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Viticulture and climate change: a socio-ecological perspective

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Table of Contents

List of figures

List of tables

Abstract

(English version)

Vineyard landscapes result from centuries of evolution between humans and nature, in which winegrowers have developed the necessary knowledge about grapes, the environment, and techniques that yield the most distinguishable wines. Nowadays, this equilibrium is threatened by climate change which poses significant challenges to many wine growing areas worldwide. Climate change impacts on viticulture have been mainly studied in biophysical terms, often neglecting the inclusion of the relationships with the human components of vineyards. This thesis explores the benefits of adopting a socio-ecological perspective to study the impacts of climate change on viticulture. The work is structured as a collection of articles that studies the multiple interrelationships between human and biophysical components of vineyards. The first chapter presents a systematic review that investigates published literature on vineyard landscapes and climate change to identify if and how a socio-ecological perspective was adopted. The second chapter focuses on the production of comprehensive geospatial data to analyse quality winegrowing regions in Europe under climate change. The third chapter presents the first climate change vulnerability assessment of viticulture at the European level, defining the degree to which quality viticulture areas are threatened by current climatic trends. Results show that the adoption of a socio-ecological perspective increases knowledge on the mechanisms that regulate the functioning of viticultural areas, giving insights on possible strategies that can enhance the resilience of these regions considering their specific context.

(Italian version)

I paesaggi viticoli sono il risultato di secoli di evoluzione tra uomo e natura, in cui i viticoltori hanno sviluppato le conoscenze di uve, ambiente e tecniche per produrre i vini migliori. Oggigiorno, questo equilibrio è minacciato dai cambiamenti climatici, che pongono sfide significative in molte regioni viticole nel mondo. Gli impatti dei cambiamenti climatici sono stati studiati principalmente in termini biofisici, spesso tralasciando le relazioni con le componenti umane presenti nei vigneti. Questa tesi esplora i benefici di un approccio socio-ecologico per lo studio degli impatti dei cambiamenti climatici sulla viticoltura. L'elaborato è strutturato in una collezione di articoli che analizzano le molteplici interrelazioni tra le componenti umane e biofisiche della viticoltura. Il primo capitolo analizza la letteratura sui paesaggi viticoli e i cambiamenti climatici, identificando se e come in questo campo sia mai stato adottato un approccio socio-ecologico. Il secondo capitolo è incentrato sulla creazione di dati geospaziali adatti all'analisi delle regioni viticole europee che producono vini di qualità nel contesto dei cambiamenti climatici. Il terzo capitolo presenta la prima analisi di vulnerabilità della viticoltura ai cambiamenti climatici a scala europea, che definisce quanto le aree viticole di qualità saranno messe in pericolo dagli attuali trend climatici. I risultati mostrano come l'adozione di un approccio socio-ecologico faciliti la conoscenza dei meccanismi che regolano il funzionamento delle aree viticole, suggerendo possibili strategie per accrescere la resilienza di queste regioni considerando il loro specifico contesto.

EXECUTIVE SUMMARY

Motivation and scientific background

The grapevine (*Vitis vinifera*) is one of the most widely cultivated plant species of agricultural interest. Grapevine domestication started 8.000 years ago near the Caspian Sea; and cultivated varieties were later introduced to the Mediterranean region, from where they were spread globally (Fontaine et al., 2021). Grape growing and wine production have been consistently significant economic activities, profoundly impacting regional cultures and the resulting landscapes. Over centuries, vintners have developed profound knowledge about grapes, environment, and techniques that yields the most distinguishable wines. This knowledge is summarized in the concept of *terroir*, a French term that refers to an area in which the collective knowledge of the interactions between the identifiable biophysical environment and the human influences develops, providing distinctive characteristics for the products originating from that area (Barnea, 2017; OIV, 2010).

While the concept of *terroir* includes both natural and human components, in wine research it has historically been primarily used to describe vineyards' functioning in biophysical terms with a specific focus on wine quality (Brillante et al., 2020). Indeed, the predominant scientific focus of *terroir* research has been on the relationships between plants, the environment, and the production methods on crop composition (C. V. Leeuwen et al., 2004). While the configuration of the physiological aspects of wine making are readily acknowledged, the human and cultural components of *terroir* and their interdependencies are still largely ignored (Brillante et al., 2020). For example, the role of tradition, environmental orientation, information and social exchange within wine regions is still not fully understood, and the cultural benefits provided to humans by *terroir* are often understudied (Caple & Thyne, 2014; Winkler et al., 2017). However, the human components of *terroir* are equally important as viticulture is primarily a human activity (C. V. Leeuwen & Seguin, 2006). This is particularly relevant because the functioning of wine regions often depends on the interplay of factors that transcend their geographic and socio-ecological boundaries (Viers et al., 2013).

In the current context of an interconnected and globalized world, multiple exogenous and endogenous pressures can endanger viticulture, changing the wine map of the world as we know it. These pressures, i.e., the global drivers of change, are directly or indirectly affecting many winemaking regions worldwide at different levels, increasingly impacting the complex balance between biophysical and socio-economic relationships that characterize a wine region's *terroir* (Hanna et al., 2013). For example, warmer climate conditions are affecting the quality and quantity of grape production (Fraga et al., 2016); the introduction of alien pest species is requiring new agricultural practices for pest control in vineyards (Caffarra et al., 2012); and changed economic and social preferences are calling for a more sustainable management of vineyards (Marín et al., 2021). These multifaceted impacts are especially important to consider as they are threatening viticultural areas in an unprecedented way, challenging centuries-old traditions that developed for winegrowing and winemaking (Fraga et al., 2016).

A socio-ecological perspective to viticulture under climate change

Despite the exponential increase in publications in the field of viticulture over recent decades, only a few studies have attempted to develop a holistic perspective on the impacts of drivers of change on this agroecosystem (Marx et al., 2017). While the concept of *terroir* would be suitable to adopt this perspective, viticultural studies have so far mainly focused on the impacts of global changes on single aspects of grape growing without developing a holistic knowledge on their functioning (Lereboullet et al., 2014). In this context, concepts, methods, and tools from other disciplines can help to advance the knowledge on the relationships between biophysical and cultural components of vineyard landscapes (Brillante et al., 2020). The socio-ecological system (SES) perspective provides a widely recognized theoretical framework to fill this gap, conceptualizing the environment as a complex system of ecological and social processes whose interaction can be disentangled to have a better understanding of the systems' functioning (Virapongse et al., 2016). This perspective describes the functioning of a SES in terms of a flow of benefits produced under the specific conditions of the ecosystem. Those ecosystem conditions are influenced by anthropogenic pressures that in turn impact the provision of benefits at its origin (Maes et al., 2018).

Among all the anthropogenic pressures that are threatening viticulture, climate change is arguably the most important in terms of impacts on viticultural SES. The climate of a winemaking area indeed plays a pivotal role in defining the SES system of each winemaking region, greatly influencing the relationship between its social and ecological components (Jones & Webb, 2010; C. van Leeuwen et al., 2019). Beyond the effects on grape quality and quantity, challenges caused by climate change are also increasingly affecting the growing suitability of grapevines and influencing the phenological stages of traditional cultivars, thereby changing the areas and techniques used to produce the best wines (Fraga et al., 2016). These changes are predicted to affect wine regions and their resilience, including not only grape growing but the entire ecological and socio-economic context (Neethling et al. 2019, Fraga et al. 2012, Santos et al. 2020).

The few studies that applied a SES perspective to study the interrelations of vineyard components mainly focused on them considering their benefits in terms of grape production. Only recently has the importance of considering multiple ecosystem conditions and services provided by vineyard landscapes been raised by certain studies (Garcia et al., 2018; Paiola et al., 2019; Winkler et al., 2017). Additionally, specific analyses of the functioning of vineyard landscapes under climate change using this perspective are lacking. This represents an important gap in the literature, as applying a SES research lens has been shown to foster research that disentangles the relationships among different components of a SES (Falardeau & Bennett, 2019). This in turn enables the study of how ecosystem conditions are affected by climate change and the related consequences concerning the provision of benefits to societies (Kluger et al., 2020). The results of this perspective would foster the growth of knowledge on the components of vineyards SESs and their interrelations (Maes et al., 2018).

Climate vulnerability of vineyard socio-ecological systems

An enhanced knowledge of the relationships and feedbacks between humans and nature in viticultural areas under climate change is pivotal to enable better-informed decision-making and develop strategies that enhance the provision of benefits while addressing the potential negative effects of a new climate (Naulleau et al., 2021). Previous approaches for developing adaptation strategies in the wine sector have mainly relied on the assessment of suitability for viticulture, assessment of future impacts on wine physiology and yield, and phenological modelling without including the role of human agency (Lereboullet et al., 2014). The application of a SES perspective to viticulture under climate change would deepen these aspects by describing how a change in one of the vineyards' system components is affected by concomitant changes in other elements, suggesting ways forward for adaptation (Lereboullet et al., 2013). This can be particularly useful for planning interventions that ensure the preservation of wine regions under new climates, as it presents the sum of the negative impacts of a new climate and the capacity of each viticultural area to react to climate change (Pickering et al., 2015).

Due to the large number and diversity of viticultural areas around the globe, it might be difficult to analyse their strengths and weaknesses in the context of a new climate. While some of the biological, physical, and economic characteristics of these areas can be assessed by developing tailored geospatial indicators or accessing statistical data, others are more difficult to grasp (Parker et al., 2019). For example, particular attention is needed in analysing the characteristics of long-established wine growing regions that might include specific regulations to protect their products (Clark & Kerr, 2017). This is the case of the *geographical indications* (GI) system that protects the unique biophysical and cultural characteristics of certain food and beverage products in Europe, linking them to a specific production area based on the concept of *terroir* (Barnea, 2017). Each GI product can be produced only inside strictly defined geographic boundaries using specific techniques that are explained in a set of documents (Marescotti et al., 2020). Wine GIs are therefore particularly threatened by climate change, as the change in their biophysical conditions might correspond to a change in their regulations and products challenging the quality and definition of the product they regulate (Clark & Kerr, 2017). A comprehensive knowledge of the natural and human characteristics of these areas can support actions that facilitate their resilience, enabling them to continue producing high quality wine products.

A climate vulnerability[1] assessment enables the analysis of the knowledge on biophysical and human aspects of an area, providing insights on its capacity to react to the adverse effects of climate change. This methodology is one of the most actively applied tools for defining the challenges and consequences of climate change on specific SES systems and geographical areas (Buzási, 2021). In the case of viticulture, climate change vulnerability depends on the

[1] Vulnerability is defined here as: "*the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity*" (IPCC, 2007).

individual characteristics of each winegrowing region. This includes its degree of climate exposure, such as the change in temperature or precipitation patterns; the sensitivity, such as the specific effects of climate changes on the grapevines grown in a wine region; and the availability of socio-economic, natural, and physical resources, which strongly determine how wine regions can adapt to climate change (Lereboullet et al., 2013). The importance of exposure and sensitivity of viticulture to climate change has already been extensively investigated in the literature, for instance by relating changes in air temperature or precipitation to relevant vine parameters such as phenology or sugar contents (Fraga et al., 2016) or analysing how grapevine suitability will be influenced under new climates (Hannah et al., 2013). However, assessments that consider exposure and sensitivity together with the adaptive capacity of winegrowing areas have been sparse and, thus far, limited to single wine regions (Merloni et al., 2018; Nicholas & Durham, 2012).

The analysis of the capacity of different wine making areas to adapt can suggest tailored adaptation strategies to climate change. Indeed, the investigation of the adaptive capacities is crucial to facilitating learning that can be generalized and operationalized to guide effective responses to change (Ostrom et al., 2007). In the context of wine regions, such an approach grants foresight and enables the proactive identification of similar actions sets that may be adopted for the mitigation of climate change effects based on specific characteristics. For example, agronomists can suggest new wine growing strategies by comparing information about different wine regions, and decision makers can plan possible actions to improve high quality grapevine production (Candiago et al., 2022). The study of these options is especially critical for regions that face strong impacts of climate change and that need to amend their regulations to continue producing high quality wine products (Barnea, 2017) due to legal constraints, e.g., GIs. In these specific regions, changes may threaten the capacity to produce traditional wines, requiring a long process for the amendments of the legal specification and an extensive access to resources and knowledge for developing successful adaptation strategies that guarantee the continued production of high-quality wine products.

Aims and structure of the doctoral thesis

The primary aim of this thesis is to apply an integrative perspective, based on the concept of SES, to study the effects of climate change on viticulture. The thesis is organized as a collection of articles around three main chapters (chapter 1 to chapter 3; see also Figure 1). The research questions addressed in this doctoral thesis are the following:

1. What are the impacts of climate change on viticulture using a SES perspective?
2. What are the factors that influence the vulnerability of quality viticulture under climate change and the possible adaptation options to foster its resilience?

Based on these questions, a short description of the three thematic chapters of this thesis is provided to facilitate its readability and highlight the connections between the separate parts.

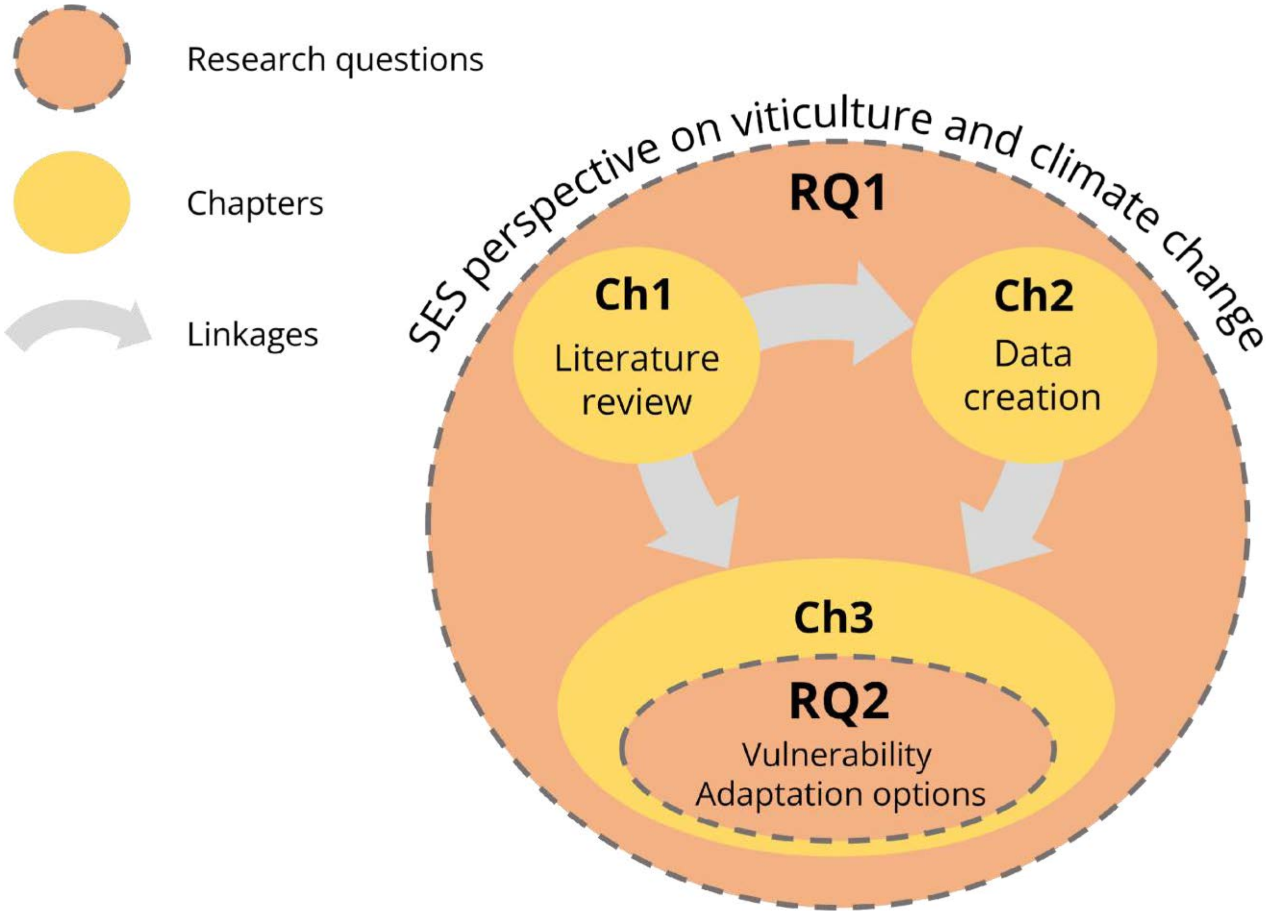

Figure 1. Structure of the doctoral thesis.

