2013)	Spain	Csa	NT+CC	4	22.58	33.29
Ruiz-Colmenero et al. (2013)	Spain	Csa	CC	4	22.58	32.51
Sánchez-Monedero et al. (2019)	Italy	Cfa	OA	3	45.69	49.48
Sánchez-Monedero et al. (2019)	Italy	Cfa	OA+BC	3	45.69	52.55
Sánchez-Monedero et al. (2019)	Italy	Cfa	BC	3	45.69	54.23
Sánchez-Monedero et al. (2019)	Italy	Cfa	OA	3	65.77	67.39
Sánchez-Monedero et al. (2019)	Italy	Cfa	OA+BC	3	65.77	68.99
Sánchez-Monedero et al. (2019)	Italy	Cfa	BC	3	65.77	68.35
Sánchez-Monedero et al. (2019)	Italy	Cfa	OA	3	55.24	63.50
Sánchez-Monedero et al. (2019)	Italy	Cfa	OA+BC	3	55.24	59.56

Sánchez-Monedero et al. (2019)	Italy	Cfa	BC	3	55.24	61.54
Steenwerth and Belina (2008)	USA	Csc	NT+CC	5	30.01	40.70
Virto et al. (2012)	Spain	Cfb	PR+NT+CC	5	39.11	47.80
Walser et al. (2007)	USA	BSk	OA	3	13.03	47.35
Walser et al. (2007)	USA	BSk	NT+CC	3	13.03	21.32
Walser et al. (2007)	USA	BSk	OA+NT+CC	3	13.03	57.89
Wolff et al. (2018)	USA	Csc	PR+CC	7	68.72	67.67
Wolff et al. (2018)	USA	Csc	PR+NT+CC	7	68.72	79.06

Appendix C

List of the studies included in the meta-analysis:

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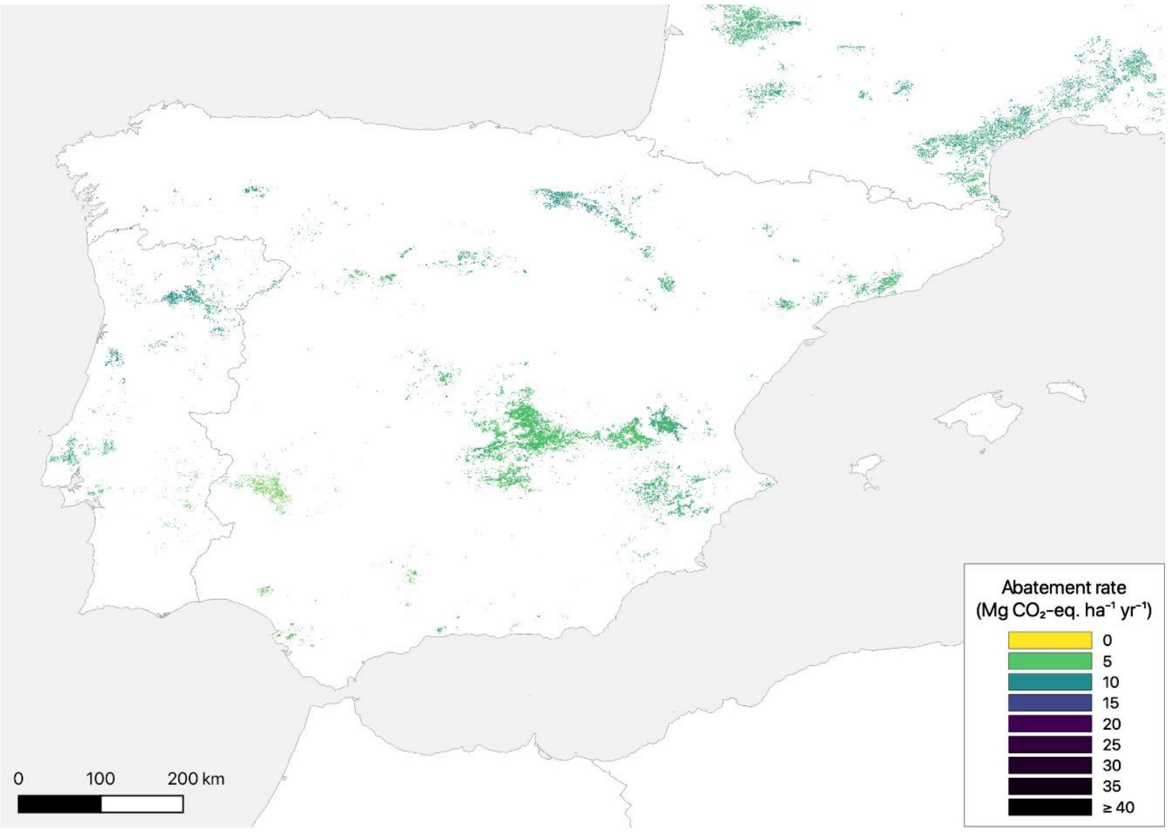
Appendix D

Maps depicting the abatement rate of viticultural land under SCS management in Spain (a), France (b), Italy (c), Portugal (d), Germany (e) and Austria (f). Higher-resolution maps, with the possibility to zoom in on specific winegrowing regions, can be found at https://f-payen.github.io/carbon-sequestration-in-vineyards/.