The first chapter presents a study that analyses the state of the art of research on viticultural systems under the impacts of climate change adopting a SES perspective. It is based on a systematic literature review that, using the concept of ecosystem services, explores the human and biophysical components studied in peer-reviewed literature produced over the past decades. In this chapter, I examined how climate change influences are related to impacts on ecosystem conditions and ecosystem services in the literature on vineyard landscapes and whether an integrative perspective to investigate the effects of climate change was adopted. My results indicate that there are still very few studies that explicitly address multiple ecosystem conditions and services together. Moreover, the categories of ecosystem services were mainly related to crop production neglecting the study of the cultural values tied to vineyards. I also found that there is a lack of integrative studies that simultaneously address the relationships between ecosystem condition, ecosystem services and climate change. To overcome these gaps and to better understand the functioning of vineyard SES under climate change, multidisciplinary, integrative, and comprehensive perspectives should be adopted by future studies. Indeed, a holistic understanding of vineyard landscapes will be crucial to support researchers and decision-makers in developing sustainable adaptation strategies that enhance the ecological condition of vineyards and ensure the provision of multiple ecosystem services under future climate scenarios.

The second chapter presents the work done for the creation of a geospatial dataset that enabled the application of a SES perspective in the study of European wine regions' vulnerability to climate change. For this aim I focused on a specific type of European GI: the wine protected designation of origins (PDO). PDOs protect high quality wines by linking them to legally defined geographic areas and a set of specific production practices. Because of the tight relation between PDO wines and the specifications defined in the official regulatory documents, these products are highly susceptible to changes in climatic conditions. Indeed, the content of these regulatory documents are based on centuries of evolution stimulated by local biophysical conditions and human management. However, this information has never been systematically analysed and summarized in a single dataset. In this chapter, I present the process of building and the potential use of the first geospatial inventory that organizes regulatory information about the 1177 wine PDO in Europe based on documents from the official European Union geographical indication register. This dataset includes essential legal information that defines the wine PDO such as the geographic boundaries, authorized cultivars and maximum yields. This inventory opens new possibilities for researchers to accurately assess, compare and map the regulatory information in each wine region at an unprecedented level of detail, supporting decision-makers in developing adaptation strategies for the preservation of PDO wine regions.

In the third chapter I synthesize the SES knowledge on literature developed in the first chapter and the data produced in the second to study with an integrative perspective the impacts of climate change on European viticulture. The choice of Europe is due to its long tradition of wine making. Due to the long coexistence with and cultivation of grapevines, European vintners have developed profound knowledge about grapes, environments, and techniques that yield the most distinguishable wines. In many regions, this knowledge has been reflected in the system of wine GI, including the PDO label. But climate change is challenging this historical union. In this chapter, using an ensemble of geospatial biophysical and socio-economic indicators chosen for their suitability to assess climate change vulnerability at the European scale, I present the first climate change vulnerability assessment of the almost 1200 European wine PDOs and propose climate-resilient development pathways. My results indicate that wine regions in Southern Europe are among the most vulnerable, with high vulnerabilities also found in Eastern Europe. Vulnerability is largely driven by the rigidity of the PDO system, which restricts the exploitation of suitable bioclimatic conditions and existing grape cultivar diversity, as well as contextual deficiencies, such as limited socio-economic resources. Building a climate-resilient wine sector will require rethinking the geographical indication system by allowing innovation to compensate for the negative effects of climate change.

Conclusions and outlook

Winegrowing areas are important agroecosystems that provide multiple economic, ecological, and cultural benefits to society, but climate change poses a present and increasing threat. To ensure the long-term provision of these benefits it is essential to understand the multiple mechanisms that regulate wine regions' functioning.

In this thesis I explored the benefits of a SES perspective to study the impacts of climate change on viticulture, concluding that it should be used more frequently to investigate wine growing regions under climate change. Indeed, the application of a SES perspective in reviewing the existing literature and in assessing the climate change vulnerability of European wine PDOs enabled me to gain novel insights into vineyard SES and the impacts of climate change. More specifically, the systematic literature review allowed me to find the main gaps in this research field and to propose possible ways forward that can fill the present lack of SES research for vineyard landscapes. The use of European quality viticulture as a case study for a vulnerability assessment shed light on the importance of considering multiple aspects of the human-nature interface in vineyards under climate change to increase their resilience.

My findings demonstrate that SES perspectives to the study of viticulture contribute to research on viticulture in three main ways: (1) the adoption of integrative SES frameworks help to provide a more complete understanding of viticulture's overall functioning in terms of ecosystem conditions and services, helping the development of strategies that support the sustainable management of viticulture under future climate uncertainties; (2) the large quantity of data and indicators developed for SES assessments sheds light on understudied aspects of winemaking areas, such as their adaptive capacity, increasing the knowledge on the biophysical and human components of viticulture; (3) the overall analysis of multiple natural and socio-economic conditions of wine regions offers a valuable perspective for the development of adaptation strategies based on the needs of each area building a more resilient wine sector.

Despite the advancements shown in this work, research on viticulture needs to further embrace SES perspectives. Views that consider multiple relationships among ecosystem conditions, services and climate impacts using a holistic approach should be fostered. Social processes (e.g., demography and economics) and human components (e.g., the role of institutions, stakeholders, and their perspective on viticulture) should be studied more in relation to climate change, as they drive the way people interact with vineyard landscapes and provide valuable insights into SES functioning. Tailored datasets on wine regions that include mapping the geographical characteristics of more wine production areas as well as socio-economic indicators and legal information need to be developed to facilitate comprehensive analyses of these SES. Finally, more importance should be given to the study of possible adaptation strategies that consider specific in-situ characteristics of each wine region at a very high resolution. These actions can ensure a durable development of our knowledge on viticulture and the increase of its resilience, safeguarding the provision of multiple benefits from vineyard landscapes under new climatic conditions.

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Chapter 1: an ecosystem service approach to the study of vineyard landscapes in the context of climate change: a review

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An ecosystem service approach to the study of vineyard landscapes in the context of climate change: a review

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Abstract
Vineyard landscapes significantly contribute to the economy, identity, culture, and biodiversity of many regions worldwide. Climate change, however, is increasingly threatening the resilience of vineyard landscapes and of their ecological conditions, undermining the provision of multiple ecosystem services. Previous research has often focused on climate change impacts, ecosystem conditions and ecosystem services without systematically reviewing how they have been studied in the literature on viticulture. Here, we systematically review the literature on vineyard landscapes to identify how ecosystem conditions and services have been investigated, and whether an integrative approach to investigate the effects of climate change was adopted. Our results indicate that there are still very few studies that explicitly address multiple ecosystem conditions and services together. Only 28 and 18% of the reviewed studies considered more than two ecosystem conditions or services, respectively. Moreover, while more than 97% of the relationships between ecosystem conditions and services studied were addressing provisioning and regulating services, only 3% examined cultural services. Finally, this review found that there is a lack of integrative studies that address simultaneously the relationships between ecosystem condition, ecosystem services and climate change (only 15 out of 112 studies). To overcome these gaps and to better understand the functioning of vineyard socio-ecological systems under climate change, multidisciplinary, integrative, and comprehensive approaches should be adopted by future studies. A holistic understanding of vineyard landscapes will indeed be crucial to support researchers and decision makers in developing sustainable adaptation strategies that enhance the ecological condition of vineyards and ensure the provision of multiple ecosystem services under future climate scenarios.

Introduction
Vineyard landscapes (VLs) are important agroecosystems that provide multiple economic, ecological, and cultural benefits, or ecosystem services, to society (Table 1). Due to the economic value of wine grapes, viticulture and winemaking shape the socio-economic system of many winegrowing regions worldwide (Azorín & García, 2020; Fraga et al., 2012). The mosaic of land uses within VLs, including croplands, forests, shrublands and riparian areas,

also supports the biodiversity and ecosystem functioning of these regions (Viers et al., 2013; Winkler & Nicholas, 2016; Winter et al., 2018). In addition to these economic and ecological qualities, VLs are also often defined as cultural landscapes that provide a variety of intangible benefits to residents and visitors alike (Winkler & Nicholas, 2016).

Table 1. Definition of the key concepts used in this review.

Term	Definition
Agroecosystem	Agricultural ecosystems including biophysical and human components and their interactions (Garbach et al., 2014)
Ecosystem conditions	The physical, chemical, and biological characteristics or qualities of an ecosystem at a particular point in time (Maes et al., 2018)
Ecosystem services	Contributions of ecosystems to human benefits obtained from economic, social, cultural and other human activities (SEEA-EEA, 2012)
Climate change	A change in climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (UNFCCC, 1992)
Vineyard landscape	A mosaic of farmers' fields, semi-natural habitats, human infrastructure (e.g., roads) and occasional natural habitats (Marshall, 2004), where the major agricultural activity is viticulture
Links	Relationship between two components of a system as they are studied in the literature (Falardeau & Bennett, 2019)

The range of ecosystem services provided by VLs is largely determined by the physical, chemical, and biological conditions, or quality, (i.e., ecosystem condition) of each agroecosystem at a particular point in time (Kokkoris et al., 2018; Maes et al., 2016). The relationship between ecosystem conditions and services is particularly evident in traditional VLs, which have developed over time as a result of a close relationship between local environmental conditions and human activities. However, different drivers of change can exert multiple pressures on ecosystem conditions and can have direct and indirect impacts on the related ecosystem services (Maes et al., 2018). In particular, climate change effects such as higher temperatures and altered precipitation regimes are already posing significant challenges to the integrity and condition of many VLs and are, thus, altering the capacity of these systems to deliver a variety of provisioning, regulating, and cultural ecosystem services (Bindi & Nunes, 2016; Hannah et al., 2013; Maes et al., 2018). Moreover, changes in climatic conditions are also reflected in more complex human–nature interactions related to land conversions, as new land at the cooler end of the vine suitability spectrum is becoming increasingly available or as established vineyards are being abandoned (Egarter Vigl et al., 2018).

Over the past years, the analysis of the relationships between ecosystem conditions, ecosystem services, and climate change in VLs has received attention in literature on viticulture. Studies have looked, for example, at the effects of climate change on those conditions and services important for food production, such as yield, plant growth, and soil fertility (Nieto-Romero et al., 2014; Tancoigne et al., 2014; Winkler et al., 2017a). Winkler et al. (2017), in their review paper, were among the first to introduce the importance of considering the multiple ecosystem functions and services provided by VLs. They found that viticulture research mainly addressed provisioning and regulating ecosystem services, looking at VLs as agrarian landscapes. Studies that address multiple ecosystem conditions or services simultaneously (i.e., comprehensive research) instead also recognize and highlight other important co-benefits (Maes et al., 2018; Power, 2010). Indeed, researchers have recently started to examine more systematically the full array of ecosystem services provided by VLs, also including socio-cultural services such as heritage, identity, and aesthetics (Garcia et al., 2018; Sottini et al., 2019).

To face the complexities of an increasingly interconnected world where disciplinary or sectoral approaches have had limited success, it is necessary to develop and apply holistic thinking (Wezel et al., 2020). In fact, the co-creation of knowledge from different disciplines (i.e., multidisciplinarity), has been listed as one of the main elements that can support the development of transformative change pathways towards sustainable food and agricultural systems (FAO, 2019). Analysing the multiple ecosystem conditions and services provided by VLs embracing a multidisciplinary perspective can provide opportunities for the sustainable management of agroecosystems that cannot be obtained by adopting single discipline approaches (Stark 1995).

In recent decades, ecosystem services research has showed the importance of considering both ecosystem conditions and anthropogenic pressures to understand how the benefits of nature are delivered to society (Maes et al., 2018). Adopting an ecosystem service approach in the study of agroecosystems fosters research that disentangles the relationships among different components of a socio-ecological system, i.e., integrative research (Falardeau & Bennett, 2019; Liu et al., 2014). Consequently, adopting an integrative approach enables one to study how an ecosystem condition is affected by climate change and which are the related consequences on the provision of an ecosystem service (Falardeau & Bennett, 2019; Kluger et al., 2020). The results of such integrative research would allow the increase of knowledge on the components of these socio-ecological systems and their relationships, providing the insights and recommendations needed to support decision makers in developing strategies that enhance the provision of ecosystem services while addressing the potential negative effects of drivers of change (Falardeau & Bennett, 2019; Maes et al., 2018). This is particularly important in view of the management of VLs under new climate scenarios.

Decision makers working to ensure the resilience of VLs under climate change require timely and thorough knowledge on the relationships between climate change, ecosystems, and desired ecosystem services. In the past, however, there has not always been the interest to explore all these relationships, and there is the need to target research to explore missing and understudied linkages to avoid maladaptation or unintended consequences to policy interventions. Understanding which relationships among VL components have been explored so far by academia is enabled by having a systematic knowledge on the studies that have been carried out on VLs. Conducting a systematic review can produce this knowledge, as it would systematically search for, appraise, and synthetize available research on selected components of VLs, following specific guidelines and ensuring rigorousness and full replicability (Grant & Booth, 2009). This would allow one to identify the links between those components for which more research is needed, and to fill important research gaps in the literature. To our knowledge, however, no systematic reviews have so far reviewed how the relationships between climate change and multiple ecosystem conditions and services in VLs have been studied in the literature.

In this study, we carry out a systematic literature review to examine how ecosystem conditions in VLs are studied in relation to the provision of ecosystem services, and how both are investigated in the context of climate change. We provide indications to researchers on which relationships among climate change, ecosystem conditions and services in VLs have been studied, and to what extent. Our objectives are:

1. To identify the main spatiotemporal patterns and the disciplines found in the literature on ecosystem conditions, ecosystem services, and climate change in VLs.
2. To analyse how the relationships between ecosystems conditions and ecosystem services in VLs are studied.
3. To understand how climate change is considered in the study of the ecosystem conditions and ecosystem services in VLs.

Materials and methods

Literature search and selection

We identified peer-reviewed publications from the online databases Scopus and Web of Science following the steps of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) methodology (Moher et al., 2009) (Figure 16), building on the search structure used also by Falardeau and Bennett (2019). We specifically looked for research papers dealing with VLs that investigated links between ecosystem conditions, ecosystem services, and climate change variables. The set of terms used to search for relevant publications included (*a set of terms relevant to winegrowing*) AND (*terms connected with climate change*) AND (*terms related to ecosystem conditions OR terms related to ecosystem services*). To thoroughly search for relevant literature regarding climate change, ecosystem conditions, and ecosystem services, we performed several queries to tailor our search on each of the ecosystem conditions and services considered in the context of climate change. We started by running a query to find articles published on the effects of climate change on the ecosystem conditions in VLs, using the European framework proposed for the Mapping and Assessment of Ecosystems and their Services (Maes et al., 2018) to define our search terms related to ecosystem conditions. Then, we ran a set of twenty-eight tailored queries, one for each ecosystem service class included in this review, to include literature on those ecosystem services, viticulture, and the effects of climate change (Tables 7 and 8). The ecosystem service classes and the related synonyms included in each of these queries were based on the work by Winkler et al. (2017). Finally, to intercept all relevant literature that studied ecosystem services in VLs, we also ran a general query without specifying any ecosystem service classes nor terms connected to climate change.

We combined the results of our search strings using the R-package "bibliometrics" (Aria & Cuccurullo, 2017) (R Core Team, 2020), (Tables 7 and 8). Our search was conducted on March 25, 2020, obtaining over 1,600 potentially relevant articles. After removing duplicates (n = 986), we screened the titles, keywords and abstracts of 661 articles by applying a set of inclusion and exclusion criteria (Table 9). To screen the content of the papers, we combined manual and automatic techniques using the QCRI Rayyan software (Ouzzani et al., 2016). Rayyan is a free systematic review software that facilitates the initial screening of abstracts and titles using a process of semi-automation (Harrison et al., 2020). The software uses machine learning to increase the speed of the screening process, using the inclusion/exclusion decisions made by the user on a sample of papers to score the likelihood that studies awaiting screening will be included. As suggested by the methodology used in previous reviews, we manually assessed 10% of the records uploaded in Rayyan to train the machine learning algorithm that automatically screened the remaining studies (Garrick et al., 2019). After applying the trained algorithm, we conducted a manual validation of the results. For this purpose, we selected an additional 10% of the automatically classified articles and checked them, paying attention to keeping training and validation datasets separate. We found a high correspondence (> 90%) between the results of the automatic classification and the results of the manual quality control. After the screening process, we assessed the full texts of 208 papers and ultimately retained 112 articles in our review.

Relationships between ecosystem conditions, ecosystem services and climate change addressed by the literature

To review with an integrative perspective how ecosystem conditions, ecosystem services, and climate change variables have been studied in the literature, we counted each time the relationship (i.e., a link) between climate change, ecosystem conditions, and ecosystem services was addressed in a reviewed paper (Falardeau & Bennett, 2019; Menegon et al., 2018; Carter et al., 1994). We considered as a "link" any relationship between system components which was investigated with qualitative or quantitative methods, even if it was found to be a non-significant correlation. The aim of the present study is indeed to understand how research on VLs has been conducted by academia until now, and not to investigate the biophysical processes occurring in VLs.

The three types of links that we considered were (Figure 2):

1. ecosystem condition → ecosystem service
2. climate change → ecosystem condition
3. climate change → ecosystem condition → ecosystem service

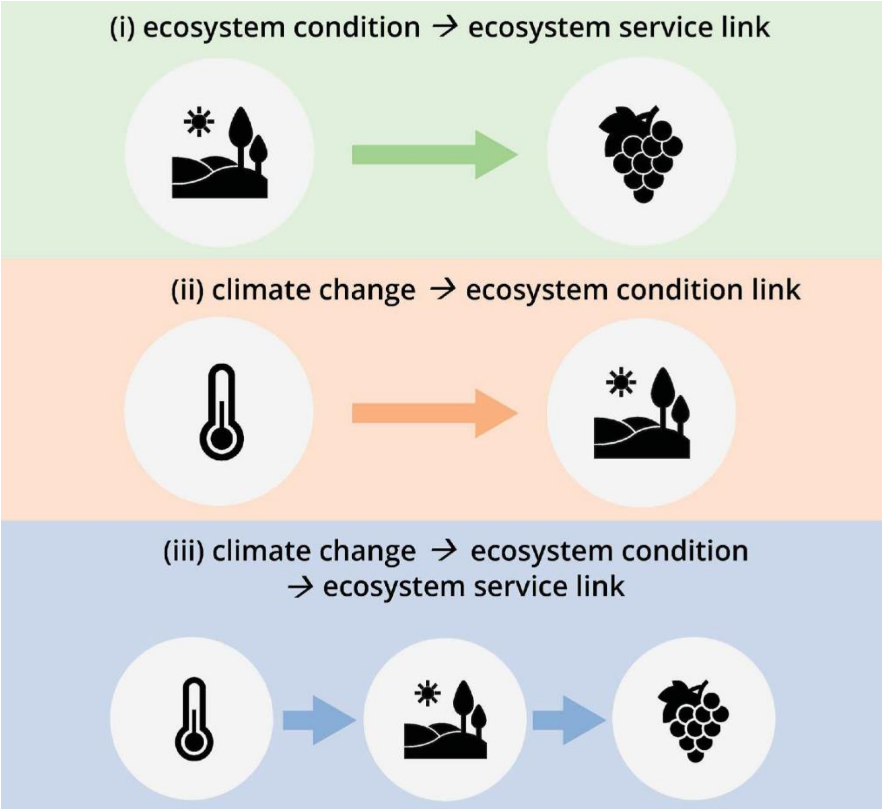

Figure 2. Representation of the three link types looked for in the review of the papers. The main components of VLs that we considered were ecosystem conditions, ecosystem services and climate change.

For example, when Fraga et al. (2019) studied the influence of phenology on the amount of grapes produced (crop production), the authors described an *ecosystem condition ecosystem service* link, specifically a phenology crop production link. In the same way, if a paper assessed an influence of temperature on phenology, then it described a *climate change ecosystem condition* link, and thus, we recorded the link temperature phenology. Lastly, if a paper described the influence of temperature on phenology and the related effects of phenology on crop production, then we recorded the integrative link temperature phenology crop production (*climate change ecosystem condition ecosystem service*). These three types of links are highly interrelated and interdependent. For this reason, we analysed them jointly by following the structure of the framework developed by the European Mapping and Assessment of Ecosystems and their Services (Maes et al., 2018). This enabled us to identify which relationships amongst ecosystem conditions, ecosystem services, and climate change were more or less frequently studied.

Extracting information from the articles

We retrieved information from the articles based on a set of structured questions (Table 2). For our first research objective, we started by analysing the context, focus and disciplines of each paper (Q1–Q7). For our second research objective, we retrieved information on how and which ecosystem conditions and ecosystem services were studied in the articles (Q8–Q10). For our third research objective, we investigated how the influence of climate change on VLs was investigated (Q11–Q12).

Table 2. Questions used to extract relevant information from the reviewed literature (n = 112).

Theme	Question	Id	Objective
Context	What is the year of publication and type of article?	Q1	(i)
	What is the spatial scale of assessment?	Q2	(i)
	What is the temporal scale of assessment?	Q3	(i)
Focus	Does the paper focus only on *ecosystem conditions ecosystem services* links?	Q4	(ii)
	Does the paper include *climate change ecosystem conditions* or *climate change ecosystem conditions ecosystem services* links?	Q5	(iii)
Disciplines	Which disciplines are involved in the study of ecosystem conditions and services?	Q6	(i), (ii)
	Which disciplines are involved in the study of climate change variables?	Q7	(i), (iii)
Ecosystem conditions and services	Which are the ecosystem conditions considered?	Q8	(ii)
	Which are the ecosystem services considered?	Q9	(ii)
	Which *ecosystem conditions ecosystem services* links are studied?	Q10	(ii)
Climate change	Which are the climate change variables considered?	Q11	(iii)
	Which climate *change ecosystem conditions* or *climate change ecosystem conditions ecosystem services* links are studied?	Q12	(iii)

Results

Context and focus of the articles

The spatial distribution of the reviewed studies corresponded to the locations of the world's main viticulture regions. Most articles have been published over the last decade and looked at European VLs (74%, Figure 3a). All the studies we found were only published after 2000, with 85% of them published since 2013 (Figure 3b). Nevertheless, most papers had a regional or local focus, while only 10% of the cases had a transnational or national scope. Regarding the temporal perspective, future scenarios were included in nine out of the 112 investigated articles, while the other articles were based on data from past and present observations.

We found that 60% of our papers focused only on *ecosystem conditions ecosystem services* links, while 40% included *climate change ecosystem conditions* or *climate change ecosystem conditions ecosystem services* links. Of those studies that focused on *ecosystem conditions ecosystem services* links, 63% were published after 2015. The number of studies that included climate change-related links remained consistent over the reviewed time period (Figure 3b).

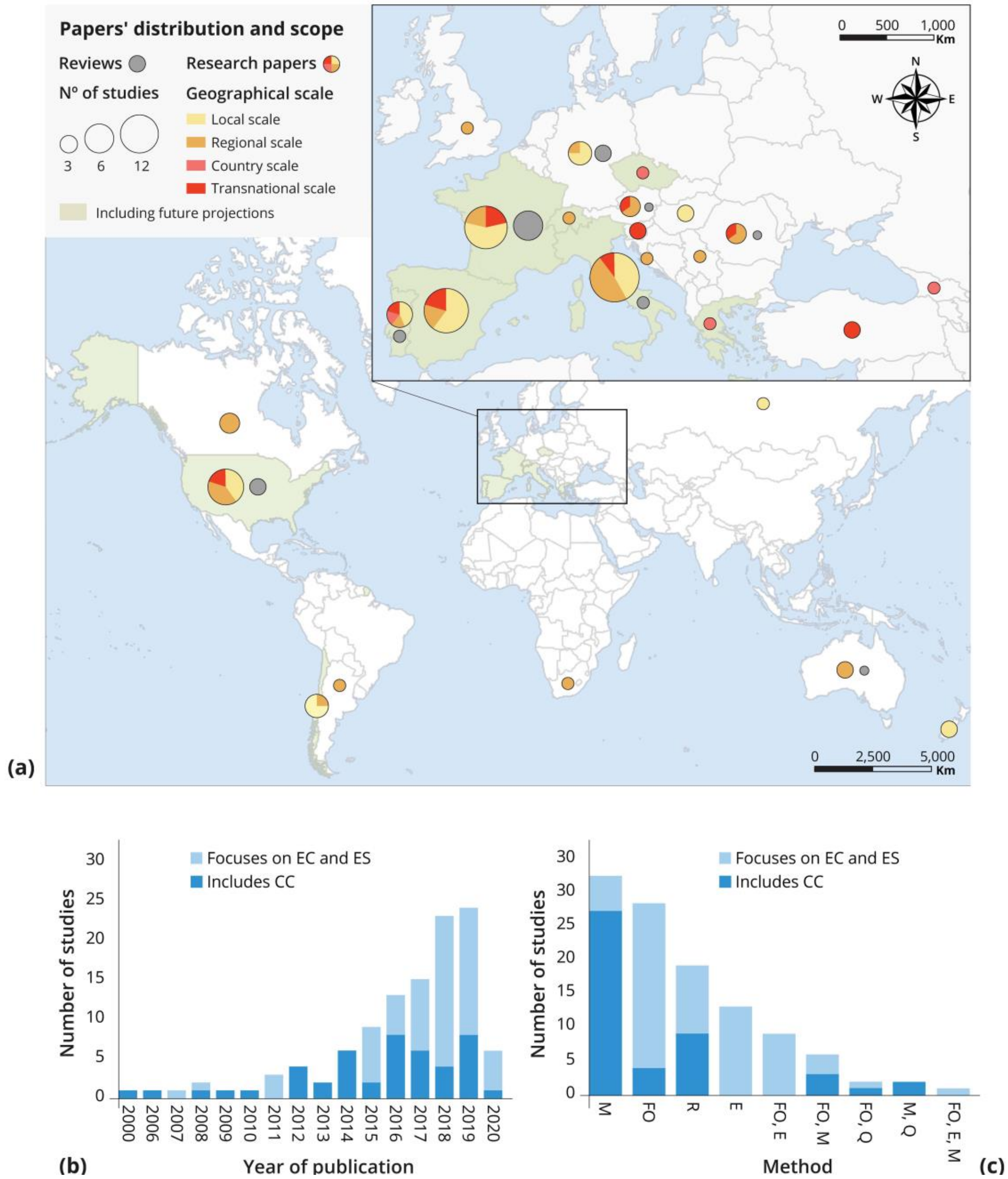

Figure 3. Key features of the 112 articles included in our literature review: (a) spatial distribution of the analysed articles. Research papers are classified based on their geographic scale and the inclusion of future projections in their analysis. Criteria for spatial and temporal classification are provided in Table 10. Review papers are classified separately (gray circles) based on their geographic location, defined using the affiliation of their first author; (b) bar chart for each year of publication, classified by the thematic focus of the articles; (c) bar chart representing the methodology used (M = model, FO = field observation, R = literature review, E = field experiment, Q = questionnaire) to study the links between ecosystem conditions (EC), ecosystem services (ES), and climate change (CC), classified by the thematic focus of the articles.

Most of the articles that used a modelling approach considered climate change variables (84%, Figure 3c), whilst the articles using field observations or experiments mainly focused on *ecosystem conditions ecosystem services* links (86 and 100% of the articles, respectively). Literature review approaches were used by both those studies that focused on ecosystem conditions and services, and those that included climate change variables. Finally, 70% of the articles that adopted more than one method were investigating *ecosystem conditions ecosystem services* links. The combination of models and questionnaires was used only in papers that included climate change-related links.

Ecosystem conditions and ecosystem services

In our review, we found a total of 276 *ecosystem conditions ecosystem services* links in 76 papers. The most studied ecosystem conditions included in this link type were ground cover conditions (38%), landscape composition (16%), local habitat conditions (14%), vineyard soil conditions (8%), presence of animals or fungi (8%), management regime (7%) and water availability (3%) (Figure 5). Most of the articles that included *ecosystem conditions ecosystem services* links considered only one single ecosystem condition (57%), (Figure 17a). The study by Winkler et al. (2017), for example, was one of the few cases that analysed how multiple ecosystem conditions, such as landscape composition, vineyard soil, canopy management strategies, and presence of natural enemies, affect the provision of multiple ecosystem services in VLs. The most studied ecosystem services were those related to the maintenance of nursery beneficial populations and habitats (32%), pest control (17%), decomposition and fixing processes and their effects on soil (17%), crop production (9%), and filtration and storage by organisms (6%). When looking at the temporal patterns in the publication of the reviewed articles, we found that although only a limited number of papers studied multiple ecosystem conditions and services (Figure 4a, b), an increasing number of linkages can be observed.