OA



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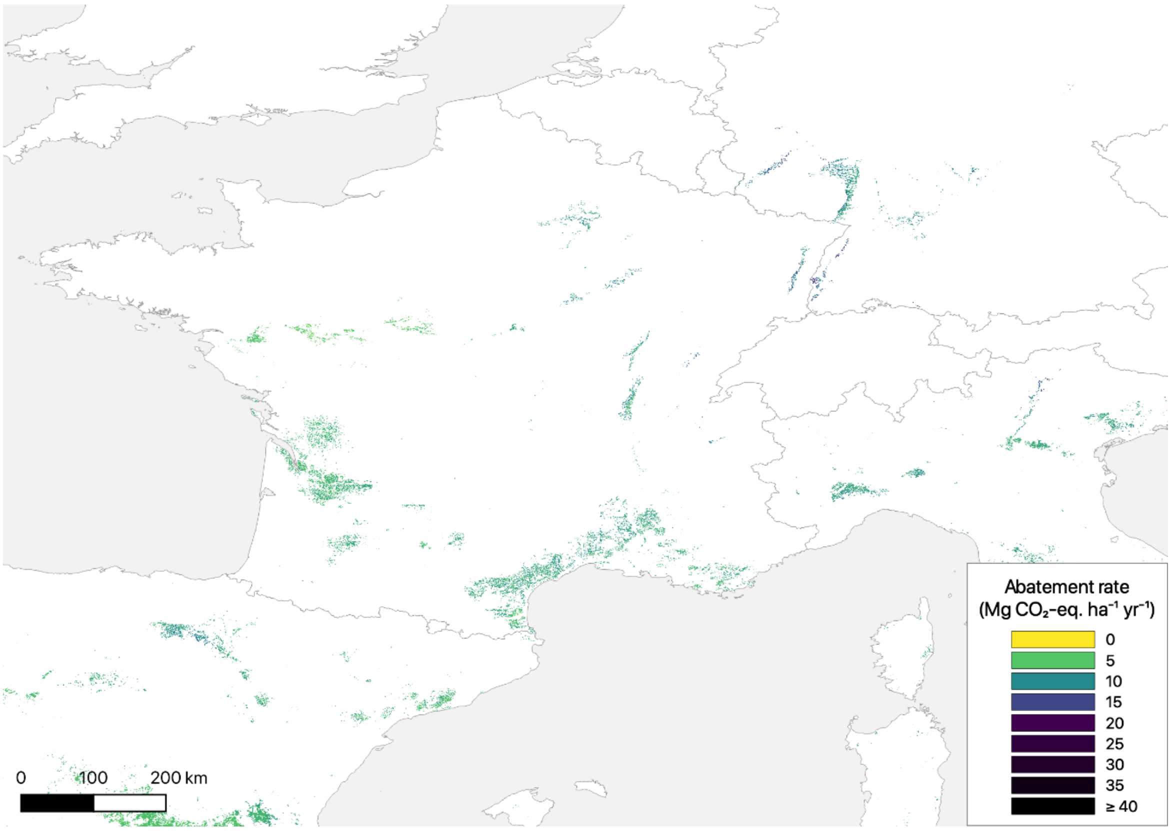
Abatement rate
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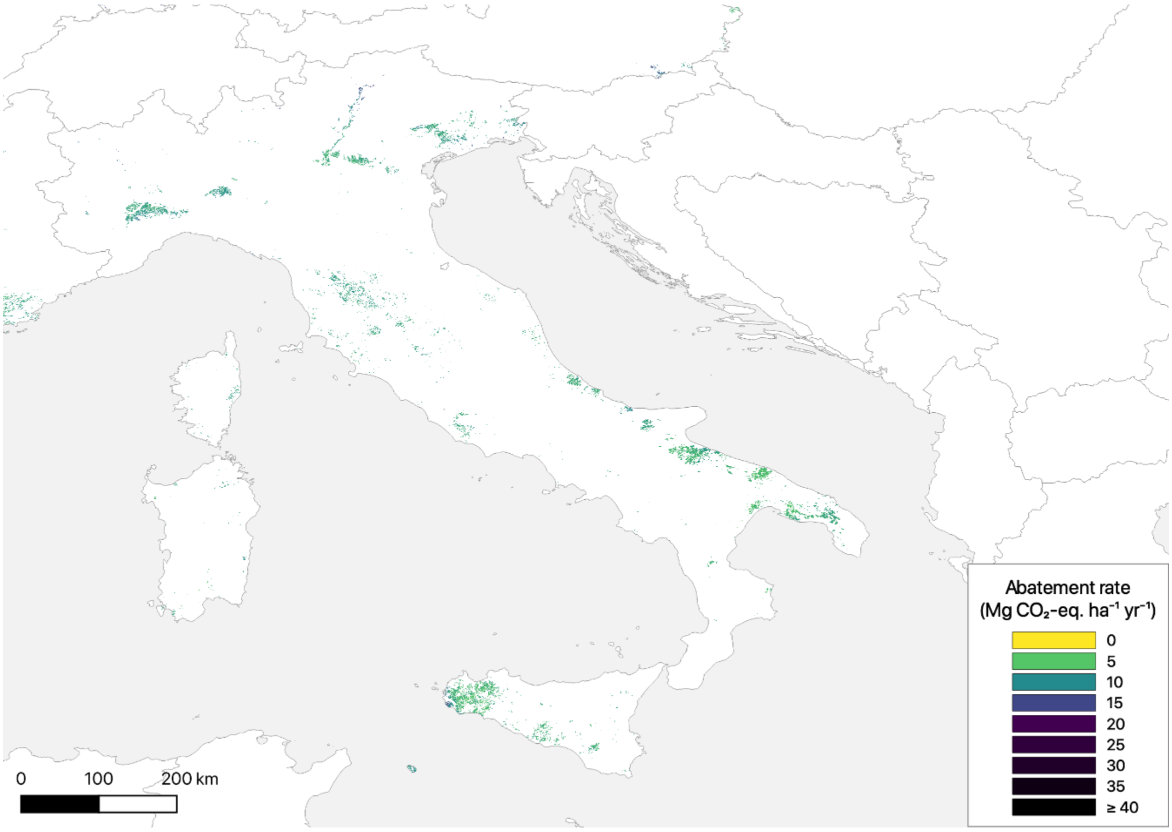
(b)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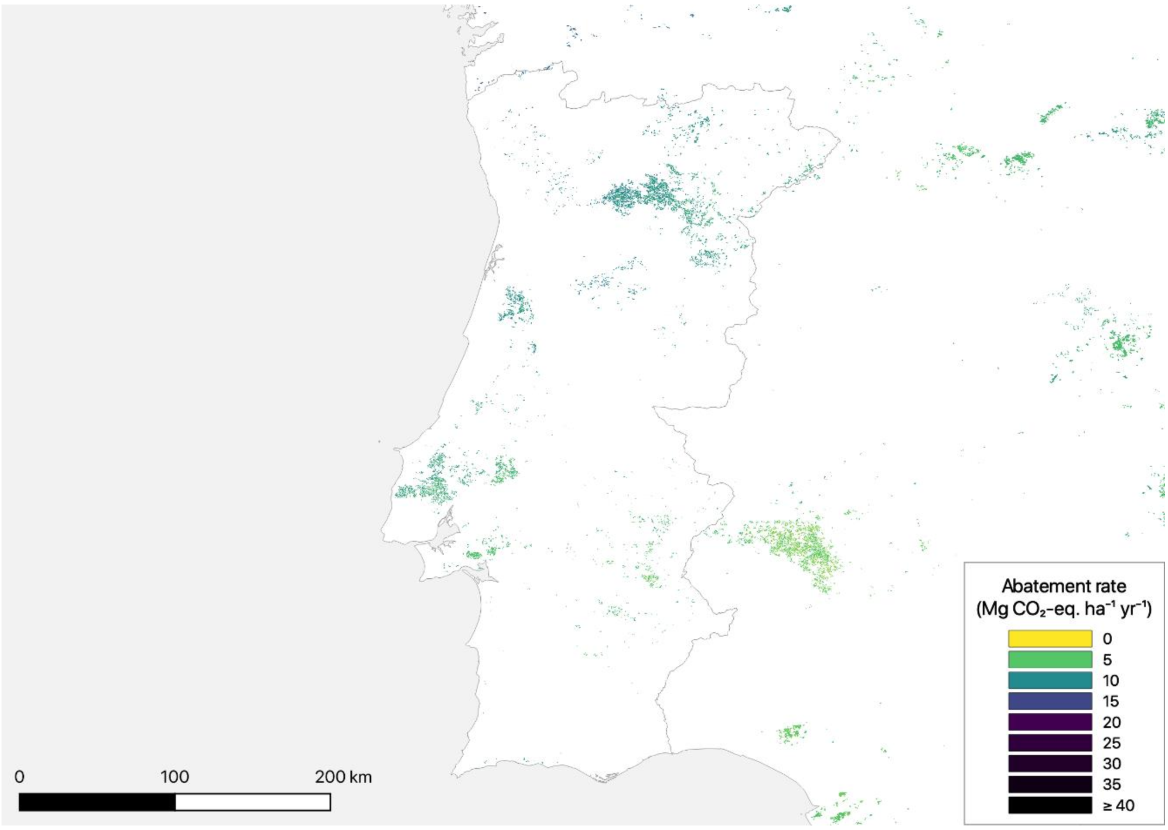
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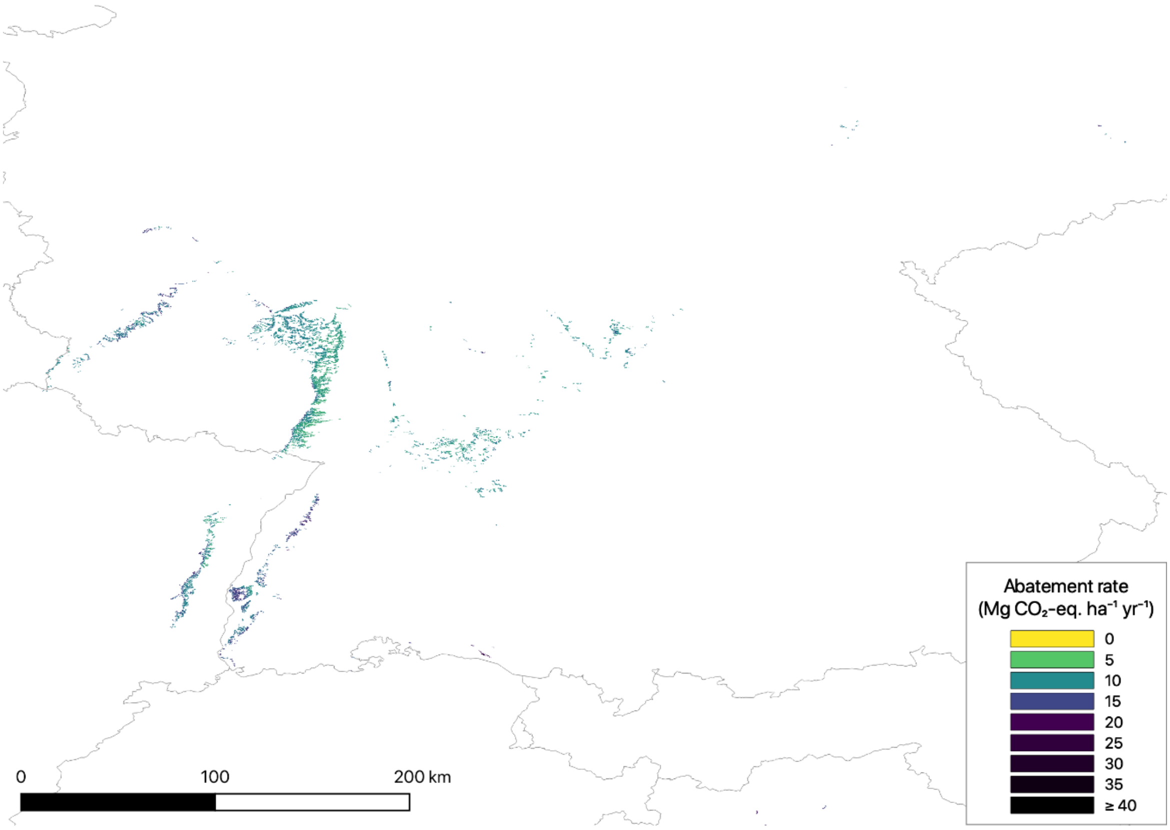
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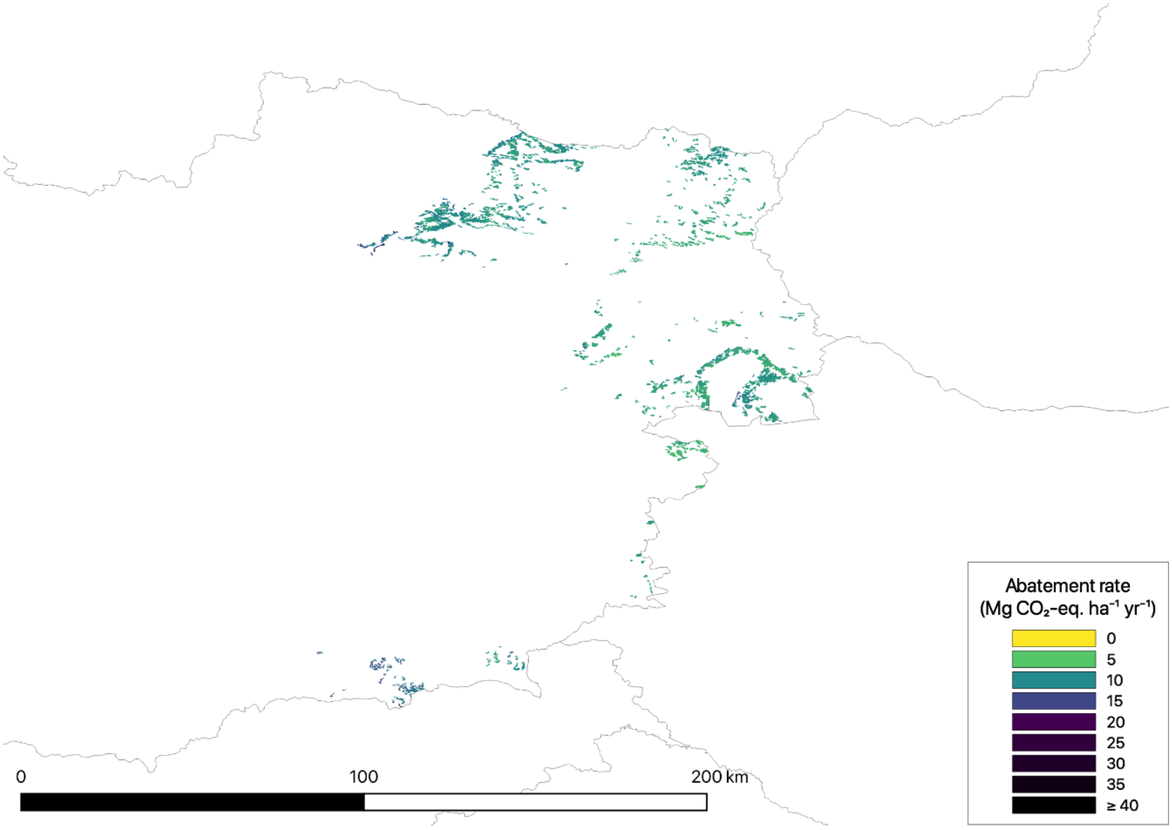
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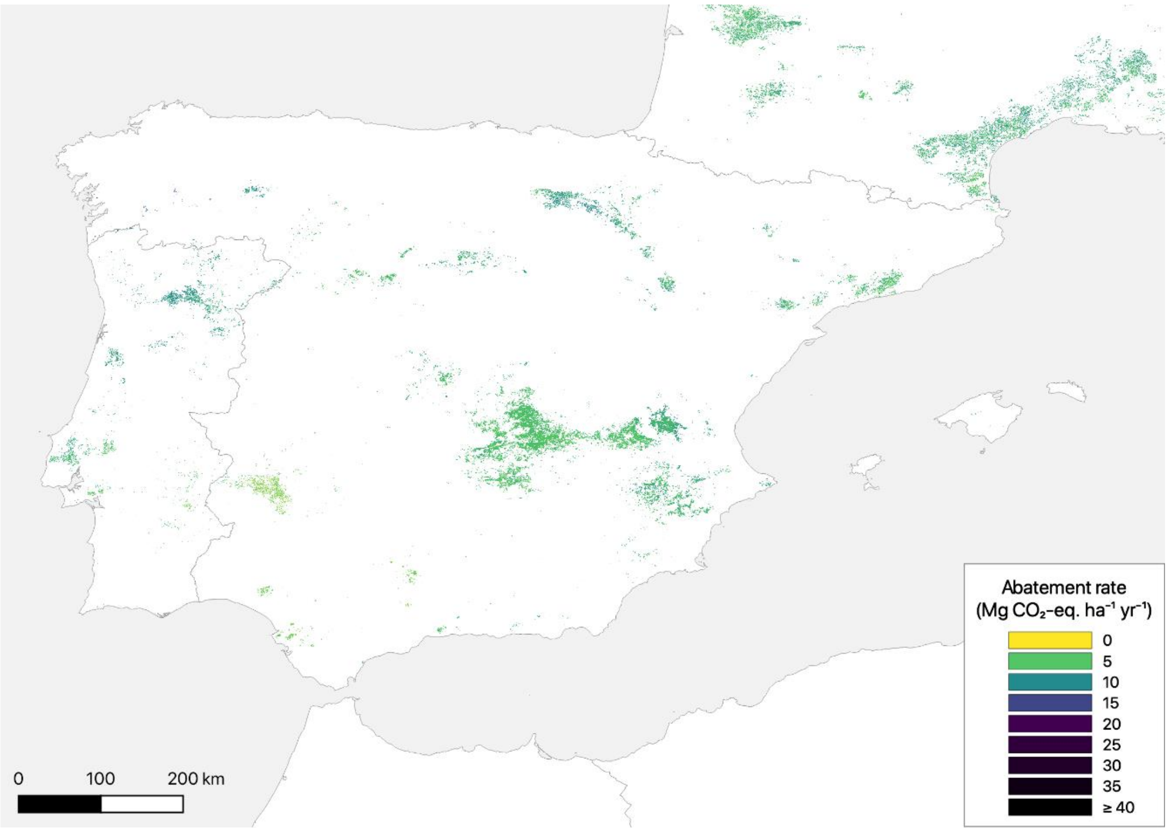
Abatement rate
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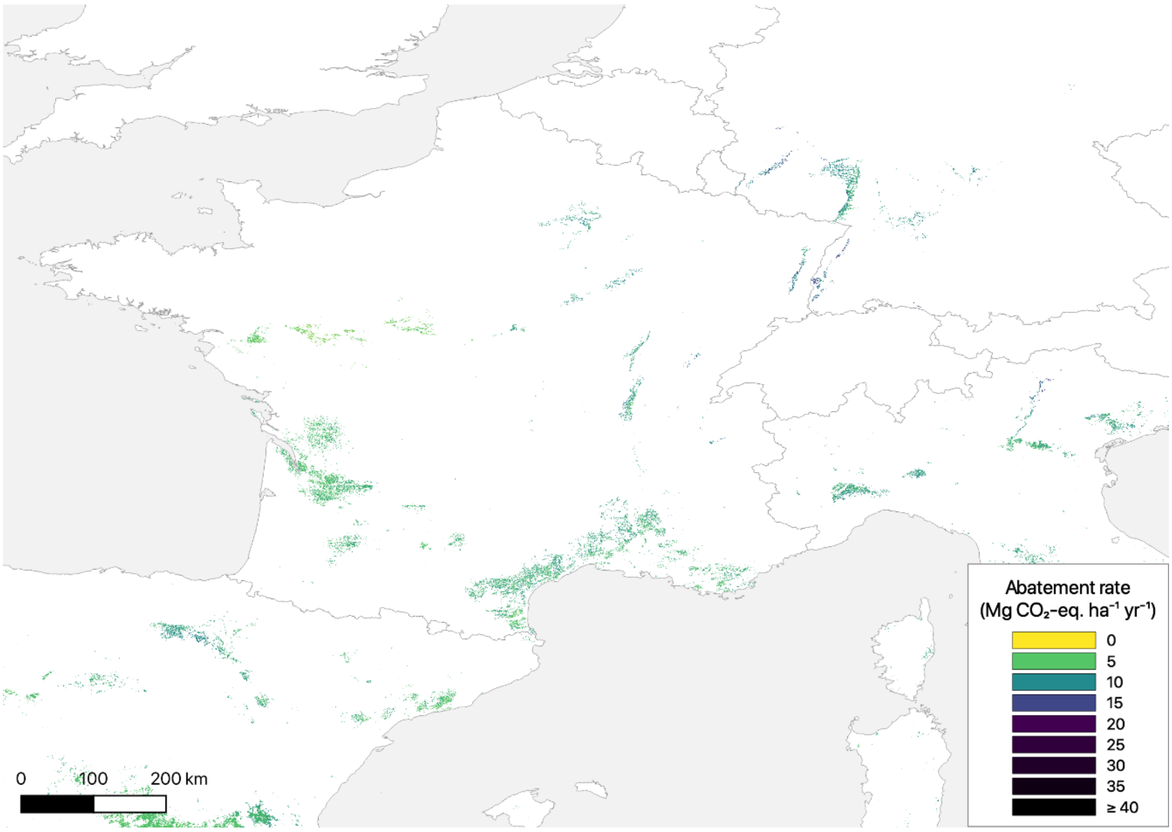
(a)