As found for ecosystem conditions, also ecosystem services were considered mainly individually. In fact, 62% of the papers that included an *ecosystem conditions ecosystem service* link considered only one ecosystem service, and 19% considered two. Studies that considered three or more ecosystem services were less than 20%. For example, Viers et al. (2013) included 11 different ecosystem services when reviewing potential benefits provided by VLs (Figure 17b).

We found that the *ecosystem conditions ecosystem services* links focused mainly on a specific set of ecosystem conditions that was particularly studied in relation to the regulating and provisioning ecosystem services that are important for wine grape production. For example, ground cover conditions in the inter-row spaces of vineyards have been extensively studied, especially for their potential to limit weed establishment and to maintain populations and habitats of species that prey on pests (16% of the links), such as in Hoffmann et al. (2017). Ground cover was also studied regarding its effect on other services, showing that it is useful for increasing the decomposition and fixing processes of the soil, regulating the water cycle, and protecting the soil against erosion, (15% of the links), (Nistor et al., 2018; Shields et al., 2016; Winter et al., 2018).

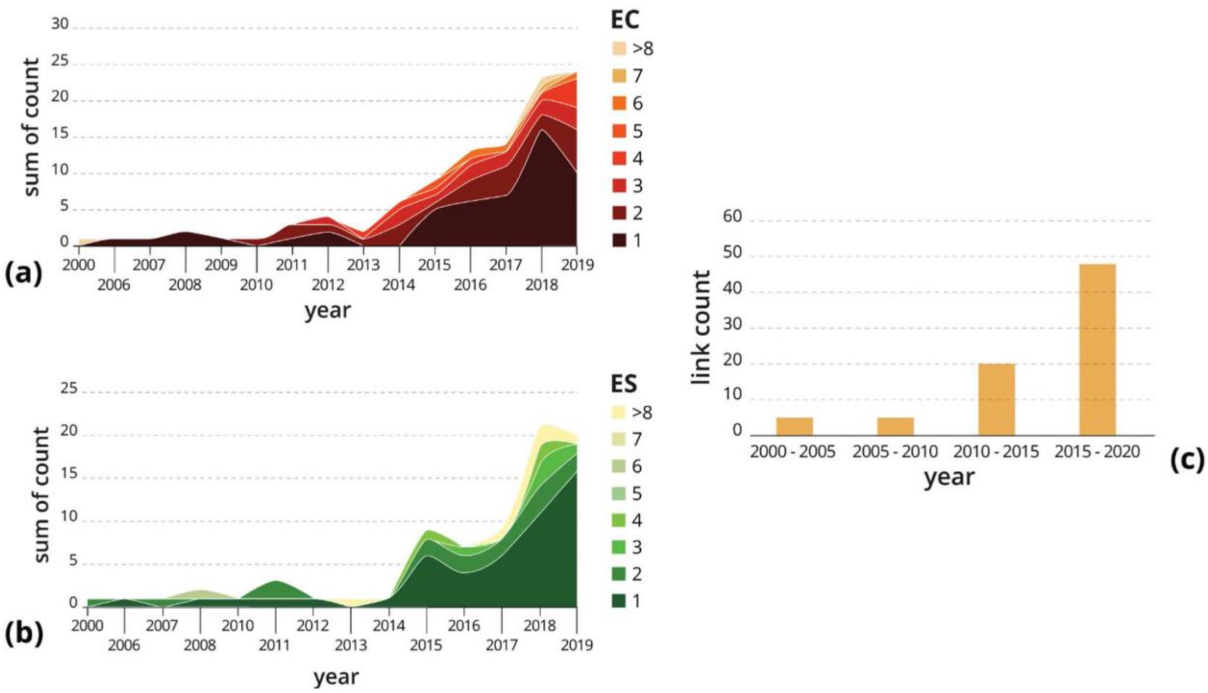

Figure 4. Number of ecosystem conditions, ecosystem services and integrative links included in our sample of papers over time. (a) Number of ecosystem conditions considered together in our sample of papers over time; (b) number of ecosystem services considered in our sample of papers over time; (c) the number of *climate change ecosystem conditions ecosystem services* links considered over time.

Landscape composition was studied in relation to the provision of many services. The presence of semi-natural areas near vineyards and landcover heterogeneity at the landscape scale were studied in relation to the capacity to provide habitats and increase the populations of species that are beneficial for vintners and for the biological control of pests (11% of the links). For example, Rusch et al. (2016) found that the presence of diverse natural habitats enhanced ground beetle species turnover, supporting more heterogeneous insect communities in simple landscapes. The same author analysed the pest control of grape berry moths in Bordeaux vineyards, concluding that landscape heterogeneity was the main variable affecting the biological control of these insects (Rusch et al., 2017). Local habitat conditions were studied based on specific elements, including the presence of solitary trees or green infrastructure such as hedgerows, that can provide habitat for beneficial animals, (5% of the links), e.g., in Polyakov et al. (2019), Rosas-Ramos et al. (2019). We found that habitats characteristic of VLs, such as stone walls and hedgerows, were also investigated for the provision of cultural services such as those related to aesthetic perceptions or cultural heritage (Assandri et al., 2018). The presence of animals or fungi was studied in terms of pest control (4% of the links). For instance, we found multiple studies that examined the activity of arthropods, birds and bats in vineyards and their role as predators against pests such as grape berry moths, e.g., Thiéry et al. (2018). In addition, we found that specific organisms, such as arbuscular mycorrhizae, were considered for their benefits to VLs, e.g., alleviation of grapevine water stress (Trouvelot et al., 2015).

Vineyard soil conditions were analysed considering ecosystem services related to decomposition and fixing processes (4% of the links), for example studying the fraction of organic carbon in the soil, which influences carbon sequestration (Nistor et al., 2018; Novara et al., 2018). Vineyard management regimes were mostly studied by analysing the effect of organic practices on the enhancement of beneficial populations, habitats, and pest control effects (5% of the links), e.g., in Muneret et al. (2019). Water availability was studied in relation to grape production (3% of the links), as Bernardo et al. (2018) and Schultz (2016) showed that this is an important condition for the formation and development of grape berries.

Climate change

We found 122 *climate change ecosystem conditions* links stemming from 46 papers. The most studied climate change variables in these links were temperature (58%), followed by precipitation (34%), extreme events (5%) and CO_2 concentration (3%) (Figure 5). In 50% of the cases, articles that included *climate change ecosystem conditions* links considered only one ecosystem condition (Figure 17d). In 46% of the cases, two or more climate change variables, especially temperature and precipitation, were included (Figure 17c). The most studied ecosystem conditions were phenology (26%), climatic suitability for viticulture (14%), the presence of animals or fungi (12%), and gross primary production (11%).

In 20% of *climate change ecosystem conditions* links, temperature was studied either in relation to the advancement of the phenological stages of grapevines, like in Fraga et al. (2016), or based on the recorded harvest dates as a proxy for vine phenology for premium wine estates, e.g., Carlo et al. (2019). Temperature was also shown to not only influence specific plant-dependent processes but also the overall climatic suitability for viticulture in many areas (10% of the *climate change ecosystem conditions* link). For example, increasing temperatures are threatening grape production in many traditional grape growing regions and increasing the suitability of new areas for viticulture (Fraga et al., 2016). The influence of temperature in the regulation of the water cycle was reflected in the number of links (7%) retrieved from studies that highlighted how the increase in temperature will decrease the water reservoirs upon which some VLs depend, e.g., in Castex et al. (2015), and increase evapotranspiration, leading to water deficits and changes in several vine yield parameters, e.g., in Leeuwen et al. (2019). Temperature was moreover investigated due to its influence on animals and fungi present in VLs (7% of the links), as it was shown to possibly increase pest activity in viticultural areas by creating more suitable climatic conditions (e.g., Nesbitt et al. (2016), Rayne and Forest (2016)). Precipitation was studied primarily in terms of water availability in vineyards and climatic suitability for viticulture (8% of the links). The decrease of water availability was shown to negatively affect the overall quantity of water for the physiological activities of the vines (Lazoglou et al., 2018). Increased moisture due to higher precipitation was related to the presence of fungi in vineyards and to the risk of fungal pathogen outbreaks and disease pressure (Neethling et al., 2019). Precipitation was also found to affect phenology (5% of the links), such as in Ramos et al. (2018). Extreme events such as hail and heavy storms were considered only in 5% of the *climate change ecosystem conditions* links, even if these events can heavily influence the gross primary productivity of vines by damaging plants in sensitive phenological phases such as budburst, as showed by Nesbitt et al. (2016) and Neethling et al. (2019). Finally, the increase in CO_2 concentration was primarily studied in relation to the presence of animals and fungi and to the changes in phenology and gross primary production (2% of the links). For example, Schultz (2016) reported that an increase in CO_2 concentration can be beneficial for the biomass production of vines but could also lead to an increase in the activity of insects, which will result in more damage to plants. A higher CO_2 concentration in combination with increased temperatures and water deficit was shown to contribute to the modification of the phenological stages of vines (Martínez-Lüscher et al., 2016).

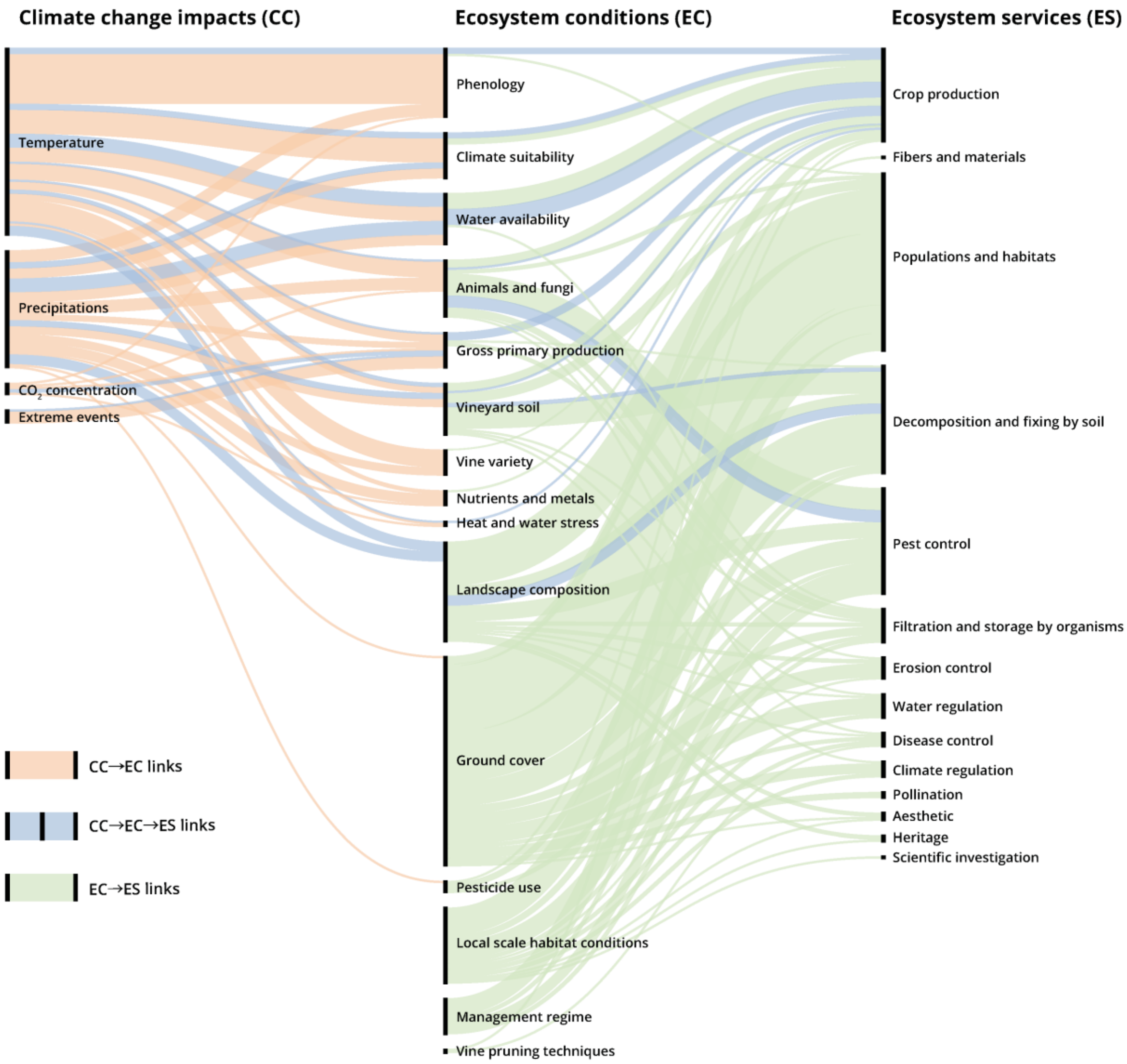

Figure 5. Sankey diagram representing the *ecosystem conditions ecosystem services* links, *climate change ecosystem conditions* links, and *climate change ecosystem conditions ecosystem services* links retrieved in our review. The thickness of the lines is proportional to the total number of links. The percentages of how much the single links' components and their relationships were studied are reported in Figure 19 and Table 13.

We found 78 *climate change ecosystem condition ecosystem service* links from 15 papers. The most studied climate change variables included in these links were temperature (52%) and precipitation (41%), while the most studied ecosystem conditions were water availability (24%), animals and fungi (21%) and landscape composition (15%). Ecosystem services considered in these links were crop production (62%), decomposition and fixing processes (21%), and pest control (18%) (Figure 5). Like in the *climate change ecosystem condition* links, many of the papers studied more than one climate change variable, while single ecosystem conditions and services were considered in the majority of the papers (Figure 17e, f, g). Notably, the number of *climate change ecosystem condition ecosystem service* links extracted from our sample is increasing in the last few years (Figure 4c).

Around 20% of the *climate change ecosystem condition ecosystem service* links were related to the study of temperature and precipitation on water availability, and the consequent effects on crop production. For example, Ramos and Martínez-Casasnovas (2010) studied how temperature and precipitation distributions associated to climate change affect water availability of rainfed vineyards, thus influencing the vine grape yield. Another 19% of the links studied the effects of changed temperature and precipitation patterns on landscape composition, and the related effects on the decomposition and fixing processes provided by VLs. Muñoz-Rojas et al. (2015) studied how soil organic carbon is influenced by changes in temperature and precipitation, which in turn affects carbon stocks. The influences of temperature and precipitation patterns were studied by 20% of the links in relation to the phenology and climatic suitability of vines to determine how they influence the provision of wine grapes, e.g., in Fraga et al. (2016), Fraga et al. (2019). Finally, 9% of the links focused on the effects of changing temperatures on the animals and fungi present in VLs. For example, as illustrated by Thiéry et al. (2018), the increase of temperature influences the abundance and diversity of natural enemies and parasitoids of vine pests in vineyards, affecting their capacity to provide pest control.

Disciplines

The reviewed papers originated from journals belonging to a limited number of disciplines. Around 41% of the articles were categorized as belonging to the agricultural and biological sciences, 37% to the environmental sciences and 7% to earth and planetary sciences. In particular, papers from the agricultural and biological sciences and from the environmental sciences have been studying VLs over time (Figure 18). Other relevant disciplines were those from the social sciences (4%) and from biochemistry, genetics and molecular biology (3%) (Figure 6a). *Ecosystem conditions ecosystem services* links were addressed in papers published mainly by agricultural and biological sciences, environmental sciences, and earth and planetary sciences journals, with more than 90% of the links originating from either the environmental sciences or the agricultural and biological sciences, showing the importance of these fields. *Climate change ecosystem conditions* links were studied in papers coming out of environmental sciences, and agricultural and biological sciences in almost 80% of the cases. *Climate change* *ecosystem conditions ecosystem services* links were studied by environmental sciences, and agricultural and biological sciences in almost 90% of the cases.

Discussion

Beyond grape provision

Our study highlighted that even if the number of ecosystem conditions and services investigated in our sample of papers has increased in recent years, there is the need to consider ecosystem conditions and ecosystem services more comprehensively. For example, we found that only 3% of the ecosystem conditions ecosystem services links retrieved by our review addressed cultural services. In addition, only 28 and 18% of the reviewed studies considered more than two ecosystem conditions or services, respectively. There is, therefore, the need to adopt a more comprehensive view both on the variables that are studied, e.g., which ecosystem conditions and services, and on how multiple variables are investigated together, e.g., multiple ecosystem conditions and services.

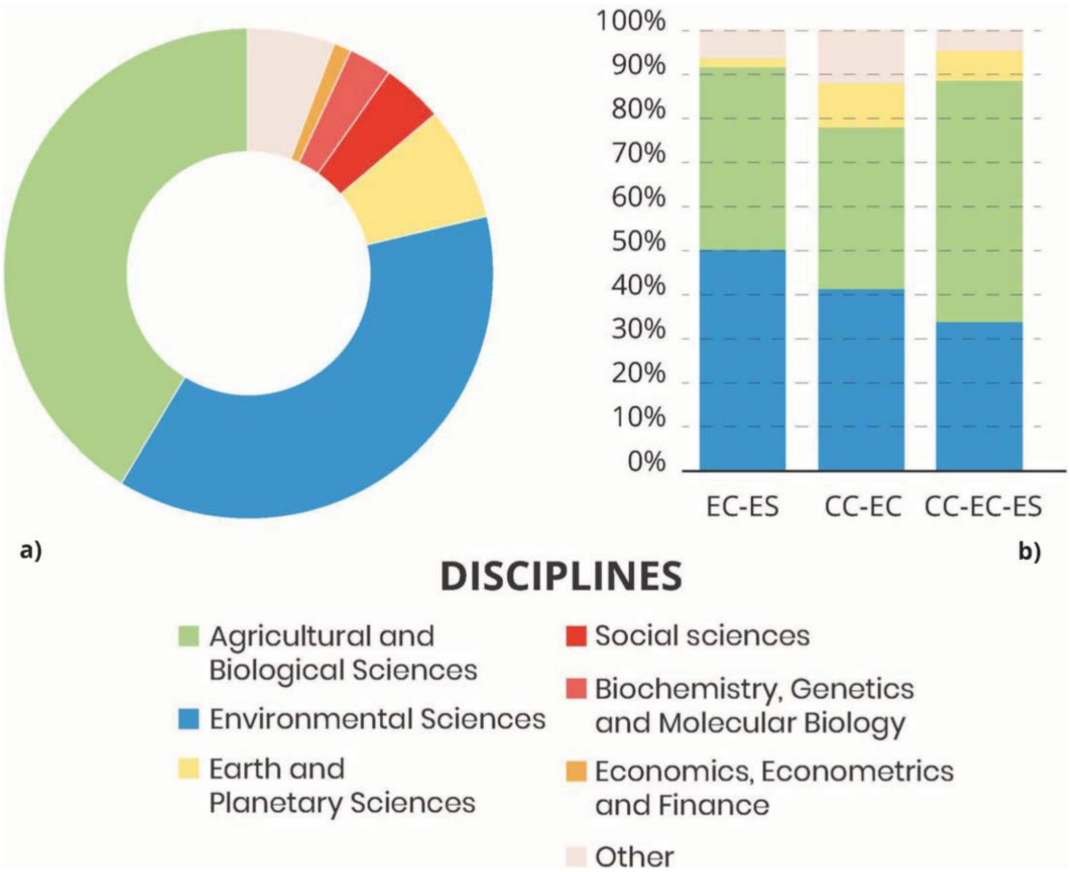

Figure 6. Disciplines included in our review: (a) categorization of the articles in our review based on the disciplines of the journal; (b) categorization of the links retrieved in our review based on the discipline of the journal. In both cases, we accounted for journals ranked in more than one discipline by creating an entry for each discipline

The results of our review suggest that there is a need to take into better consideration a wider range of ecosystem conditions and services in VLs. To foster more comprehensive research, future studies on VLs should focus on understudied ecosystem conditions such as vine variety, water availability, and the characteristics of vineyard soil, and understudied ecosystem services such as the provision of fibers and materials, water regulation, and erosion control. More attention should moreover be placed on the intangible services provided by VLs and on the potential of VLs for supporting outdoor recreation, and bequest and existence values. For example, there is evidence that assessments of relational values can support the development of policies that leverage farmers' sense of identity, such as when designing payments for ecosystem services schemes to support biodiversity conservation and soil conservation practices (Allen et al., 2018; Chan et al., 2016). As also found by previous reviews on VLs (Paiola et al., 2019; Winkler et al., 2017b) , and on other ecosystem types, i.e., forest, coast, arctic or mountain (Falardeau & Bennett, 2019; Liquete et al., 2013; Mengist et al., 2019; Mengist & Soromessa, 2019), literature on ecosystem services often focuses on the restricted range of services that are involved in the production of material goods and can be easily quantified (Martín-López et al., 2012). Thus, approaches that study agroecosystems without an exclusively instrumental viewpoint, but that also include intrinsic and relational values, should be adopted more frequently (Himes & Muraca, 2018). A more comprehensive approach to the study of VLs could, therefore, provide critical information that can foster the transformation and adaptation of these socio-ecological system.

Our review has moreover found that the majority of articles that study ecosystem services in VLs investigate a single ecosystem condition or ecosystem service. In some cases, there are scientific and practical reasons why a study would focus on a single ecosystem condition. For example, those studies that are aiming to gain an understanding of the functioning of vines under warmer temperatures often look at their phenology because this condition allows the quantification of the differences in the development of the plants starting from the budbreak to the harvest of grape clusters (Fraga et al., 2016; Fraga et al., 2019). In other cases, however, focusing on a higher number of ecosystem conditions would allow the better understanding of the interplay of ecosystem services at the ecosystem and landscape scale. In our review, we found only six papers that studied more than two ecosystem conditions and services together. This is the case of Capó-Bauçà et al. (2019) who analysed three ecosystem services (decomposition and fixing processes by soil, water regulation, the provision of populations and habitats) and two ecosystem conditions (ground cover conditions, vineyard soil) to highlight the benefits provided by green cover crops in Mediterranean vineyards. The other five papers were literature reviews, and this is the reason why a high number of ecosystem conditions and services was included in their study. These reviews were moreover investigating widely studied ecosystem services and conditions, such as ground cover conditions, the presence of animal and fungi, the provision of population and habitats, and decomposition and fixing processes by soil. More comprehensive research on VLs could be fostered by including those ecosystem conditions that are very important for providing multiple services. For instance, in our review local habitat conditions were studied only in a limited number of papers, despite the fact that they affect a wide range of ecosystem services such as pest control, soil quality, and decomposition and fixing processes (Polyakov et al., 2019; Rosas-Ramos et al., 2019; Tixier et al., 2015). Moreover, applying a holistic perspective to address climate change challenges, such as changes in precipitation patterns, could foster the simultaneous study of all the ecosystem conditions and services involved in the process, e.g., in the water cycle. Given the lack of multifunctional research in VLs, conducting research that sheds light on the relationships among the understudied components of VLs would be a first step towards a more complete understanding of these socio-ecological systems (Rusch et al., 2021).

While the study of VLs' multifunctionality helps to grasp the agroecosystems' capacity to support various aspects of ecosystem resilience and of human well-being, attention should be placed on the issues related to its assessment methods. Indeed, since only a subset of all the possible functions and services present in an ecosystem can be quantified, multifunctionality measures are not absolute and depend on the ecosystem services or functions included in the studies (Manning et al., 2018). Multifunctionality can be described by different indices which underline the total supply (e.g., average) or the diversity (e.g., alpha diversity) of multiple ecosystem services at different scales (Manning et al., 2018). In addition, some approaches might be better suited than others to consider the trade-offs and synergies occurring between ecosystem services (Schaafsma & Bartkowski, 2020). To overcome these gaps, the concept of multifunctionality should be approached carefully, adopting specific methodological steps that can limit some of its drawbacks e.g., incorporating the most important ecosystem services and weighting them based on stakeholders' priorities (Neyret et al., 2021). In many cases, as suggested by Giling et al. (2018), the methods to assess ecosystem multifunctionality may need to be selected on a case-by-case basis developing tailored hypotheses, functions, and analytical methods (Giling et al., 2019). To conclude, the considerations of multiple ecosystem conditions and ecosystem services would enable a systematic deepening of our knowledge on the functions and services provided by VLs, advancing our capacity to manage them.

Promoting multidisciplinary research in viticulture

Our review highlighted the diverse disciplinary and methodological perspectives adopted in studying ecosystem conditions, ecosystem services, and the effects of climate change on VLs. Although VLs were also investigated by studies published in journals classified in the fields of economics, earth and planetary sciences, social sciences, and other fields, 78% of the reviewed papers have been published by the agricultural and biological sciences and by the environmental sciences for almost 20 years. For example, we found many papers that used a crop modelling approach to study the effects of climate change on yield (such as Fraga et al. 2019), or studies that used a landscape ecology lens to investigate the role of landscape composition in influencing pest control in VLs (such as Rusch et al. 2017). On the other hand, papers included in our sample and that were classified in the discipline category of multidisciplinary studies were rare and included only a few links.

The lack of multidisciplinary approaches in the study of the provision of ecosystem services has been reported in previous reviews about agricultural and other ecosystems (Liquete et al., 2013; Tancoigne et al., 2014; Vári et al., 2022). Indeed, applying multidisciplinarity is often difficult for several reasons: limited funding allocation due to a traditional academic structure that discourages multidisciplinary collaboration, practical challenges related to the management of resources and researchers, and methodological challenges related to the connection between disciplines or the use of established ways to approach a research theme (Pooley et al. 2014; Thompson et al. 2020; Dick et al. 2016). However, having a multidisciplinary approach is important considering the challenges that VLs will face due to climate change and the fact that these challenges are characterized by a high degree of complexity due to the interactions of climate change with other drivers of change (Lopez-Bustins et al., 2013; Savé et al., 2010).

To overcome the lack of multidisciplinarity in literature on VLs, communication between different disciplines should be fostered more. A first step towards this target would be the creation of a common vocabulary and shared definitions of the most important concepts that are relevant for VLs. In our review, we found that the concept of ecosystem services has not yet penetrated the journals of agronomy and biological sciences that deal with viticulture, and that some papers had no reference to this concept at all. For example, Fraga et al. (2016) and Gristina et al. (2019) studied crop production and carbon sequestration without explicitly considering them as ecosystem services. Where the ecosystem services concept is used explicitly, several different definitions and classifications are adopted, if specified at all. The same holds for ecosystem conditions, for which we had to rely on a general classification developed for studying agroecosystems at the European scale that we had to adapt to the specific case of viticulture (Maes et al., 2018). In fact, also in papers that included many ecosystem conditions, e.g., Thiéry et al. 2018, we did not find any reference to a common definition or classification system. Future research should, therefore, lay down a shared definition of ecosystem conditions and services for VLs to facilitate a common understanding on these concepts and to advance our understanding of viticulture in a multidisciplinary perspective.

The combination of mixed methods in single studies is another approach that can foster the production of new multidisciplinary knowledge. This is facilitated when research is conducted by a heterogeneous team with different backgrounds (O'Cathain et al., 2008). In our review, we found nine studies that applied mixed methods coupling field observations with experiments or models, and three studies that coupled questionnaires with models or field observations. While the papers that coupled field observation with experiments or models were mainly doing this inside the boundaries of the same discipline, for example comparing results from a field survey with a controlled experiment in the same vineyard plot, the combination of models and questionnaires was done applying a 'true' multidisciplinary perspective. Some of the studies that coupled models and questionnaires shed light on specific aspects of VLs that would have been hardly grasped using a monodisciplinary focus. For example, Lereboullet et al. 2014 complemented present climate data and its projections with in-depth interviews of local stakeholders to analyse the adaptive capacity of the Languedoc–Roussillon winemaking region (FR). Holland and Smit 2014 applied a similar approach to evaluate the adaptation strategies that are employed by wine producers in Prince Edward County (CA). These methods can increase the knowledge of VLs as a socio-ecological system and can foster the adoption of strategies that support climate change adaptation. In addition, such multidisciplinary methods could be applied also to study other drivers that are increasingly threatening VLs, e.g., socio-economic pressures, land use change, and biodiversity loss (Hoppert et al., 2018; Viers et al., 2013). To conclude, adopting methods that are used in different disciplines, such as questionnaires and models, should be prioritized in the future, as they can increase the multidisciplinary knowledge on VLs.

Benefits of an integrative perspective

Our findings highlighted that integrative studies, i.e., studies that included *climate change ecosystem conditions ecosystem services* links, were underrepresented in the literature. Out of the total 476 links retrieved in our review, we found that only 78 were integrative. Of the fifteen studies that included integrative links, seven were literature reviews (including more than 50% of all the integrative links), and six were research papers. The ecosystem services addressed by such integrative studies were provisioning in 62% of the cases and regulating in 38%. Of the fifteen ecosystem conditions considered in this review, only eight were addressed in these types of studies.

To foster studies with an integrative perspective it would be important to better investigate some specific ecosystem conditions that have the potential to develop integrative knowledge. This is the case of ecosystem conditions such as the presence of animals and fungi, and vineyard soil that were considered in both *climate change ecosystem conditions* and *ecosystem conditions ecosystem services* links but were not addressed by integrative studies. Indeed, since knowledge about these two separate link types has been already produced for these ecosystem conditions, this knowledge can be the basis for developing an integrative understanding of the relationship between climate change attributes and ecosystem services. Another way to develop more integrative knowledge would be to study those ecosystem conditions and services that have not yet been assessed in studies featuring *climate change ecosystem conditions ecosystem services* links. For instance, ground cover conditions and local scale habitat conditions have never been studied in relation to both climate change attributes and ecosystem services, and we did not find any integrative link that included cultural ecosystem services. The inclusion of these conditions and services in integrative studies would complement the many studies already available on *ecosystem conditions ecosystem services* links, underlying the role of climate change in regulating such biophysical processes and ecosystem services provision.