Abatement rate
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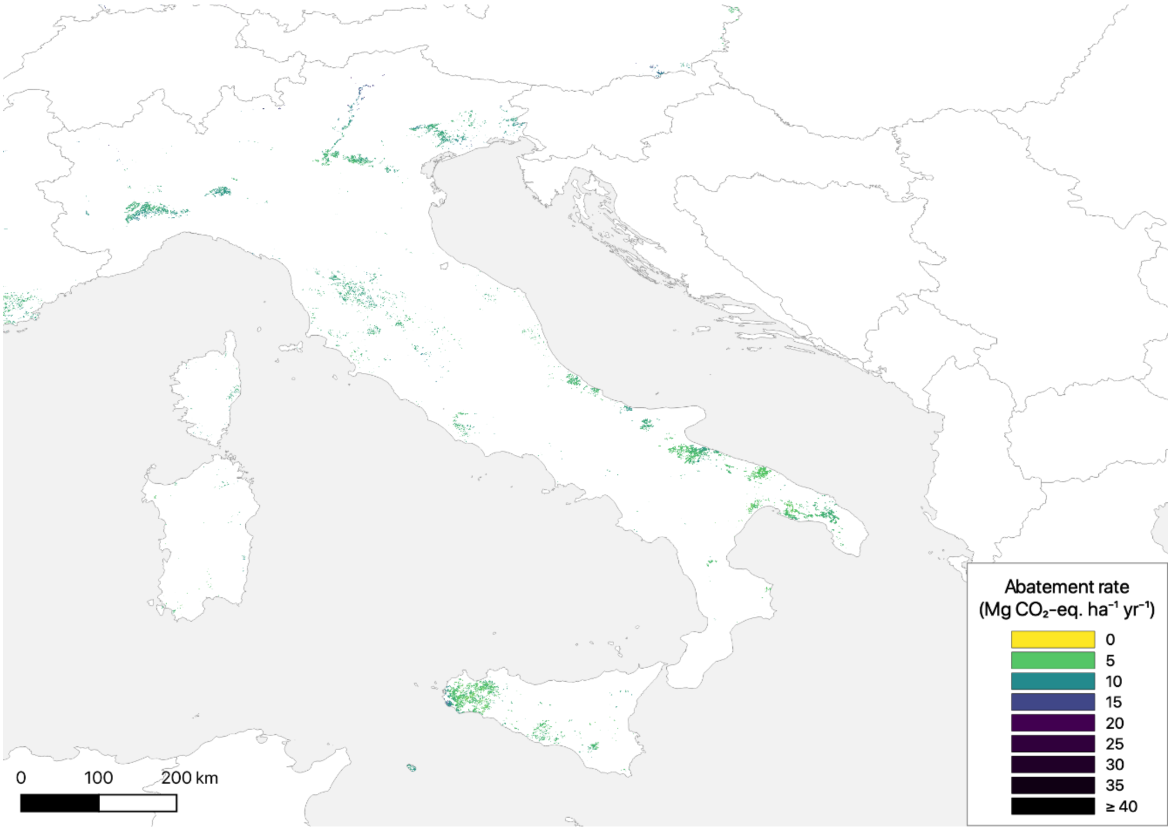
(b)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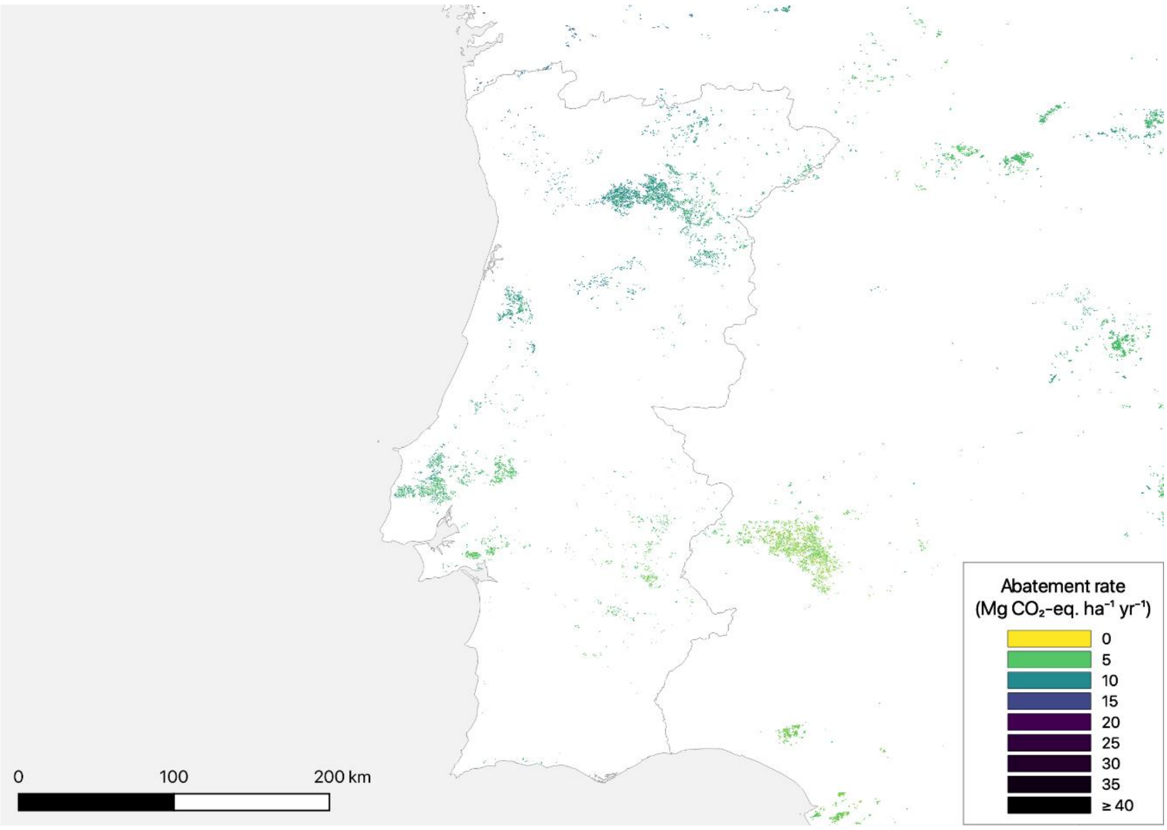
(c)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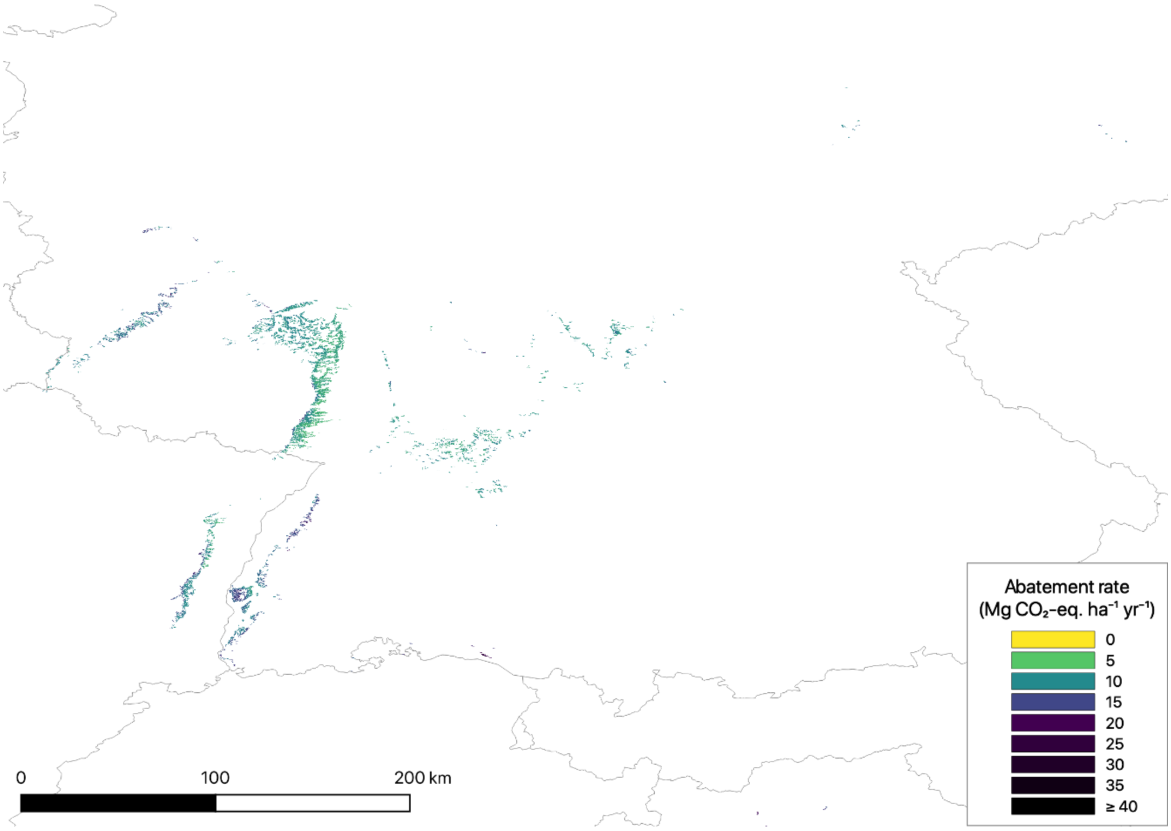
Abatement rate
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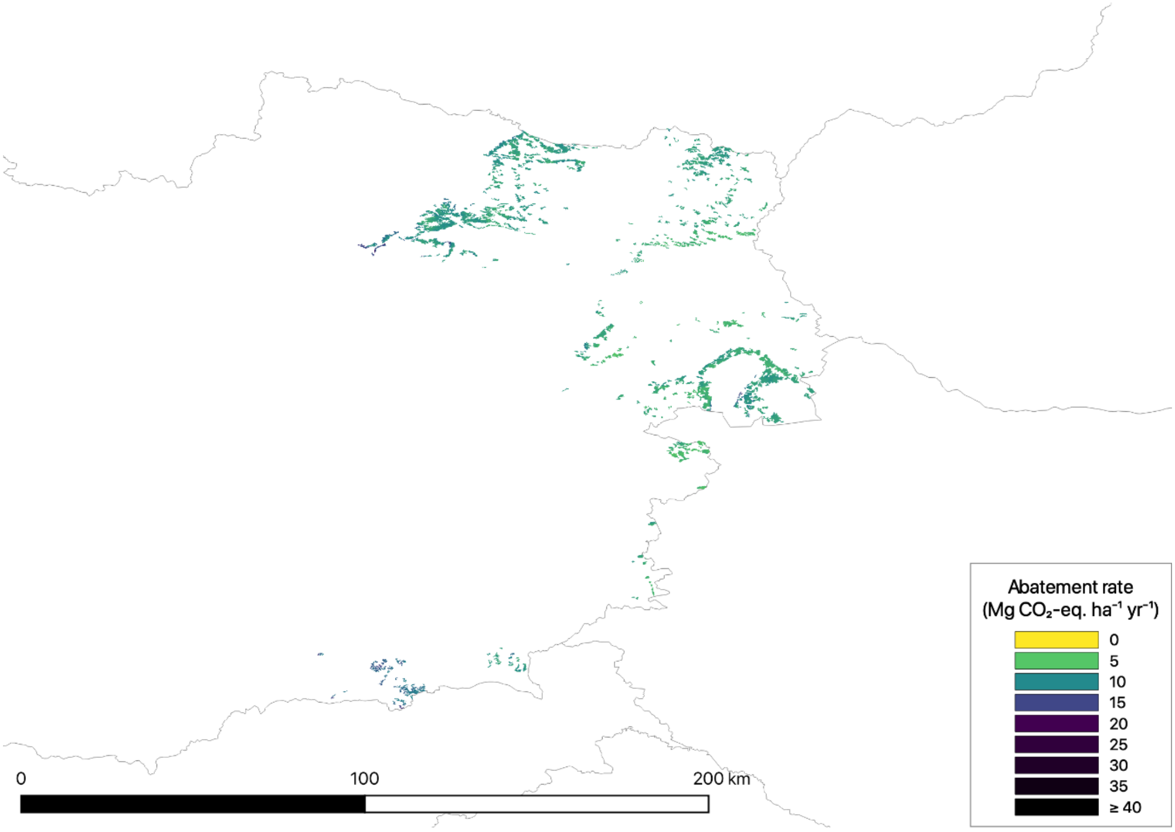
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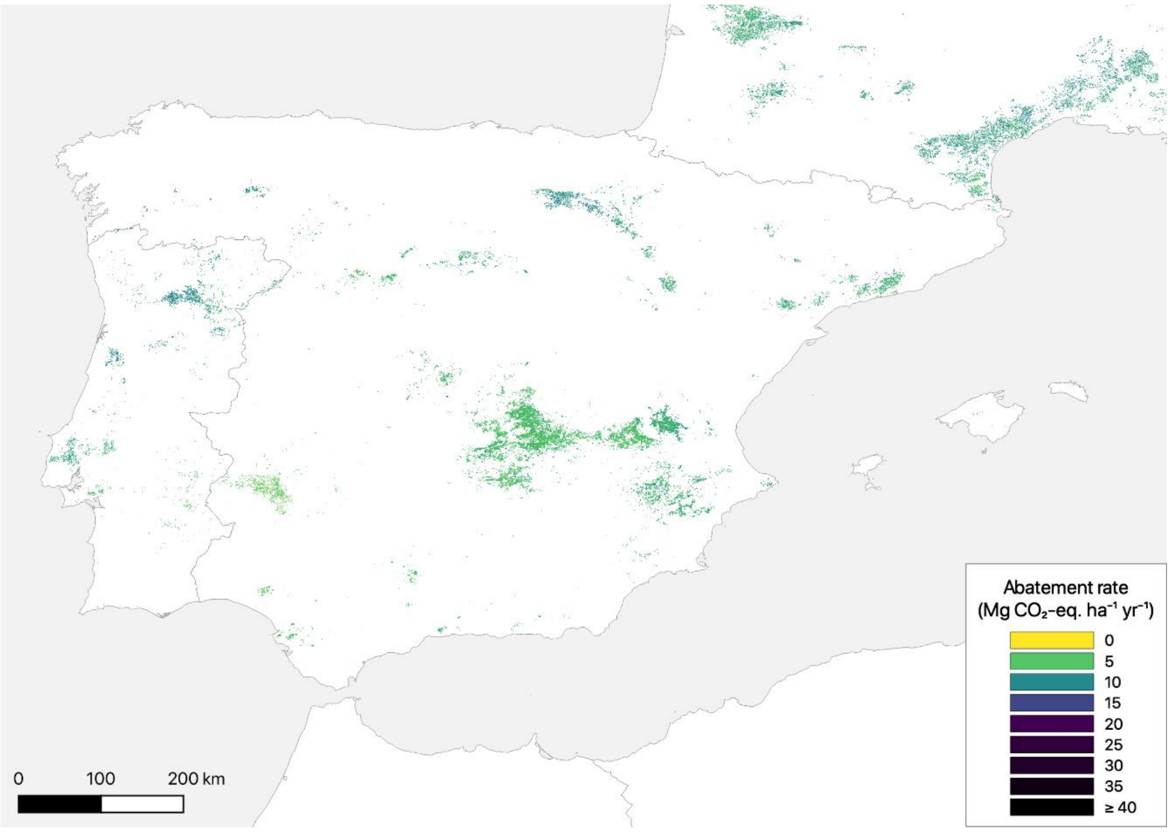

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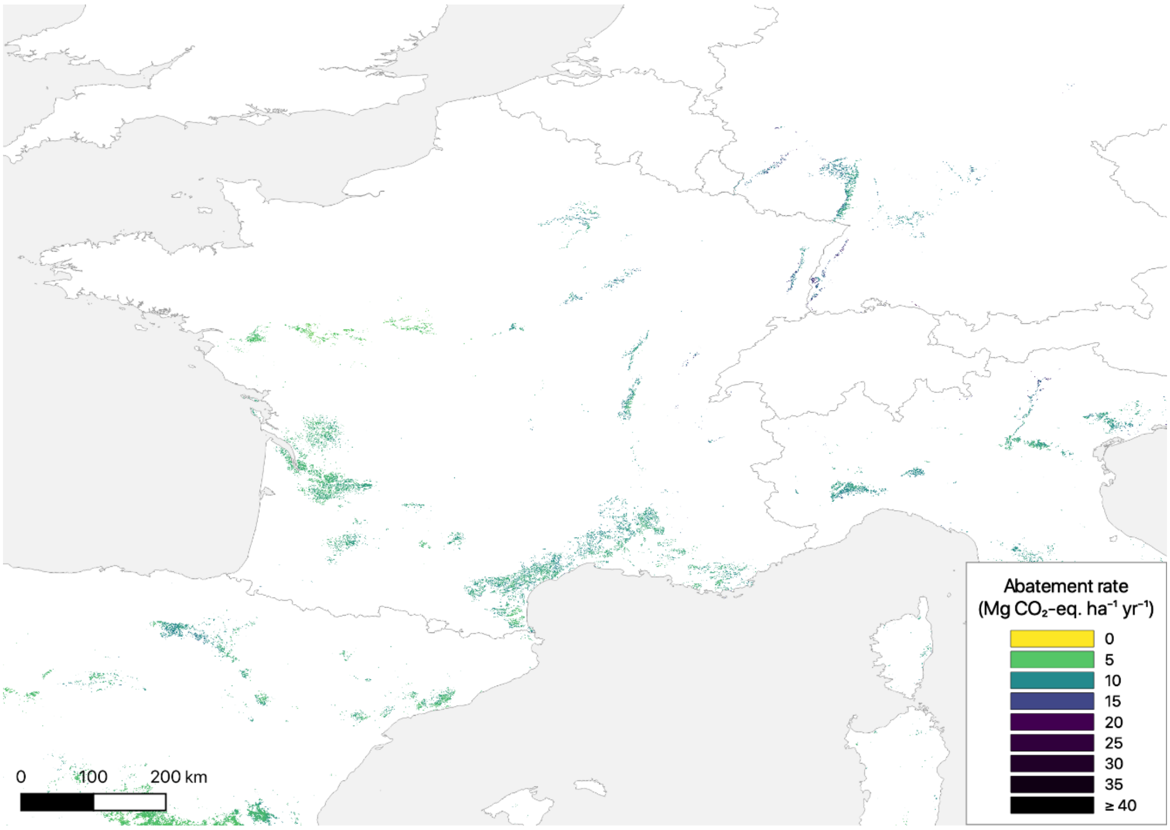