Integrative research papers can provide critical information on the cascading effects that would be difficult to grasp focusing only on parts of the socio-ecological system, i.e., the other two link types (Falardeau & Bennett, 2019). This knowledge allows researchers and decision makers to shed light on the functioning of each VL, supporting the development of strategies that can shape more resilient and sustainable VLs. This is particularly important in VLs that are often distinguished based on the concept of terroir, which defines the unique aspects of each growing region (Winkler et al., 2017b). For example, those *climate change ecosystem condition ecosystem service* links that studied the effects of climate change on the climatic suitability of vines and the related effects on yield in specific winegrowing areas may constitute an entry point for the identification of possible adaptation options that take into consideration the complexity of each VL. This is the case of the study of Biasi et al. (2019), which characterized the genotypic-specific response to climate change of a set of local and international vine varieties in the Umbria Region (IT) and thus enabled the development of viticultural practices in line with the local climate. Future studies on the specific consequences of climate change on ecosystem conditions and services should, therefore, be promoted to foster the development of tailored regional adaptation strategies.

Further developments

Although we mapped how extensively the relations between the VL components were studied, our approach did not quantify the impacts of climate change on the ecosystem conditions and services. Future studies could conduct a dedicated meta-analysis based on the data included in the literature. Future studies can also expand our approach including additional information on the relationships between ecosystem conditions, ecosystem services, and climate change in VLs by including possible feedbacks occurring between these components, as we considered only the description of direct effects of ecosystem conditions on ecosystem services, and of a set of climate change attributes on them. For example, we did not study the effects of ecosystem conditions on other ecosystem conditions, although, for instance, certain management practices may impact other sets of conditions by using fewer external inputs (e.g., in organic farming). These influences of the ecosystem conditions can boost the sustainability of a VL and increase the presence of beneficial organisms such as natural enemies of crop pests (Muneret et al., 2019). Even though we excluded human-interacting feedbacks in VLs, some of the reviewed papers considered specific socio-economic drivers together with climate change in the analysis of VLs (Bernardo et al., 2018; Castex et al., 2015; Neethling et al., 2017; Sgubin et al., 2019). In these papers, however, it was difficult to identify how such socioeconomic drivers would affect the provision of ecosystem services in VLs. The use of system-thinking methods and tools such as causal loop diagrams and stock-flow models, which have been successfully applied to study complex problems related to agroecosystems, could be effective for analysing the complexity of VLs including human dimensions (Sterman, 2000; Turner et al., 2016; Walters et al., 2016). The application of these methods could promote a holistic understanding of agricultural landscapes, their environment, and food production, which will be essential to meet policy objectives such as the sustainable development goals (Ortiz et al., 2021).

Conclusions

VLs are important agroecosystems that provide multiple economic, environmental, and cultural ecosystem services. The literature on VLs, however, is missing a comprehensive, multidisciplinary, and integrative approach to the study of ecosystem services and conditions in the context of climate change. To fill this gap and to promote more multifunctional approaches in the study of VLs, future research should focus on the least studied ecosystem conditions (e.g., vineyard soil characteristics, vine variety) and services (e.g., cultural ecosystem services), with a focus on those key ecosystem conditions that are linked to the provision of multiple ecosystem services. In addition, more efforts should be put in developing common definitions for key ecosystem services and conditions in viticulture and in applying mixed methods to study VLs. This would foster the production of new knowledge that crosses the boundaries of single disciplines. Finally, to develop more integrative research on VLs, attention should be placed on the ecosystem conditions that can potentially link existing knowledge on climate change and on ecosystem services. The knowledge developed in such comprehensive, multidisciplinary, and integrative studies will help researchers and decision makers to gain a more complete understanding of agroecosystems' overall functioning and to identify effective adaptation strategies that can support the sustainable management of VLs under future climate uncertainties.

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Chapter 2: creating geospatial information for the wine Protected Designations of Origin in Europe

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Part 2

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Part 1: harmonising regulatory information on wine protected designation of origin in Europe

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Abstract
Wine Protected Designation of Origin (PDO) products are strictly regulated and therefore highly susceptible to changes in climatic, environmental, and socioeconomic conditions. Analysing the impacts of such changes has so far been challenging because the legal specifications of wine PDOs in Europe have never been summarised in a harmonised dataset. Here, we present how we created the first inventory of regulatory information for the 1177 wine PDO in Europe, based on the geographical indication register of the European Union.

Rationale
The Protected Designation of Origin (PDO) label is a European Union (EU) quality scheme that protects products made in specific areas, under distinctive physical and biological conditions and using strictly defined production practices (Clark & Kerr, 2017). It therefore includes strict regulations regarding cultivation and production processes together with the definition of the area where the grapes must be cultivated. These regulations are included in a set of documents e.g., product specification, that are reviewed and accepted by the European Commission.

Due to the strong relationship between PDO wines and the specific conditions and production practices defined in the regulation documents, these products are highly vulnerable to any changes in the climatic, environmental, or economic conditions in the production area. For example, warmer climate conditions are affecting the growing suitability of several traditional cultivars, the introduction of alien pest species is endangering the health of vines, there is social and economic pressure to adopt new and more sustainable production practices, such as organic viticulture (Caffarra et al., 2012; Fraga et al., 2016; OIV, 2021). All these factors are often in conflict with the specifications defined in the regulatory documents. To maintain their quality standards, PDO areas therefore may need to use different production practices to those authorised in the regulatory documents. For this reason, there is a need to thoroughly plan and develop specific adaptation strategies that consider the local conditions and legal specifications of individual PDO regions. Such strategies require knowledge about the legal specifications that characterise each PDO, which is currently only available in the regulatory documents of each wine PDO and not as a harmonised dataset.

Here we describe how we created the first geospatial inventory of regulatory information for the 1177 PDO areas registered in Europe, giving insights into its structure and potential uses.

Building the inventory

We collected, standardised and spatialised a set of regulatory information using the legal documents included in the EU geographical indication register eAmbrosia (European Commission, 2021*)* and aggregated it in a harmonized dataset. We collected only regulatory information that was available for all considered countries and could be standardised among all PDO areas, (see Table 3 for a description of some of the selected regulatory information). For this reason, we had to exclude information that was not consistently reported, such as the training system, chemical composition of wines, or alcoholic content, although potentially useful for developing adaptation strategies, e.g., to climate change. The regulatory specifications were then spatialised using the boundaries of the municipalities included in each PDO (Figure 7).

Table 3. Selected regulatory information included in the inventory.

Information	**Contents**
Name	Official name of the PDO
Wine products	Types of wine products authorised for production, following the definition of Regulation (EU) No 1308/2013
Vine varieties	List of the vine varieties authorised for PDO wines production; varieties have been standardised based on OIV nomenclature
Yield	Maximum yield allowed, expressed in hl or kg/ha
Planting density	Minimum planting density allowed, expressed in n° of stocks/ha
Irrigation	Possibility to use irrigation, expressed as yes or no
Municipalities	List of the municipalities included in the PDO
Link to regulatory documents	Web link to the eAmbrosia page containing the regulatory documents of the PDO

Inventory structure and potential uses

We developed a freely available geospatial inventory for all the 1177 wine PDO areas in the EU (as of 4 November 2021) that contains a set of regulatory information that can be used by researchers and decision makers. A comprehensive description of the dataset is available in Candiago et al., 2022. The database is freely available online (Candiago et al., 2022) as a set of three files that contain: (1) the geographical boundaries of each PDO, (2) the related regulatory information summarised at the PDO level, and (3) the regulatory information summarised by category of wine product. Using the provided datasets, it is possible to visualise and analyse the main characteristics of European wine PDO regions (Figure 8, 9).

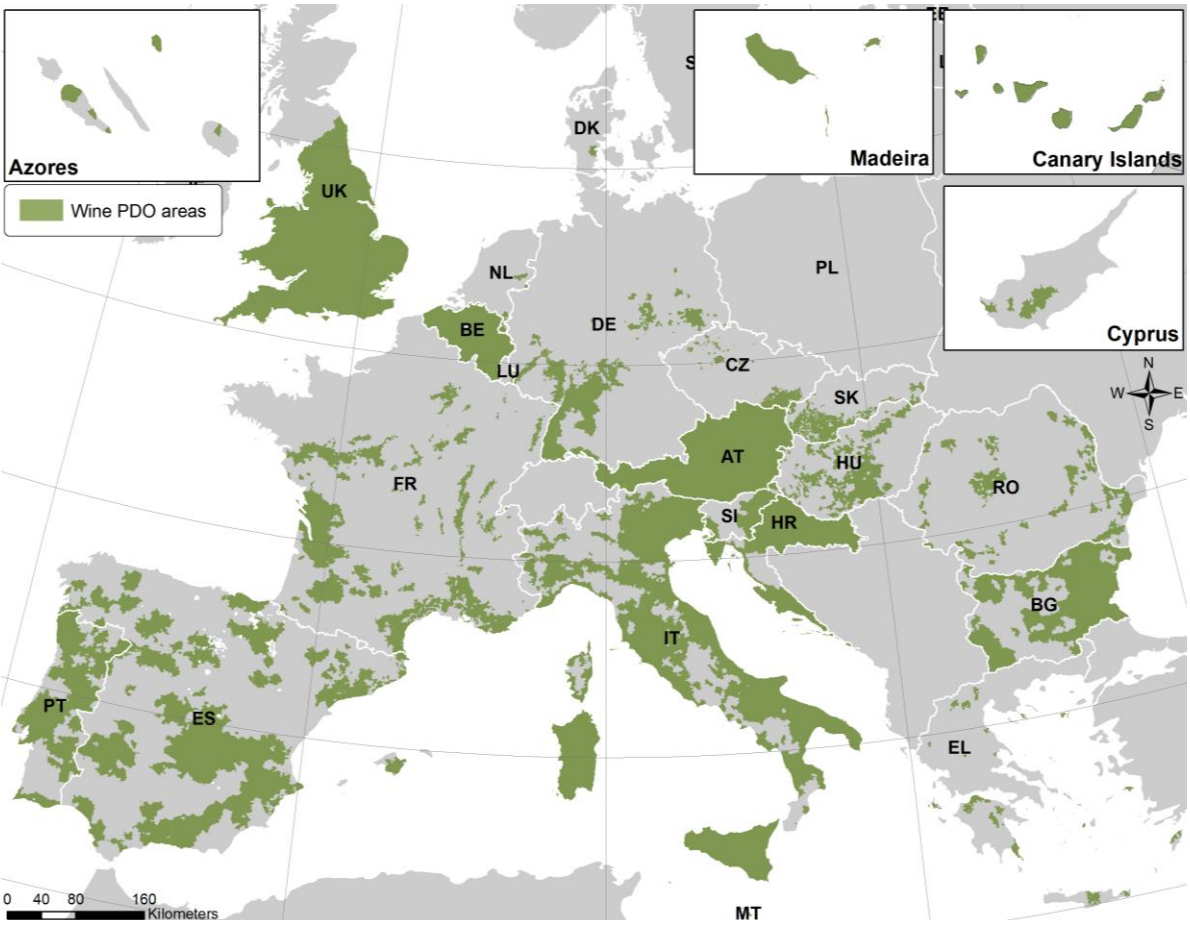

Figure 7. Wine PDO areas included in the inventory, based on the municipality boundaries from Eurogeographic (© EuroGeographics 2022).

This dataset is particularly useful for researchers and decision makers in the field of viticulture. For example, information about planting density and yield can be used by researchers to run crop models calibrated based on the characteristics of each PDO and assess the specific impacts of climate change in a region (Fraga et al., 2016). The comparison of the characteristics of different PDOs, that must always be carried out considering each PDO's contextual specificity, can give insights into adaptation strategies that include the introduction of new vine cultivars suitable for producing high quality products, or the authorisation of irrigation in specific areas (Candiago et al., 2022). Analysing the contents of PDO documents can also improve our understanding of the critical factors that determine the sustainability and reputation of PDO regions, for example showing that there is a need to pursue more environmental regulations.

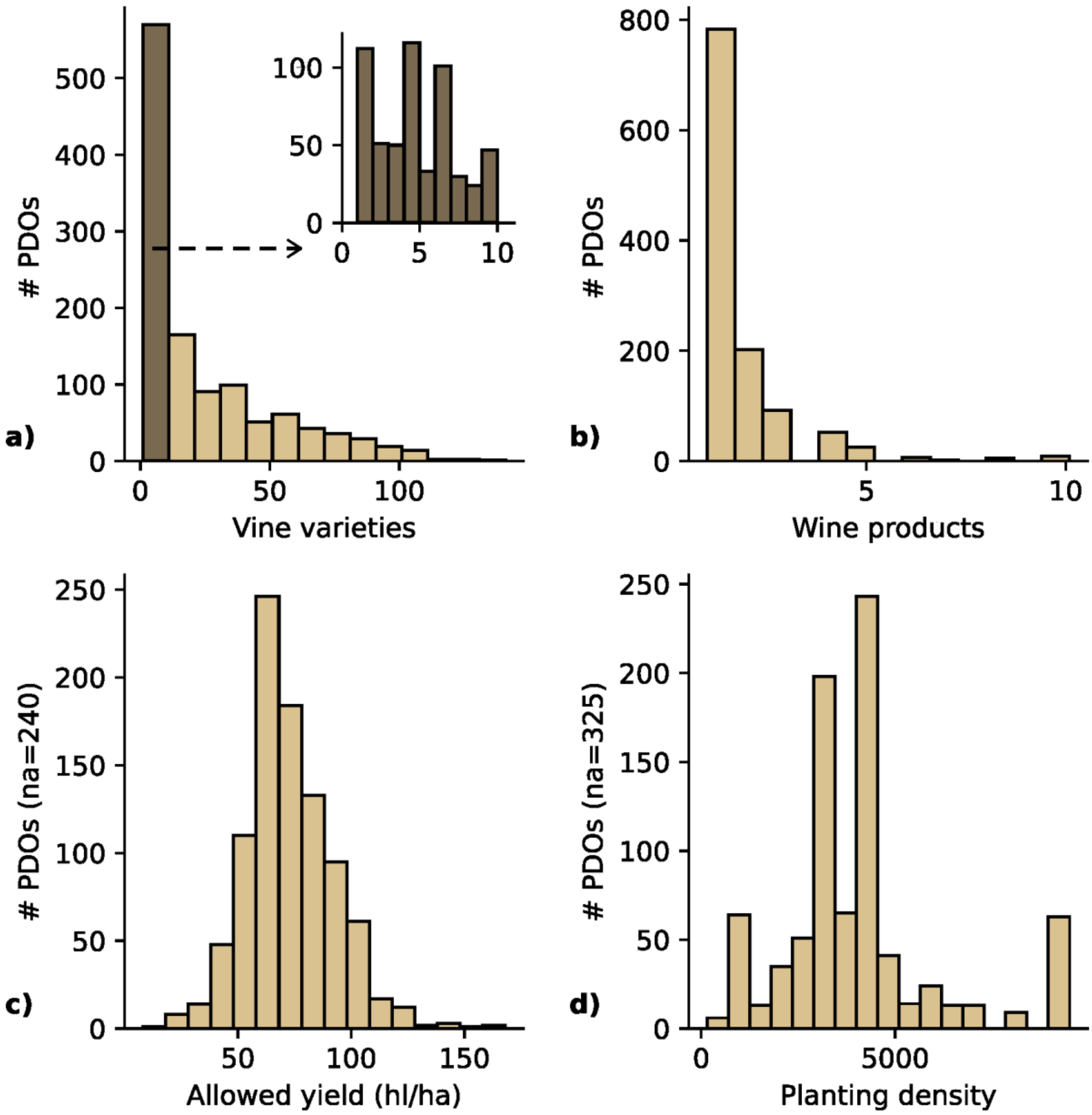

Figure 8. Histograms representing the variability in the (a) number of authorised varieties (with a focus on PDOs that authorise 1 to 10 cultivars), (b) wine products, (c) allowed yield, and (d) planting density in the PDOs included in the inventory.

Concluding remarks

Regulatory information on wine PDO products has never been summarised in a unique spatial database. Here, we provide the first freely available geospatial inventory of PDO regulatory information at the European level. This dataset will allow the comparison of information among different wine PDOs, enabling researchers and decision makers to analyse specific characteristics of each PDO region. This will facilitate the development of tailored adaptation strategies in the face of the current global drivers of change.

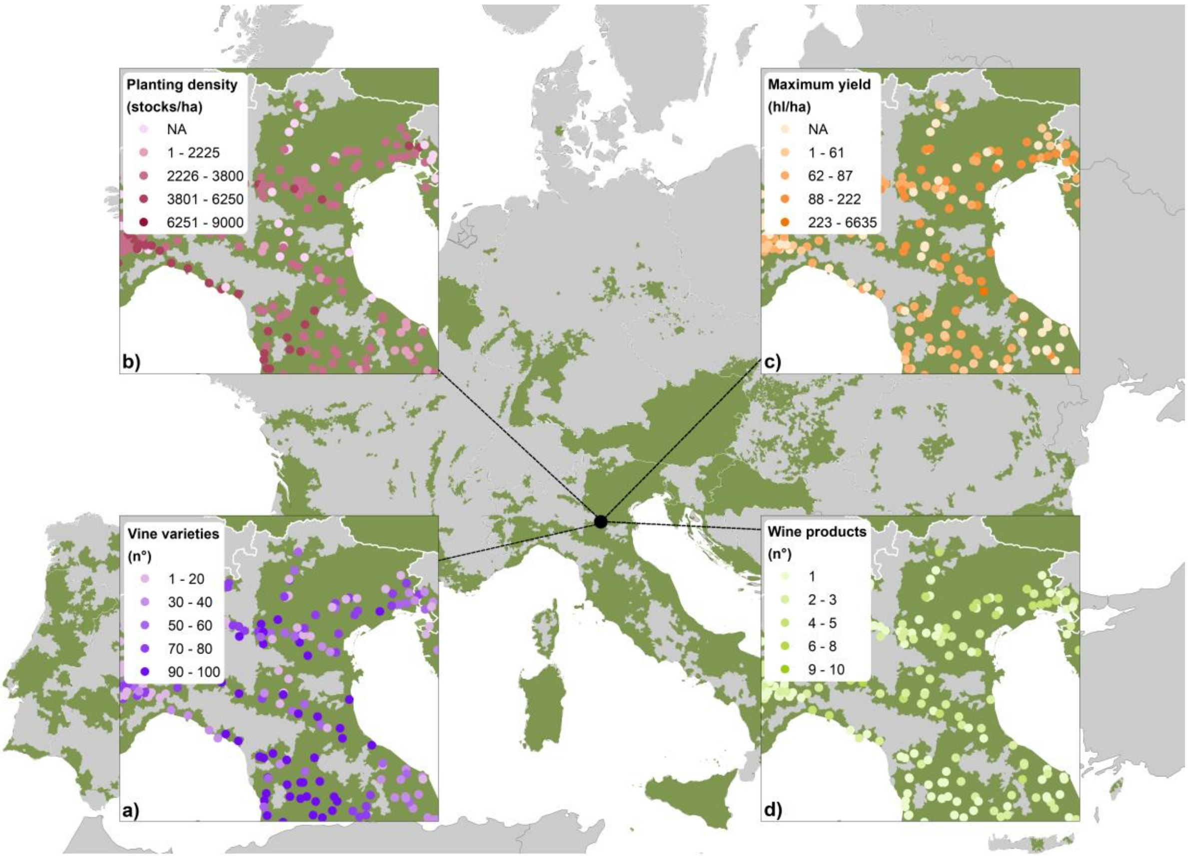

Figure 9. Map showing a set of selected key variables included in the inventory for the area of north-eastern Italy. a) Vine varieties, b) planting density, c) maximum yield, and d) wine products. Points on the maps represent the centroids of the PDOs.

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Part 2: a geospatial inventory of regulatory information for wine Protected Designations of Origin in Europe

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Abstract
The Wine Protected Designation of Origin (PDO) label is a European quality scheme that protects high quality wines by linking them to legally defined geographic areas and a set of specific production practices. Because of the tight relation between PDO wines and the specifications defined in the official regulatory documents, these products are highly susceptible to changes in climatic, environmental, or socioeconomic conditions. However, the content of these regulatory documents has never been systematically analysed and summarized in a single dataset. Here, we present the first geospatial inventory that organizes regulatory information about the 1177 wine PDO in Europe based on the documents from the official EU geographical indication register. It includes essential legal information that defines the wine PDO such as the geographic boundaries, authorized cultivars and maximum yields. This inventory opens new possibilities for researchers to accurately assess, compare and map the regulatory information in each wine region at an unprecedented level of detail, supporting decision makers in developing adaptation strategies for the preservation of PDO wine regions.

Background & Summary
The Protected Designation of Origin (PDO) label is a European Union (EU) quality scheme that protects products made within closely defined areas, under specific physical and biological conditions and using strictly defined production practices (Clark & Kerr, 2017; European Commission, 2022b). In the overall list of products that are registered and protected by the EU, wine plays a major role and includes the largest share of recognized PDO (65%) (European Commission, 2022a). The 1177 European wine PDO comprise 21 countries and a broad range of wine products, including still, sparkling, and liquor wine. As such, PDO viticulture and winemaking represent a key socioeconomic activity (European Commission, 2021), for instance, in 2018 more than 81 million hl of PDO wine were produced, with an export business value of around 9 billion € (European Commission, 2022c).

The quality scheme for PDO wines was set up to protect the unique characteristics of specific wine products and to promote their high quality (Zappalaglio, 2019). It includes strict regulations regarding cultivation and production processes together with the definition of the area where the grapes must be cultivated. For example, a PDO regulation may require that wines are exclusively produced from traditional vine cultivars of a region, or that they are aged for a certain amount of time in wooden barrels. To be labelled as a PDO product, a wine needs to be formally recognized by the European commission, which requires applicants to establish a direct link between the quality attributes of the product and its geographical origin (Marescotti et al., 2020). In this process, the producers need to elaborate a detailed documentation that specifies the production requirements of each wine product, i.e., the product specification, and summarize it in a stand-alone report, the so-called single document. Once a wine product is recognized and registered as a PDO, the product specification along with the single document can only be amended after presenting specific reasons why the changes are required (Ruiz et al., 2018). The documents produced during the application and all eventual amendments are published online in the official EU indication register eAmbrosia, that represents the legal repository of all the geographical indications for agri-food production, wine and spirits registered and protected in the EU (European Commission, 2019b; European Commission, 2013).

Because of the strong relation between PDO wines and the specific conditions and production practices defined during the application process, these products are highly vulnerable to any changes in the climatic, environmental, or economic conditions in the production area (Clark & Kerr, 2017; OIV, 2010). For example, warmer climate conditions are already affecting the growing suitability of several cultivars, posing significant challenges to many labelled wine products from PDO regions (Fraga et al., 2016, 2020; Hannah et al., 2013; Neethling et al., 2019; Tscholl et al., 2021). Moreover, the introduction of alien pest species from other wine growing areas is endangering the health of vines, requiring vineyard managers to use new agricultural practices for pest control (Caffarra et al., 2012; Daane et al., 2018; Santos et al., 2020). Economic and social preferences, on the other hand, are pushing for a more sustainable management of vineyards encouraging many European winegrowers to adopt new production practices, such as organic viticulture (Marín et al., 2021; Strub et al., 2020; OIV, 2021). All these factors are impacting wine PDO throughout Europe and are often in conflict with the regulations defined in the application documents. For instance, to maintain their quality standards, PDO areas may need to use new production practices that are different from those specified in the regulatory documents. For this reason, there is a need to thoroughly plan and develop specific adaptation strategies that consider the local conditions and legal regulations of single PDO (Clark & Kerr, 2017; Neethling et al., 2017). However, such strategies require knowledge about the legal specifications that characterize each PDO, which is currently only available in the regulatory documents of each wine PDO and not as a harmonized dataset.

Here, we present the first geospatial inventory of regulatory information for all 1177 PDO areas across Europe (as of 04.11.2021). We collected, standardized, and spatialized a set of regulatory information from the EU indications register eAmbrosia and aggregated it in a harmonized dataset. This information is intended to be a fundamental support to inform research and decision making in the field of viticulture. For instance, crop modellers can use the information to model possible scenarios of climate impacts and adaptation in wine PDO areas. Agronomists can suggest new wine growing strategies by comparing information about different PDO, and decision makers can plan possible actions to improve high quality grapevine production.

Methods

Extraction and standardization of the information from the legal documents was carried out during the period March 2021 – November 2021 using the EU geographical indication register eAmbrosia as a source (European Commission, 2022a). The last time we checked for any changes to the legal documents of the PDO regions was on 04.11.2021; PDO areas or amendments that were published after this date are therefore not included in the present dataset. We focused on all PDO recognized in the EU and the United Kingdom. The two main steps of the process were: (1) the spatialization of the wine PDO cultivation areas and (2) the selection and standardization of regulatory information for each PDO (Figure 10). Team members were fluent in Italian, French, German, Spanish, Portuguese, and English. The knowledge of these languages was helpful, because in most cases the regulatory documents are provided in the language of the country where the PDO is located and 80% of European wine PDO are located in Italy, France, Germany, Austria, Spain and Portugal. In case the team was not fluent in the language of a document, we had to use Regulation (EU) No 1308/2013 (European Commission, 2013) and the commission implementing regulation (EU) 2019/33(European Commission, 2019a) and 34 (European Commission, 2019b). These documents specify the rules for PDO regulation in the EU and the guidelines to write the application as PDO for wine products, respectively, and are translated in all the EU languages. We used them to find relevant keywords in the different EU languages that we were not fluent with and then used these keywords to find the relevant information in the regulatory documents. This was necessary for part or all of the PDOs located in Bulgaria, Belgium, Croatia, Cyprus, Czech Republic, Greece, Hungary, Romania, Slovakia and Slovenia. If any of the official documents were not available in the eAmbrosia register, we searched on dedicated websites for each country or contacted the related governmental institution to obtain the missing information.

STEP 1: spatialization of PDO cultivation areas

In the vast majority of legal documents, the PDO area was defined by including a list of municipalities where the cultivation of grapes for the PDO wines is allowed. For this reason, we georeferenced the wine PDO areas using the administrative boundaries at the municipal scale provided by the EuroRegionalMap dataset (© EuroGeographics, 2022) as the minimum mapping unit. For each PDO, we copied the municipality names from the legal document one-by-one, manually extracted the corresponding boundaries in the geographic dataset, merged all the single municipalities and finally exported the PDO boundary as a single shapefile. For countries where the EuroRegionalMap did not include information on the municipality boundaries, we used administrative boundaries from other repositories (UN OCHA, 2022; Geodata.gr, 2022). This was necessary for Bulgaria, Hungary, Slovenia, Romania, Denmark, United Kingdom and Greece.

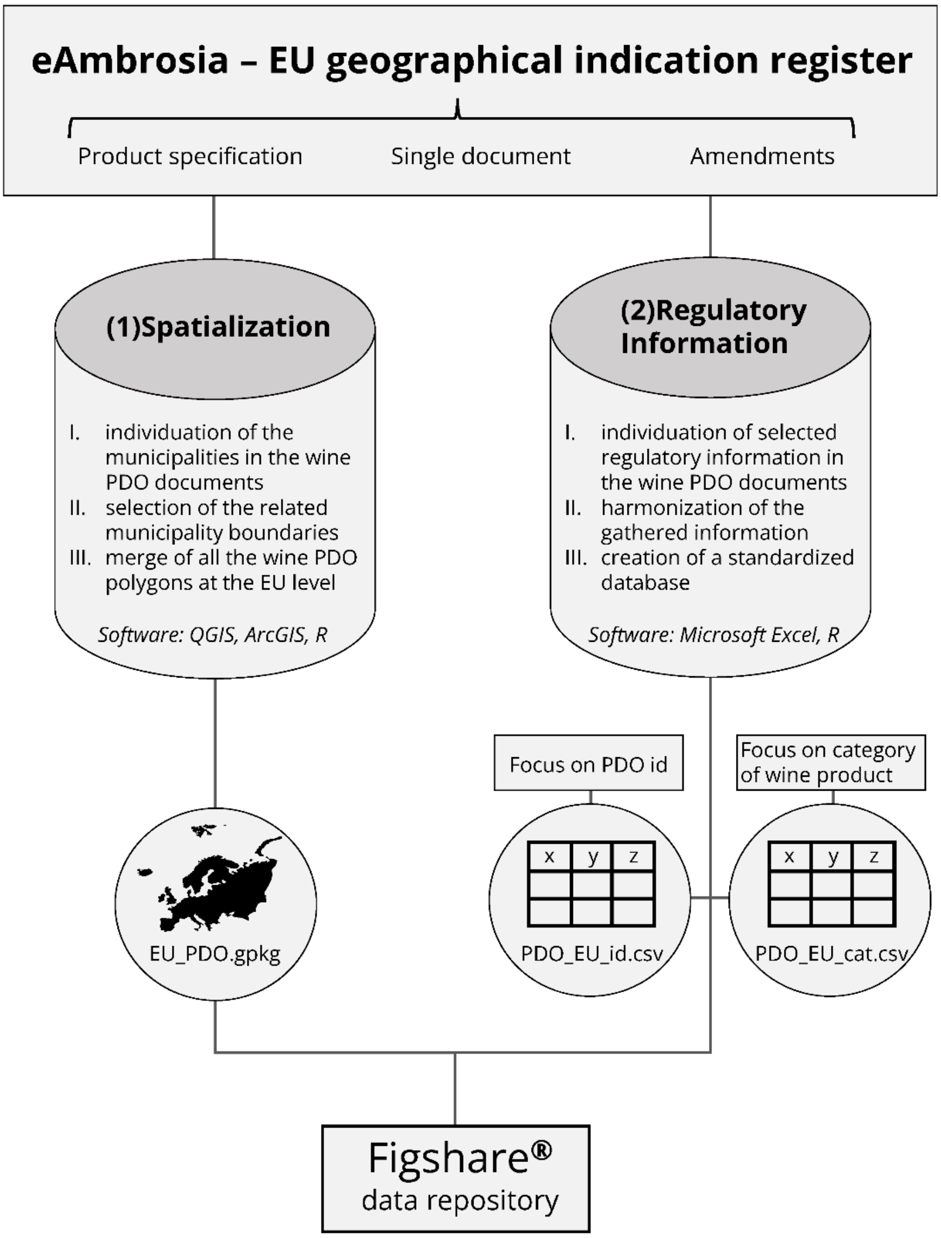

Figure 10. Conceptual diagram of the methodology and data formats used to build the inventory. (1) Spatialization: mapping of the municipalities included in the wine PDOs, creation of a .gpkg spatial dataset. (2) Regulatory information: extraction and harmonization of selected regulatory information, creation of two different .csv datasets one with a focus on the PDO level and the other with a focus on the categories of wine products in each PDO.