Abatement rate
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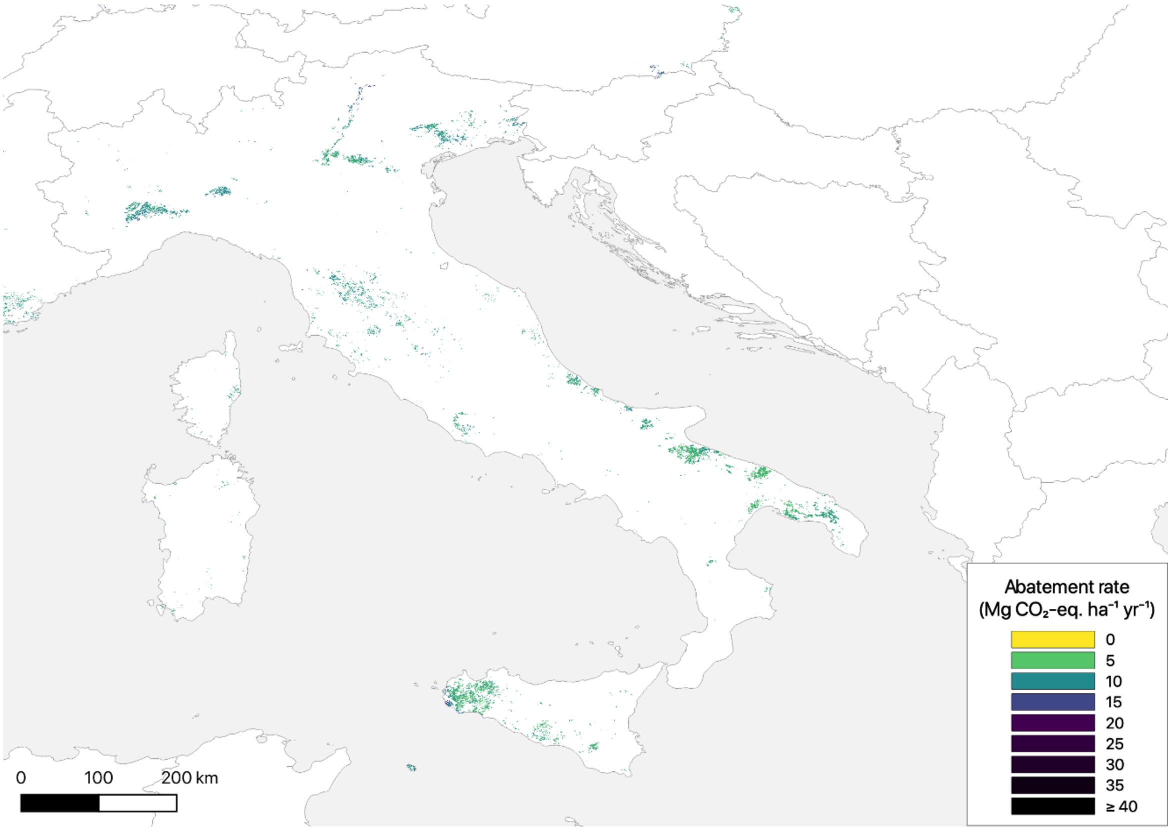
(b)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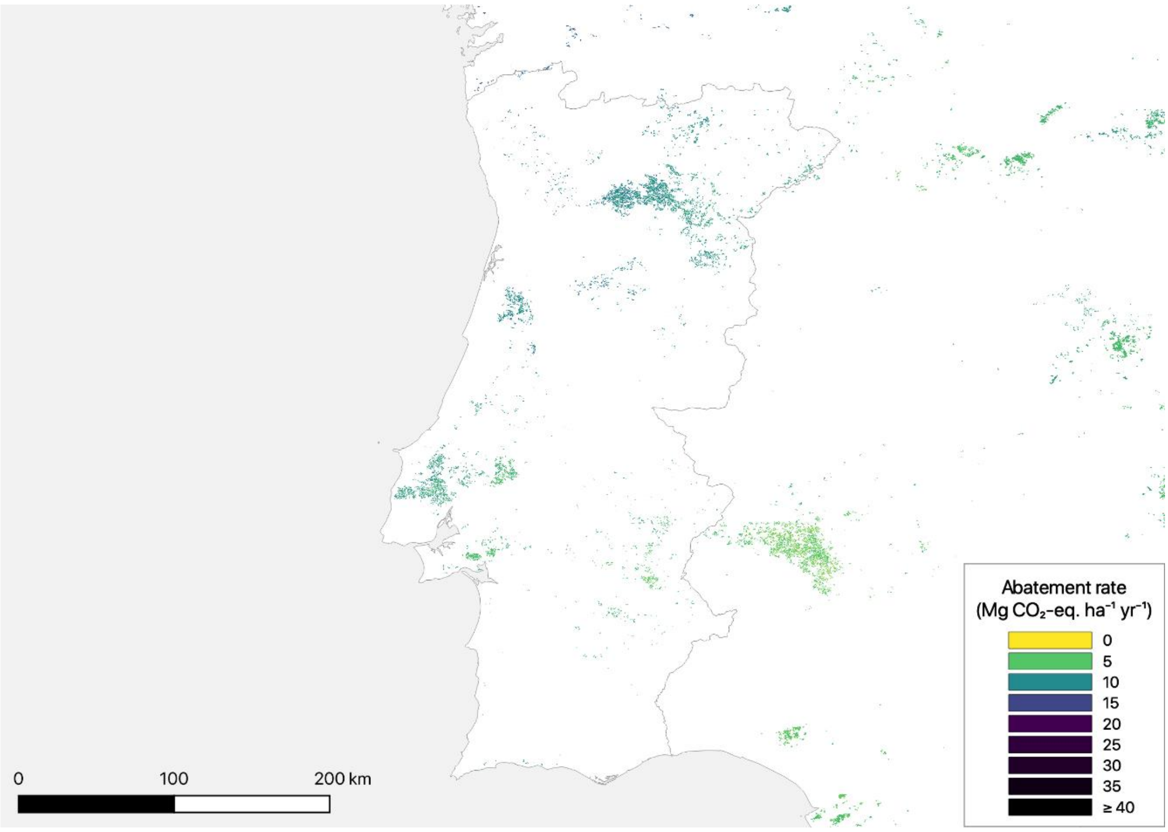
(c)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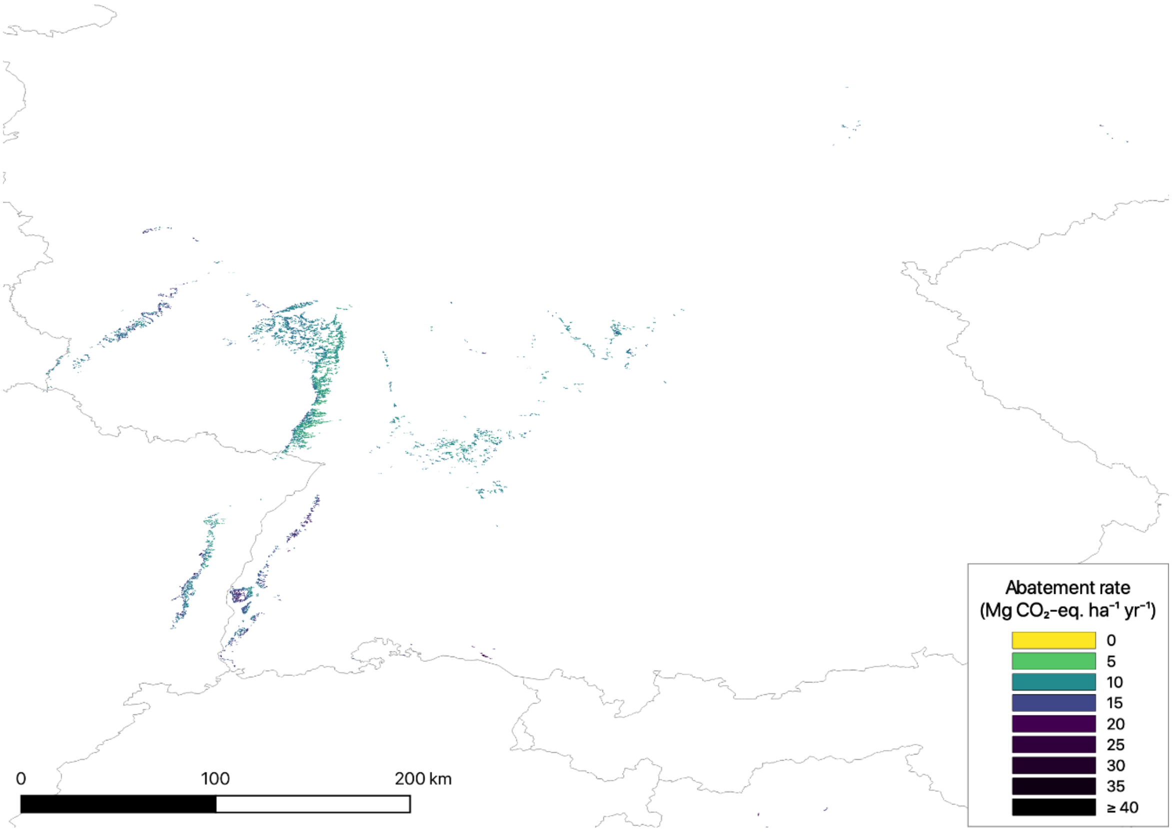
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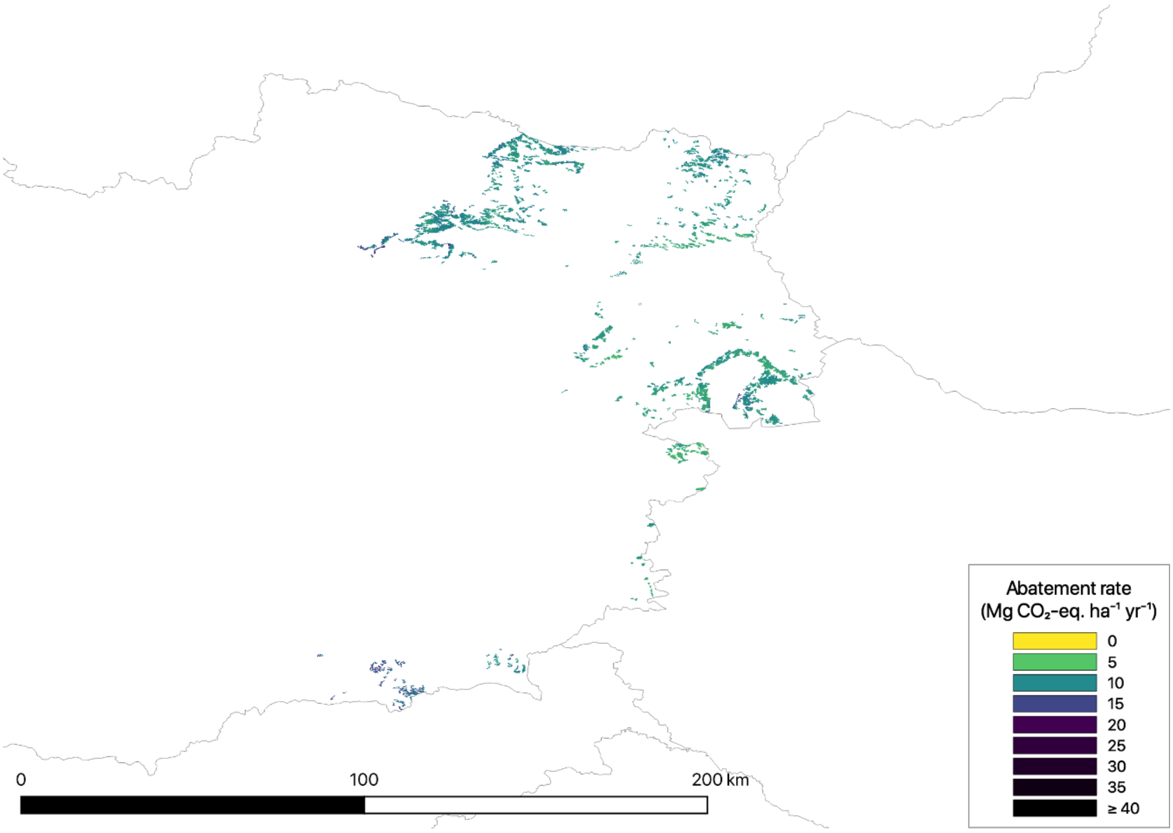
Abatement rate
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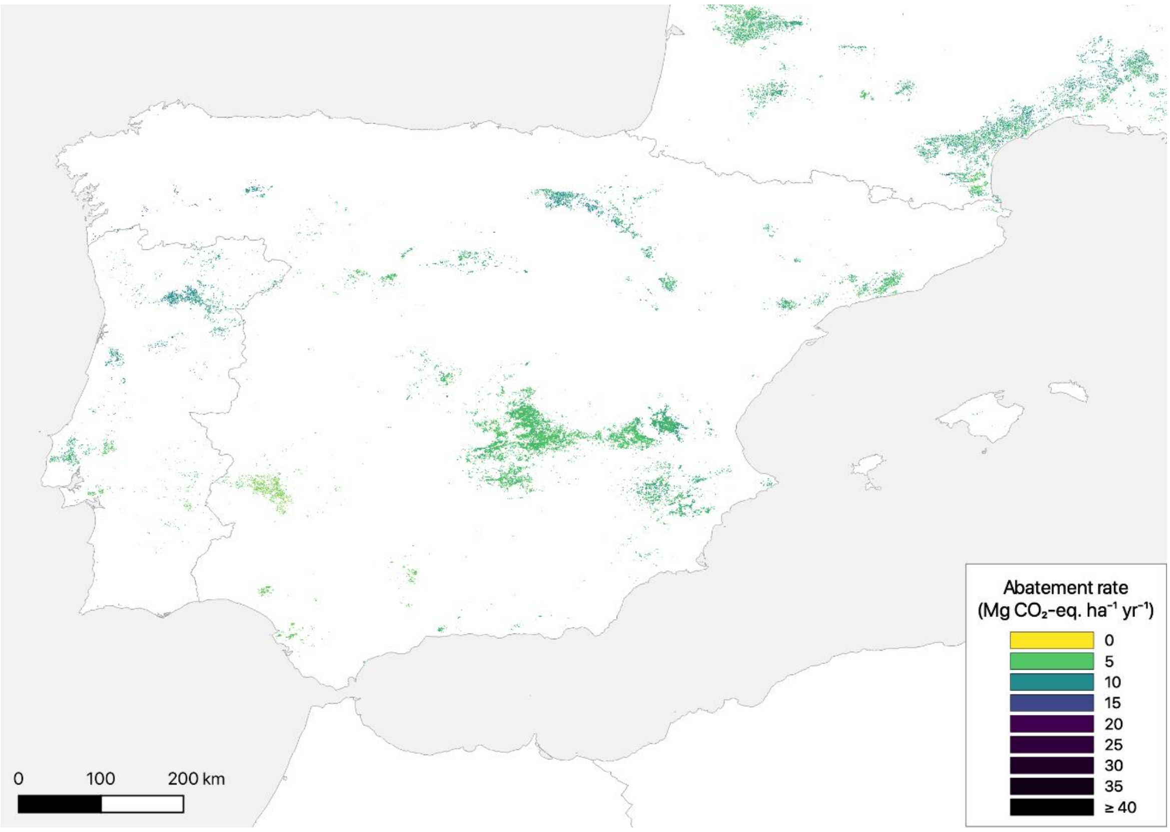
(f)

NT+CC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(Mg CO₂-eq. ha⁻¹ yr⁻¹)
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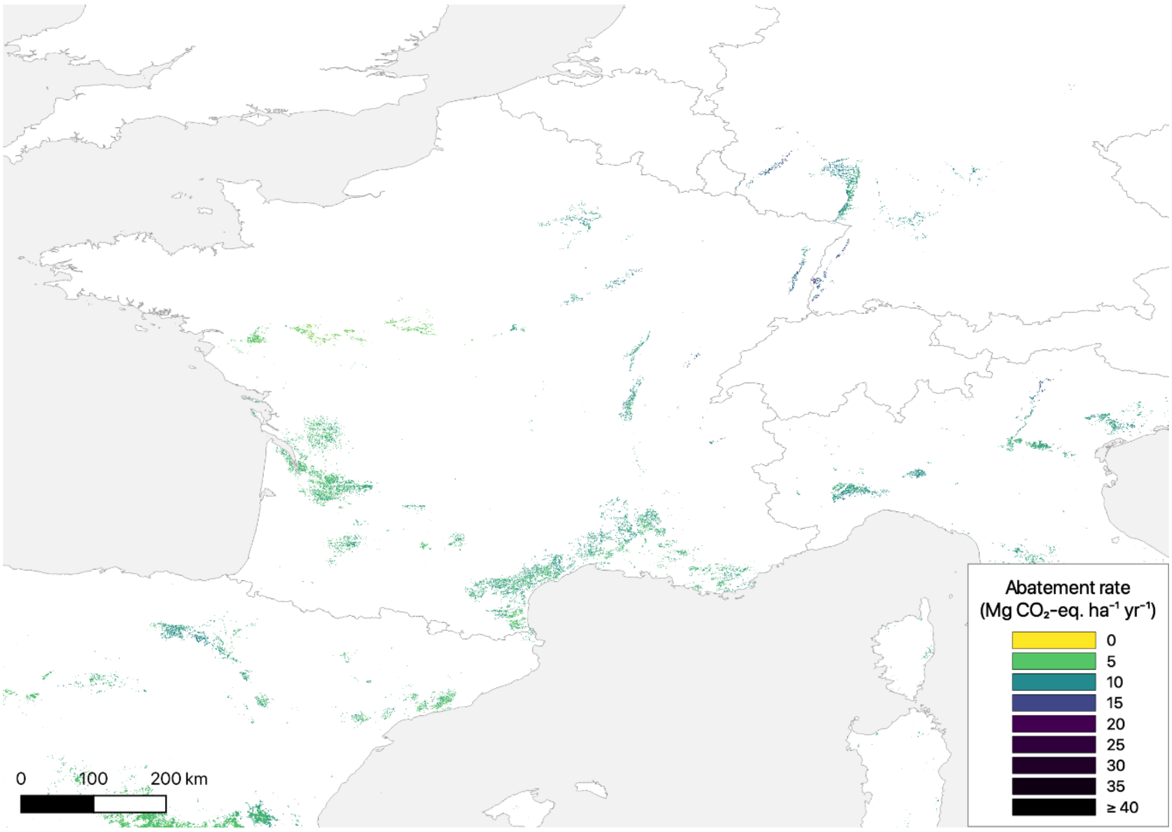
🟩 5
10
🟦 15
20
25
30
35
≥ 40
0
100
200 km

(a)


Abatement rate
(Mg CO₂-eq. ha⁻¹ yr⁻¹)
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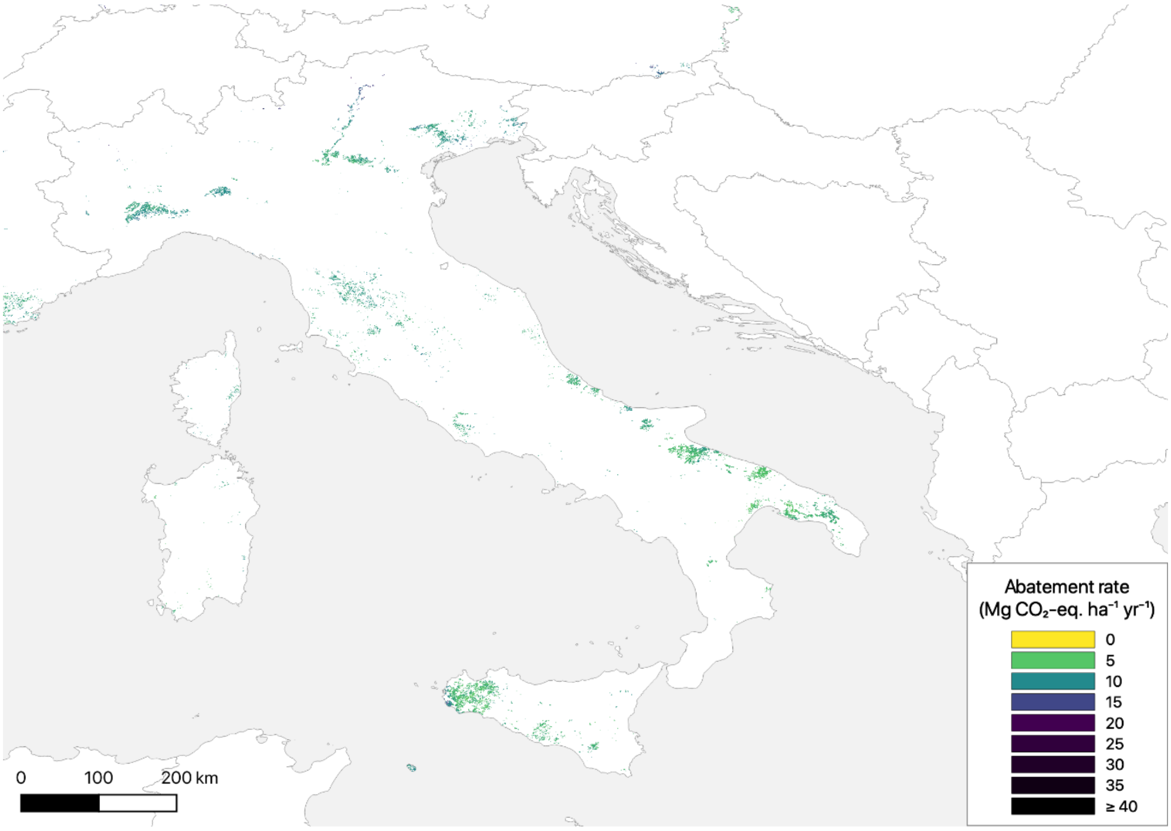
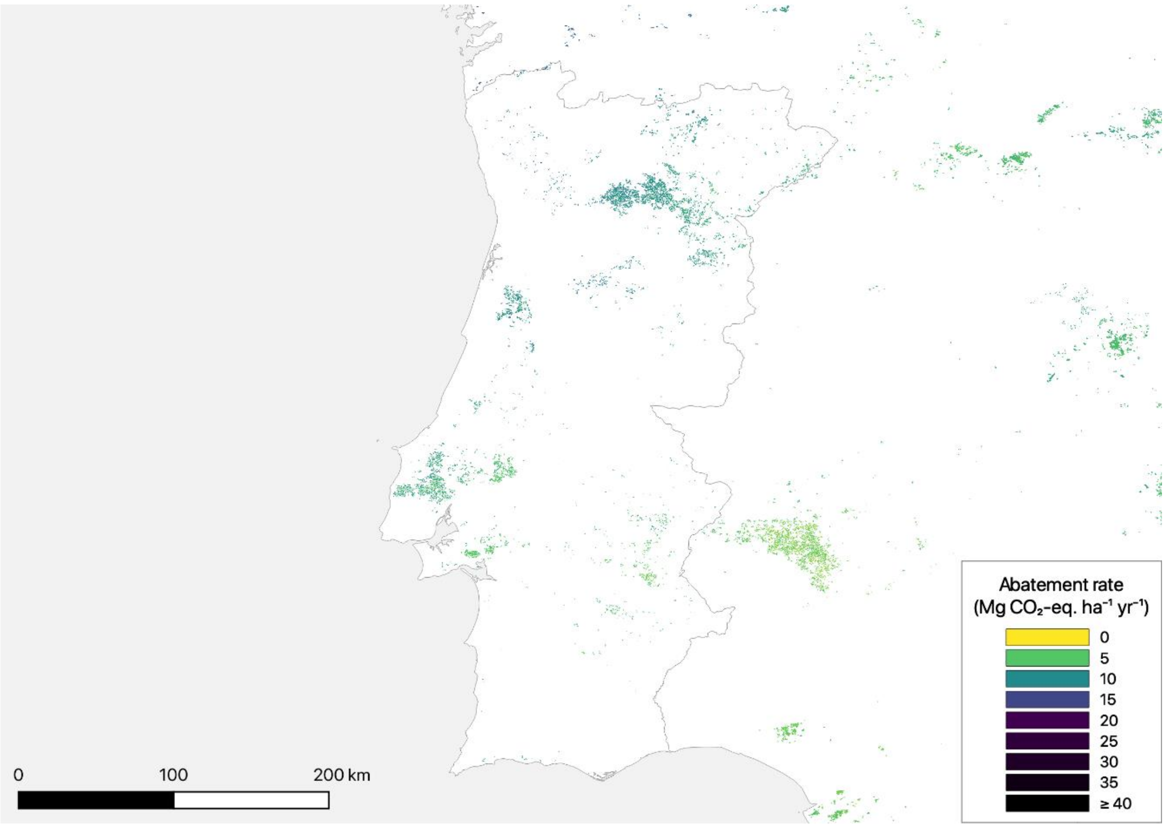
🟩 5
10
🟦 15
20
25
30
35
≥ 40
0
100
200 km

(b)


0
100
200 km
Abatement rate
(Mg CO₂-eq. ha⁻¹ yr⁻¹)
0
5
10
15
20
25
30
35
≥ 40

(c)


0
100
200 km
Abatement rate
(Mg CO₂-eq. ha⁻¹ yr⁻¹)
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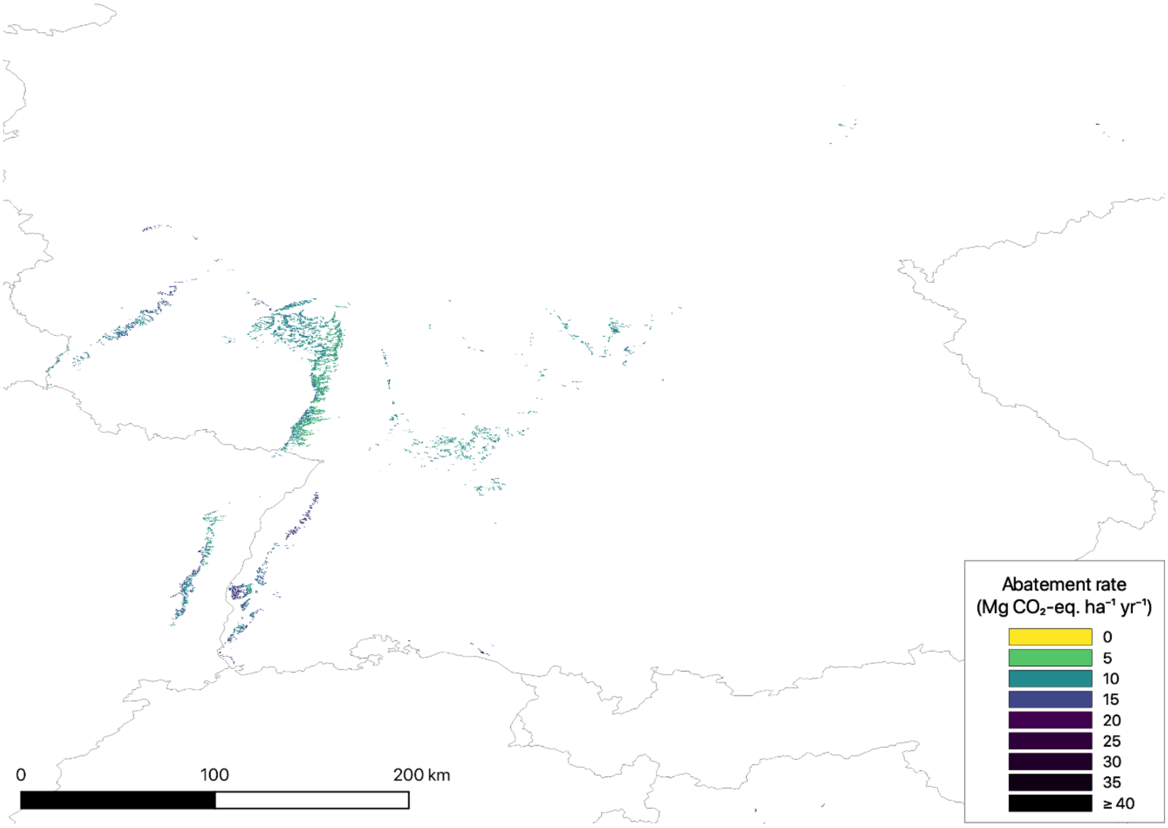
5
10
15
20
25
30
35
≥ 40

(d)


Abatement rate
(Mg CO₂-eq. ha⁻¹ yr⁻¹)
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5
10
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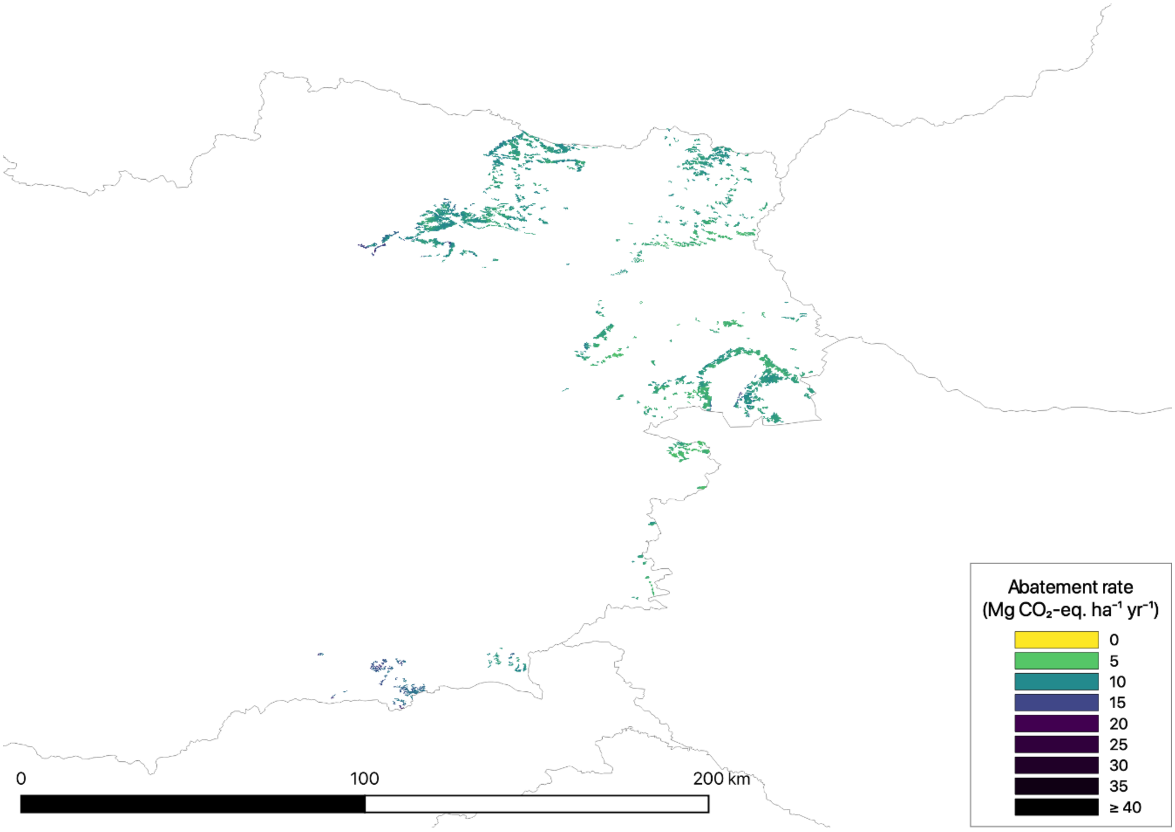
≥ 40
0
100
200 km

(e)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(Mg CO₂-eq. ha⁻¹ yr⁻¹)
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10
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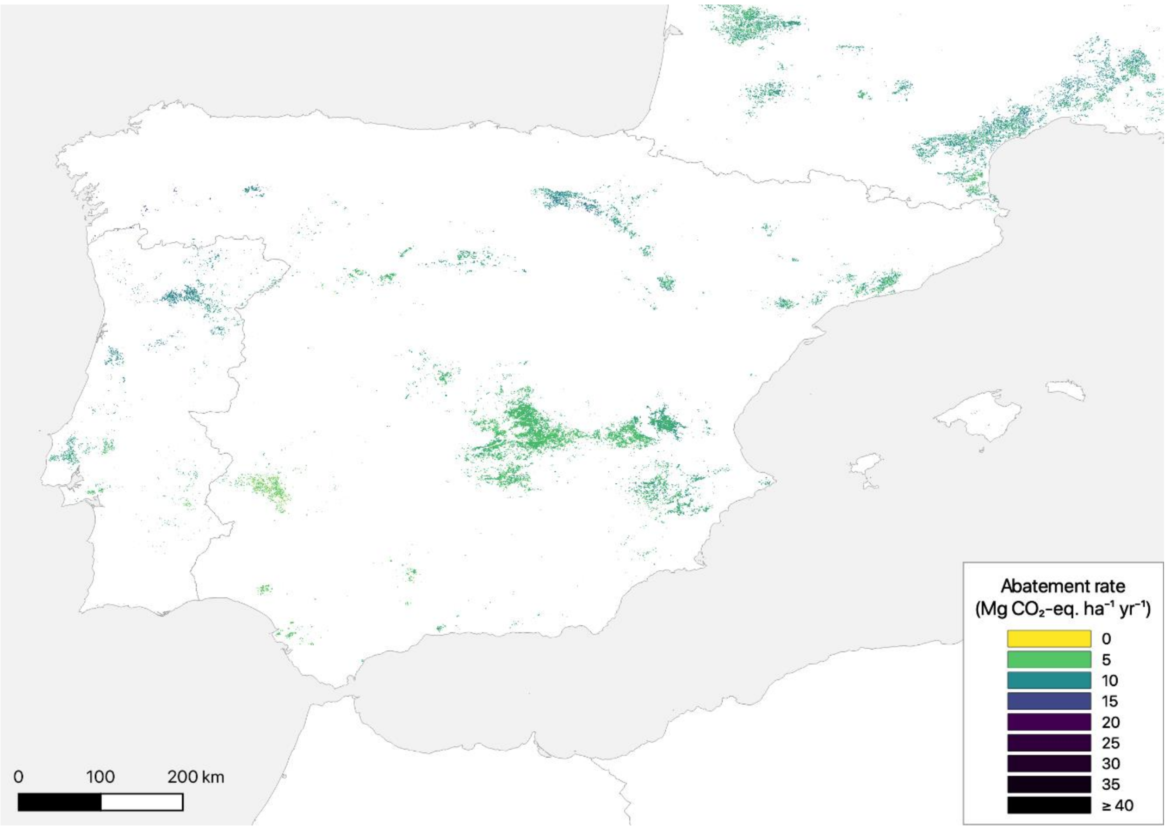
≥ 40
0
100
200 km

(f)


Abatement rate
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5
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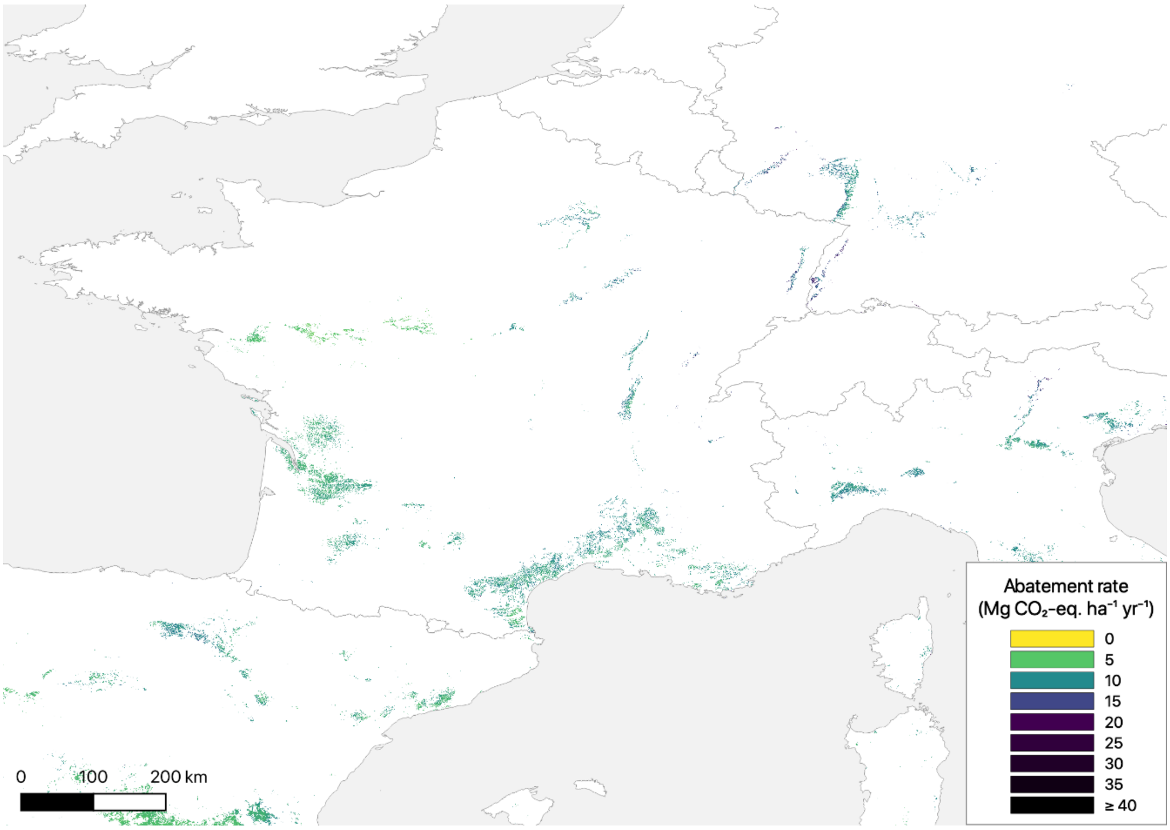
≥ 40
0
100
200 km

(a)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(Mg CO2-eq. ha⁻¹ yr⁻¹)
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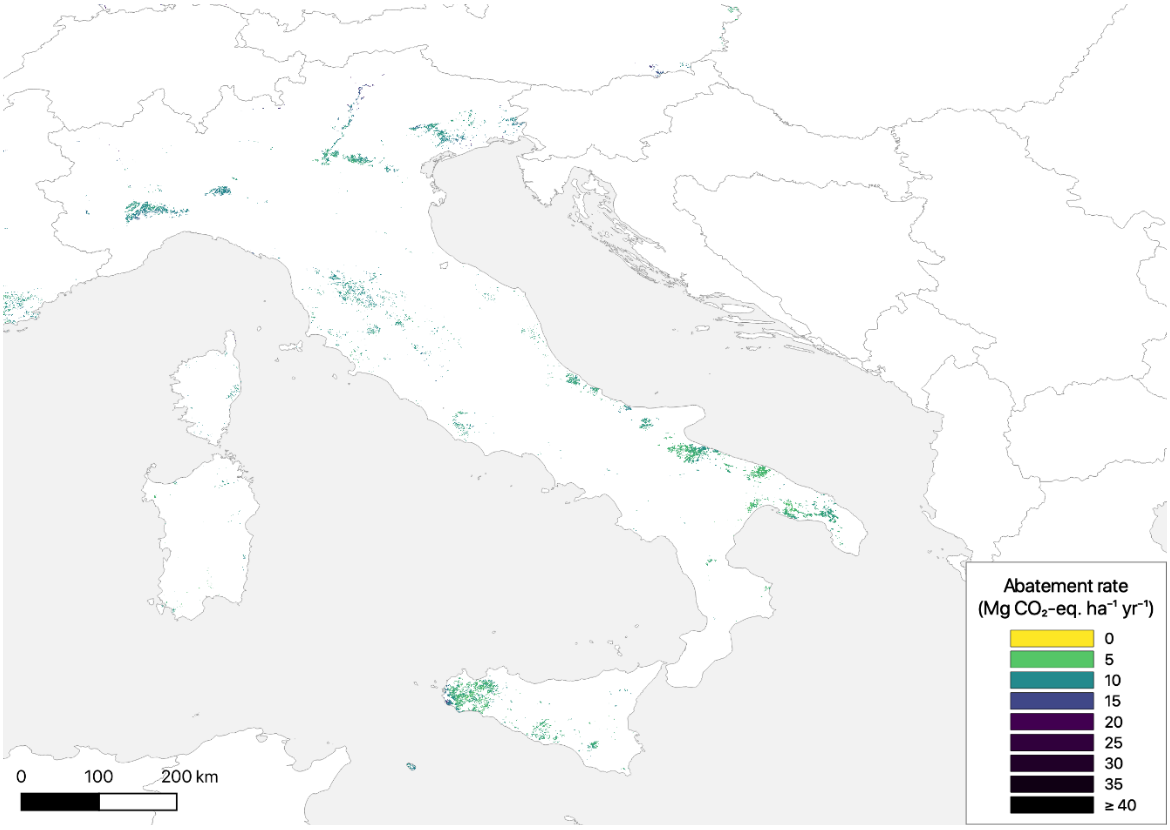
≥ 40
0
100
200 km

(b)


0
100
200 km
Abatement rate
(Mg CO₂-eq. ha⁻¹ yr⁻¹)
0
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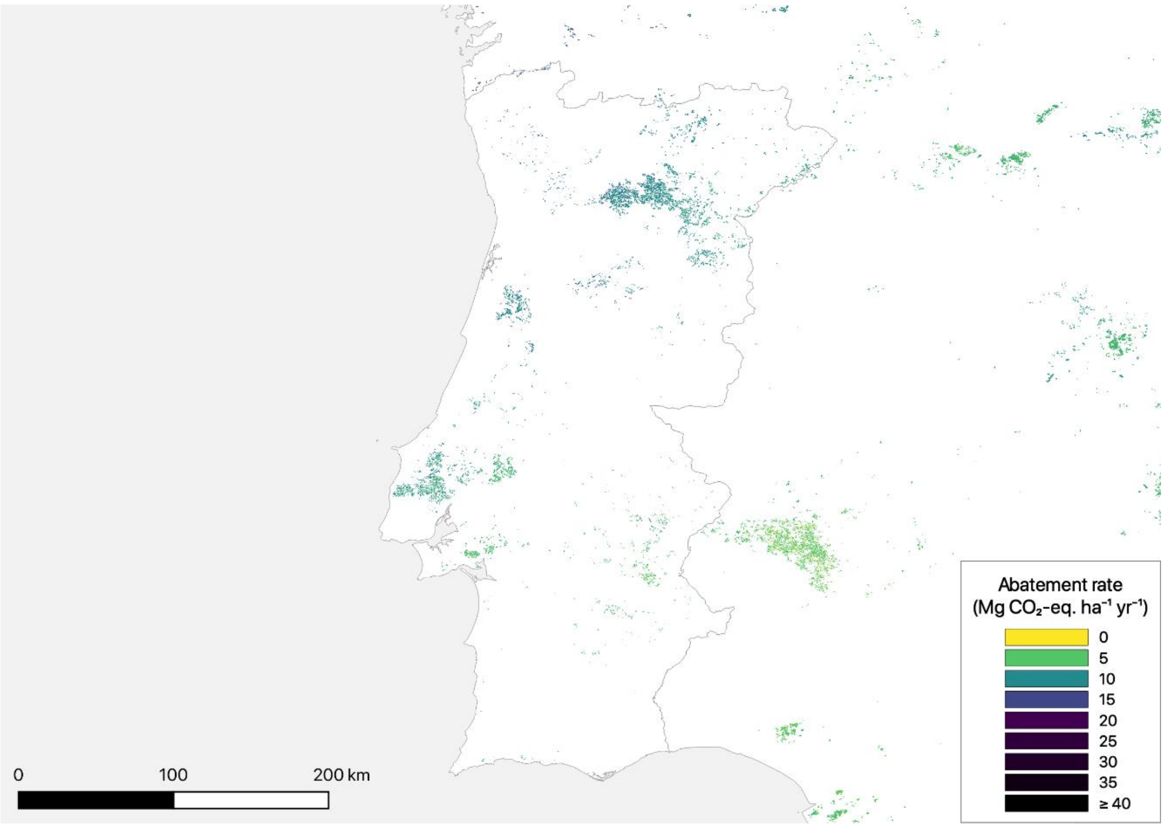
30
35
≥ 40

(c)


0
100
200 km
Abatement rate
(Mg CO₂-eq. ha⁻¹ yr⁻¹)
0
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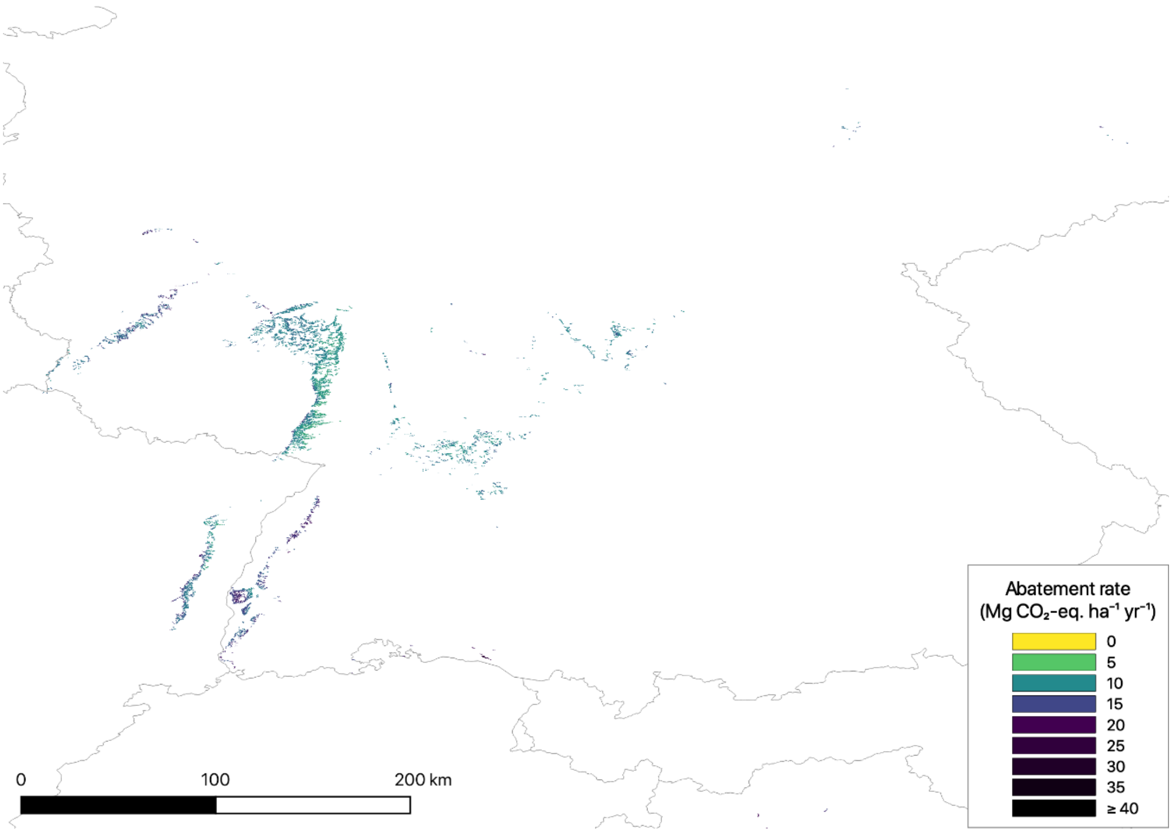
30
35
≥ 40

(d)


0
100
200 km
Abatement rate
(Mg CO₂-eq. ha⁻¹ yr⁻¹)
0
5
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15
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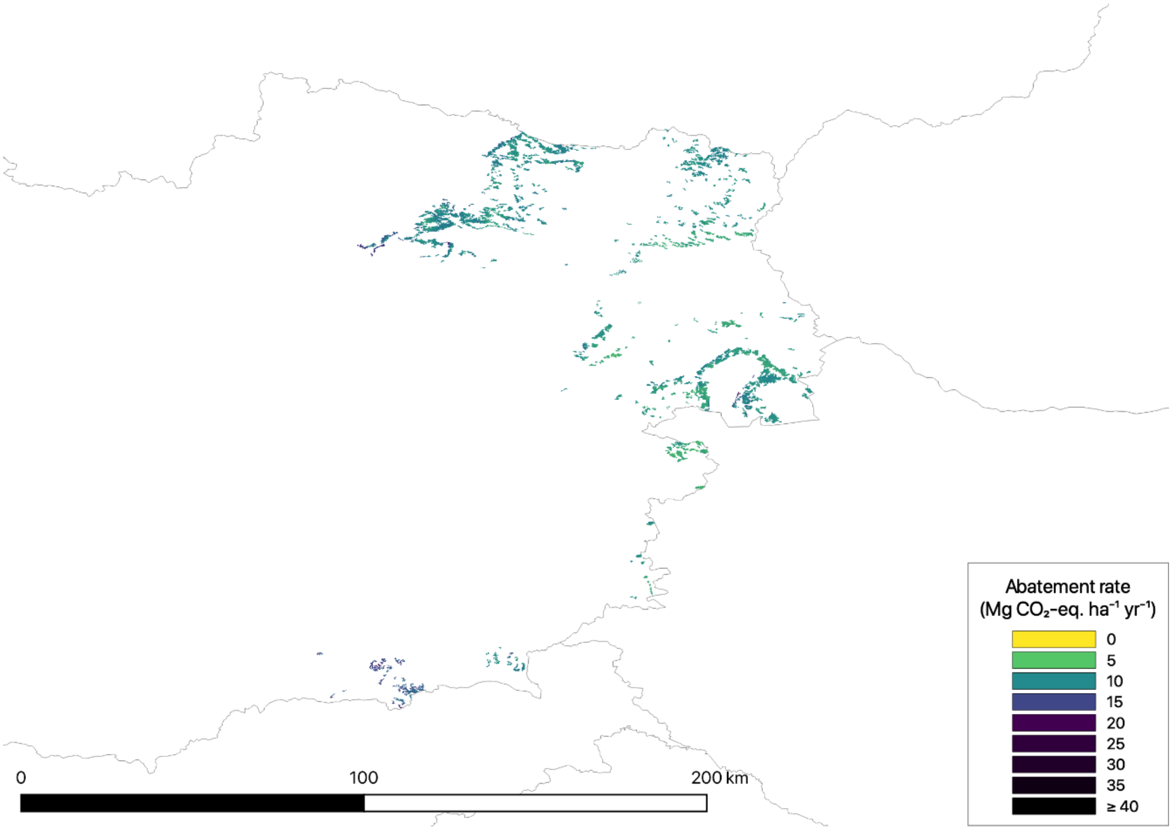
35
≥ 40

(e)


0
100
200 km
Abatement rate
(Mg CO₂-eq. ha⁻¹ yr⁻¹)
0
5
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20
25
30
35
≥ 40

(f)

Appendix E

Questionnaire used in Chapter 4. (The questionnaire was administered in French.)

I. Winegrower characteristics

- Are you…?
    - Male
    - Female
    - Other
- Which year were you born?
- What is your highest level of education?
    - Primary school
    - Secondary school
    - Higher education
    - Other
- Do you have a viticultural degree?
    - Yes
    - No
- Are you…?
    - The farm manager
    - The co-manager
    - The spouse of the farm manager (working on the farm)
    - Other
- Do you own your viticultural land in its entirety?
    - Yes
    - No, I rent my viticultural land
    - Other
- If you are the owner of your vineyard, did you inherit it?
    - Yes
    - No
- Are you…?

- An independent winegrower
    - A winegrower working in a cooperative
    - Other

II. Farm characteristics

- In which *département* is your vineyard located?
- What is the surface area of your viticultural farm?
    - Lower than 5 ha
    - Between 5 and 15 ha
    - Between 15 and 30 ha
    - Between 30 and 50 ha
    - Higher than 50 ha
- How many people work on a permanent contract (whether full-time or part-time) on your viticultural farm?
- When was the majority of your vines planted?
    - Before 1950
    - Between 1950 and 1969
    - Between 1970 and 1989
    - Between 1990 and 1999
    - Between 2000 and 2010
    - Between 2011 and 2019
- Which type of geographic indication does the wine you produce qualify for?
    - Protected Designation of Origin (PDO)
    - Protected Geographical Indication (PGI)
    - Wine Without Geographical Indication (WWGI)
    - Other
- Did your viticultural farm receive one or several of the following labels…?
    - High Environmental Value (label HVE)
    - Organic agriculture (label AB)
    - Biodynamic (label Demeter or Biodyvin)
    - My viticultural farm did not receive any of these labels
    - Other
- Do you practise irrigation on your viticultural farm?

- ○ Yes
- ○ No

III. Access to information and involvement in policy instruments

- Are you in contact with a viticultural advisor?
    - ○ Yes
    - ○ No
    - ○ I do not know
- Have you ever heard of the ‘4 per 1000’ initiative?
    - ○ Yes
    - ○ No
    - ○ I do not know
- Are you participating in one or several agri-environment measures?
    - ○ Yes
    - ○ No
    - ○ I do not know
- If yes, please indicate all the measures that you are participating in:
- Did you receive subsidies as part of the National Programme of Support to the Viticultural and Wine Sector developed by FranceAgriMer?
    - ○ Yes
    - ○ No
    - ○ I do not know

IV. Adoption of soil carbon sequestration practices

- Do you return pruning residues to the soil in your vineyard?
    - ○ Yes
    - ○ No
    - ○ I used to, but I stopped
- Do you apply organic amendments (such as compost, mulch, manure, etc.) in your vineyard in-between harvests?
    - ○ Yes
    - ○ No
    - ○ I used to, but I stopped

- Do you apply biochar amendments in your vineyard in-between harvests?
    - Yes
    - No
    - I used to, but I stopped
- Is there, from one year to the other, a cover crop (temporary or permanent) growing in your vineyard?
    - Yes, under the vine rows
    - Yes, in the inter-rows
    - Yes, under the vine rows and in the inter-rows
    - No
    - There used to be some, but I stopped
    - Other
- Are there hedges on the edge of or within your viticultural farm?
    - Yes
    - No
    - There used to be, but I removed them
- Have you implemented no-tillage practices in your vineyard (*i.e.* absence of ploughing or a very shallow and occasional ploughing of the soil)?
    - Yes
    - No
    - I used to, but I stopped

V. Statements about the use of soil carbon sequestration practices in viticulture

- Please, indicate whether you agree or not with the following statements:
    - “SCS practices increase viticultural productivity.”
        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
    - “SCS practices allow for the production of better-quality wine.”
        - Strongly disagree
        - Disagree

    - Neither agree nor disagree
    - Agree
    - Strongly agree
- "SCS practices decrease profits."
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
- "SCS practices increase production costs."
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
- "SCS practices are less time-consuming."
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
- "SCS practices represent new economic opportunities."
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
- "SCS practices reduce greenhouse gas emissions."
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
- "SCS practices decrease soil quality."

        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
    - “SCS practices increase vineyard resilience.”
        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
    - “SCS practices decrease grape yield.”
        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
- Please, indicate whether you agree or not with the following statements:
    - “I have enough time to implement SCS practices in my vineyard.”
        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
    - “I need more workforce to be able to implement SCS practices in my vineyard.”
        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
    - “I have enough financial resources to implement SCS practices in my vineyard.”
        - Strongly disagree

        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
    - "My current agricultural tools and technologies are not enough to implement SCS practices in my vineyard."
        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
- Please, indicate whether you agree or not with the following statements:
    - "I understand perfectly how to implement SCS practices in my vineyard."
        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
    - "I trust my abilities and skills enough to implement SCS practices in my vineyard."
        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
    - "Implementing SCS practices is not my responsibility."
        - Strongly disagree
        - Disagree
        - Neither agree nor disagree
        - Agree
        - Strongly agree
    - "SCS practices are difficult to set up."
        - Strongly disagree
        - Disagree

    - Neither agree nor disagree
    - Agree
    - Strongly agree
- Please, indicate whether you agree or not with the following statements:
  - "Most people around me think that I should implement SCS practices in my vineyard."
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
  - "Most people around me encourage me to adopt SCS practices in my vineyard."
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
  - "Most people around me would disapprove if I were to implement SCS practices in my vineyard."
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
  - "Most winegrowers that I know have adopted SCS practices in their vineyard."
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree

Appendix F

Survey used in Chapter 5. (The survey was circulated in French.)

I. Introduction

- Are you…?
    - The farm manager
    - The co-manager
    - Other
- In which *département* is your vineyard located?

II. Adoption of soil carbon sequestration practices

- Do you return pruning residues to the soil in your vineyard?
    - Yes
    - No
    - I used to, but I stopped
- If you do return pruning residues to the soil, what are the main reasons that motivate you to do so?
- If you do not return pruning residues to the soil (or not anymore), what are the main barriers (*e.g.*, economic, technical, etc.) that prevent you from doing so?

- Have you applied organic amendments in your vineyard (excluding pruning residues) between the 2018 harvest and the 2019 harvest?
    - Yes
    - No
    - Other
- If yes, what are the main reasons that motivated you to apply organic amendments?
- If not, what are the main barriers (*e.g.*, economic, technical, etc.) that prevent you from doing so?

- Have you applied biochar amendments in your vineyard between the 2018 harvest and the 2019 harvest?

  - Yes
  - No
  - Other

- If yes, what are the main reasons that motivated you to apply biochar amendments?
- If not, what are the main barriers (*e.g.*, economic, technical, etc.) that prevent you from doing so?

- Is there, from one year to the other, a cover crop (temporary or permanent) growing in your vineyard?
  - Yes, under the vine rows
  - Yes, in the inter-rows
  - Yes, under the vine rows and in the inter-rows
  - No
  - There used to be some, but I stopped
  - Other
- If yes, what are the main reasons that motivate you to use cover cropping?
- If not, what are the main barriers (*e.g.*, economic, technical, etc.) that prevent you from doing so?

- Are there hedges on the edge of or within your viticultural farm?
  - Yes
  - No
  - There used to be, but I removed them
- If there are hedges in your vineyard, what are the main reasons that motivated you to plant or keep them?
- If there is not any hedge in your vineyard, what are the main barriers (*e.g.*, economic, technical, etc.) that prevent you from planting some?

- Have you implemented no-tillage practices in your vineyard (*i.e.* absence of ploughing or a very shallow and occasional ploughing of the soil)?
  - Yes
  - No

  - I used to, but I stopped
- If yes, what are the main reasons that motivated you to adopt no-tillage?
- If not, what are the main barriers (*e.g.*, economic, technical, etc.) that prevent you from adopting no-tillage?

- Which actions would allow you to overcome some of the barriers identified above and implement some of the practices that you are not using currently?

III. Subsidies and agri-environment schemes

- Did you receive subsidies as part of the National Programme of Support to the Viticultural and Wine Sector developed by FranceAgriMer?
  - Yes
  - No
  - I do not know
- Are you participating in one or several agri-environment measures?
  - Yes
  - No
  - I do not know
- If yes, please indicate all the measures that you are participating in:

IV. Attitudes towards agri-environment measures

- Please, indicate whether you agree or not with the following statements:
  - "I try to participate in agri-environment measures as much as possible"
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
  - "I am not interested in agri-environment measures"
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree

    - Strongly agree
- "Agri-environment measures are important elements to fight against climate change"
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree
- "Payments from agri-environment measures are not high enough"
    - Strongly disagree
    - Disagree
    - Neither agree nor disagree
    - Agree
    - Strongly agree