In some cases, the documentation provided a detailed outline of the boundaries of the PDO area but did not include any reference to the municipality, typically only indicating specific landscape features such as roads and rivers. In these cases, we manually selected the relevant municipalities using satellite images from various sources (e.g., Esri (ESRI, 2022), Google

Earth (Google, 2022)) as a reference. Once we obtained the municipal polygons that together constitute the total PDO cultivation area, we dissolved them first to have a single polygon per PDO and then merged each single PDO together to build a unified spatial dataset (Figure 11). The steps to spatialize the PDO areas were carried out using the QGIS (QGIS, 2022), ArcGIS (ArcGIS, 2022) and R (R, 2022) software.

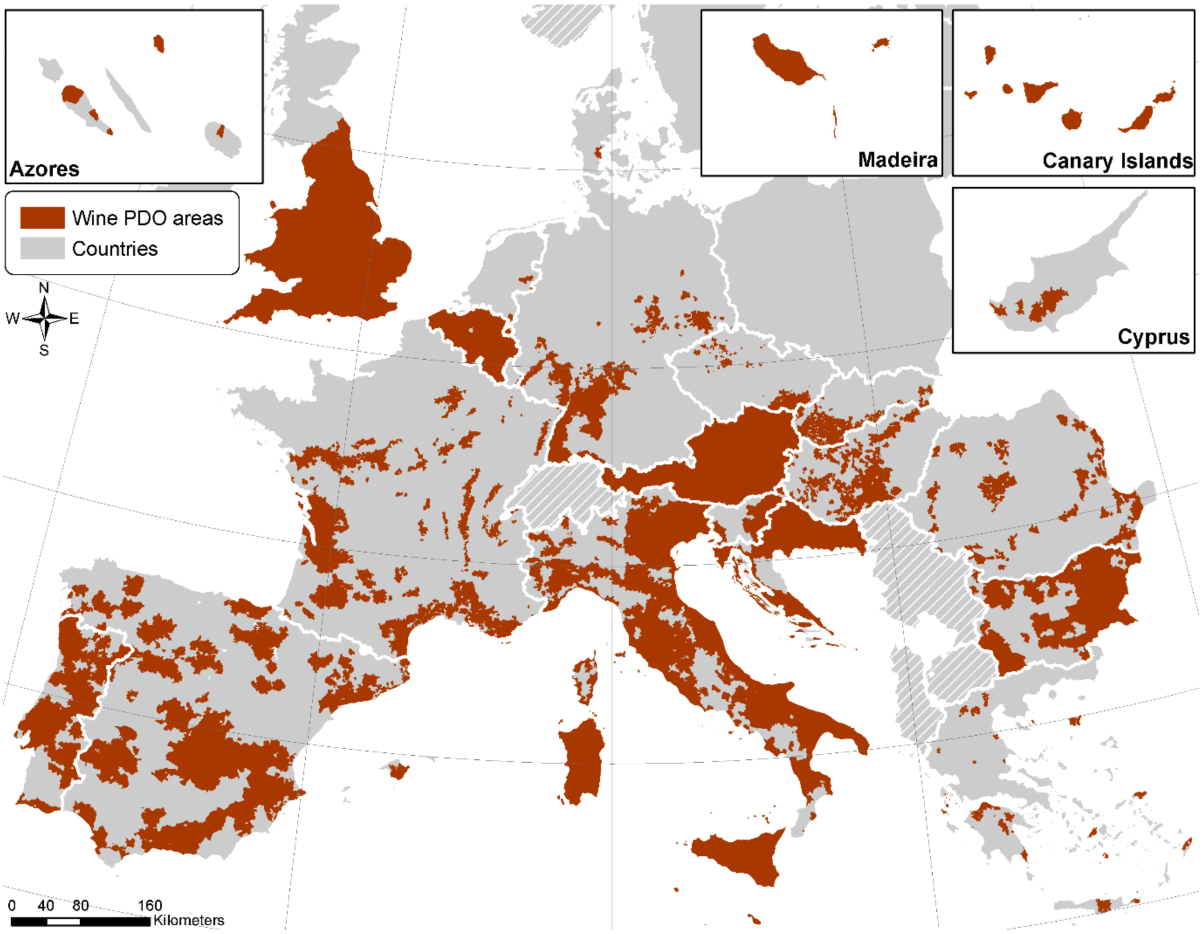

Figure 11. Overview of the area covered by the 1177 PDO included in the inventory. Non-European countries are represented by the striped pattern, we included United Kingdom as it was part of the EU until recently (© EuroGeographics for the country boundaries).

STEP 2: extraction of PDO regulatory information

In the second step, we extracted a set of regulatory information from the official documents in the eAmbrosia portal. The available information was heterogenous between the single EU countries, with some of them providing very detailed information while others provided only very little information. We collected only regulatory information that was available for all included countries and could be standardized among all PDO areas. Therefore, we had to exclude a set of information such as the training system, chemical composition of wines (e.g., sugars and acid contents), organoleptic profiles and alcoholic strength. For some PDO areas, mostly those located in Italy and France, we also found that more detailed regulations regarding planting densities or yields are available, that are specified depending on varieties, wine product or even topographic conditions (e.g., localization in steep slopes). We aggregated information from more detailed regulations to the same level of detail as in the other countries. The selected regulatory information that we extracted is presented in Table 4, including the methodology that was used for standardization. To extract the regulatory information from the legal documents and insert them into our dataset, we copied the relevant entries and pasted them in a dedicated spreadsheet table before proceeding with their standardization, using the Excel software (Microsoft Corporation, 2018).

Table 4. Regulatory information included in our inventory dataset. Each row corresponds to a unique field in the regulatory information dataset (the name of the field is indicated in brackets). The table includes the methodology used to standardize the information.

Regulatory information	**Method**
Country name (*Country*)	The ISO 3166-1 code of the country where the wine PDO is located.
PDO identifier (*PDOid*)	The official id of the wine PDO as defined in eAmbrosia.
PDO name (*PDOnam*)	The official name of the wine PDO as defined in eAmbrosia.
PDO registration date (*Registration*)	The date of registration of the wine PDO.
Category of wine product (*Category_of_wine_product*)	The wine product categories allowed in each PDO, following the definition of Regulation (EU) No 1308/2013.
Vine varieties (*Varieties_OIV*)	The list of the vine varieties allowed in the wine PDO, using the nomenclature adopted by the International Organization of Vine and Wine (OIV, 2013).
Vine varieties (*Varieties_Other*)	The list of vine varieties allowed in the wine PDO that are not included in the OIV list.
Yield (*Maximum_yield_hl*)	The maximum yield allowed in the PDO areas expressed in hl/ha.
Yield (*Maximum_yield_kg*)	The maximum yield allowed in the PDO areas expressed in kg/ha.
Planting density (*Minimum_planting_density*)	The minimum planting density allowed in a PDO, expressed in number of vine stocks/ha.

Irrigation (*Irrigation*)	The extent to which it is possible to use irrigation in the PDO. Possible values are: • "allowed", if irrigation is allowed. This includes the cases in which irrigation is: (i) allowed in all situations; (ii) allowed upon request to a specific regulatory organization; (iii) allowed only in emergency situations; • "prohibited", if irrigation is prohibited in any cases; • "na", if no information about irrigation is provided in the documents.
Presence of amendments (*Amendment*)	The presence or absence (Yes/No) of changes in the original application documents of the PDO. We considered an amendment only when a justification of the changes was provided.
General information on the PDO (*PDOinfo*)	The link to the eAmbrosia page that include the regulatory documents about a wine PDO.
Municipalities included in the PDO (*Municip_nam*)	The name of the municipalities included in the wine PDO.
Date of final check for changes in the legal documents of the PDO *(begin_lifes)*	The date when we last checked the eAmbrosia database for possible changes in the legal documents. In our case, this corresponds to 04.11.2021.

Once all the regulatory information for the European wine PDOs was gathered, we aggregated them either based on their PDO identifier (*PDOid* field) or based on the wine product information (*Category_of_wine_product* field). This was necessary because we wanted to provide both, a dataset that gives an overview of the wine PDOs in Europe and their main characteristics, and a dataset that is dedicated to wine products. Therefore, two distinct files were compiled:

I. A dataset containing 1177 entries, one for each PDO. It gives an overview of the main regulatory information, including the maximum yield, the minimum planting density and a list field with all the authorized vine varieties in a PDO. All the data regarding the remaining regulatory information are included in full detail.

II. A dataset containing 1983 entries, with a focus on the wine products of each PDO. It includes information about maximum yield and minimum planting density per category of wine product that is produced in each PDO. The authorized vine varieties for each category of wine product are specified in a list field. All the data regarding the remaining regulatory information are fully included.

Table 5 summarizes some of the information gathered in STEP 1 and STEP 2. Figure 12 represents a selection of key variables included in our inventory for different countries.

Table 5. Summary of some characteristics gathered in the geospatial inventory, aggregated at the country level. PDO (n°): total number of PDOs per country; Municipalities (n°): number of municipalities within PDO regions per country; PDO area (km²): area of the municipalities within PDO regions per country; Cultivated varieties (n°): number of varieties allowed for cultivation in the PDOs of a country; Wine products (n°): number of wine products that can be produced in the PDOs of the respective country; CLC vineyards included in PDO boundary [%]: the percentage of vineyards from the Corine Land Cover (EEA, 2022) that is included in the PDO area, the "–" symbol indicates countries for which no vineyard was present in the Corine Land Cover dataset. Percentages have been rounded.

Country	**PDO (n°)**	**Municipalities (n°)**	**PDO area (km^2)**	**Cultivated varieties (n°)**	**Wine products (n°)**	**CLC vineyards included in PDO boundary [%]**
Austria	24	2096	83930	40	2	100%
Belgium	7	570	31232	47	3	-
Bulgaria	52	156	69770	49	2	89%
Croatia	18	515	47816	154	5	100%
Cyprus	7	78	970	24	3	44%
Czech Republic	11	380	5840	69	11	100%
Denmark	1	1	605	8	1	-
France	361	4999	88496	163	7	91%
Germany	19	1473	37631	142	5	100%
United Kingdom	3	348	178271	83	2	-
Greece	33	502	8746	39	5	43%

Hungary	33	621	25748	84	5	98%
Italy	408	4923	209706	514	9	100%
Luxemburg	1	12	245	15	2	100%
Malta	2	68	313	31	4	-
Netherland	6	18	1499	25	8	-
Portugal	30	2101	55427	237	5	95%
Romania	40	339	25510	68	4	56%
Slovakia	8	702	12562	44	8	97%
Slovenia	14	123	10285	51	2	100%
Spain	99	2858	174734	167	10	98%

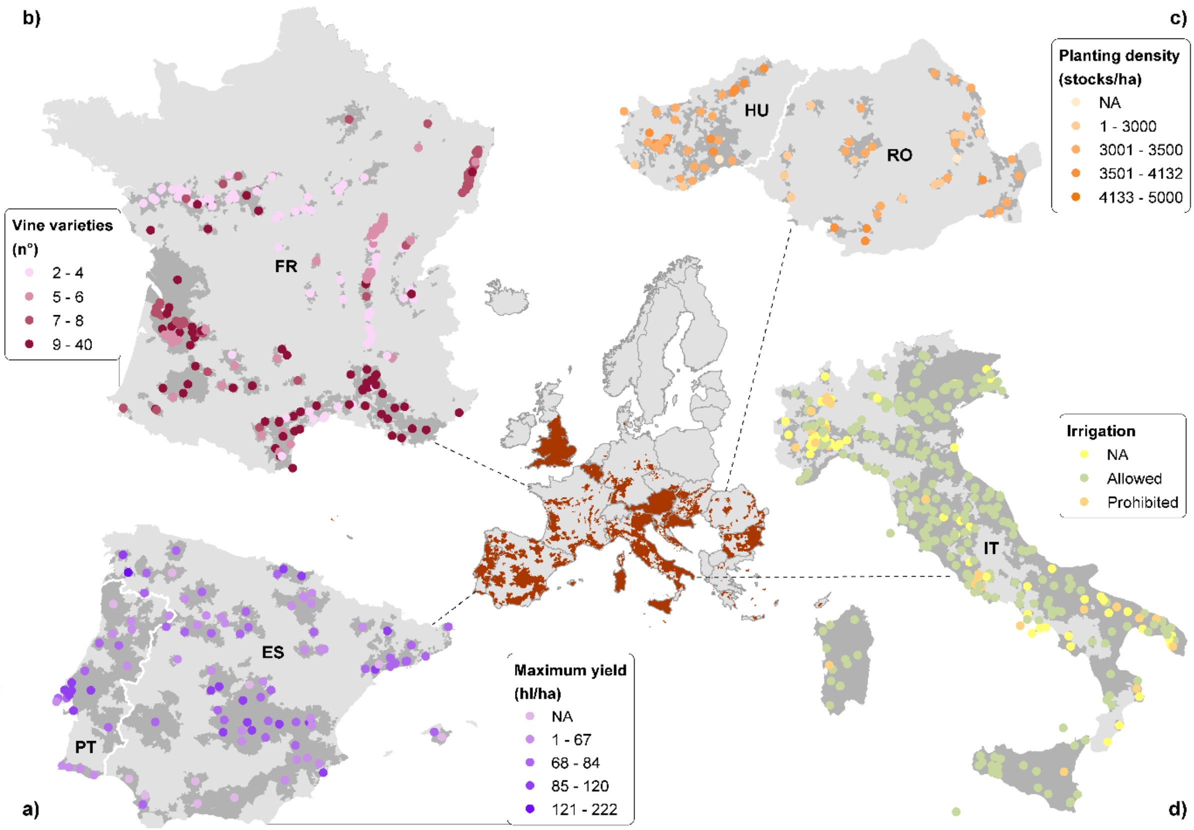

Figure 12. Selection of key variables included in our inventory for different countries. (a) Maximum allowed yield, (b) number of vine varieties per PDO, (c) minimum allowed planting density, (d) possibility to use irrigation. PDO areas are represented in red in the overview map

and in dark grey in the inset maps. The points in the maps represent the centroids of the PDO regions.

Data Records

We present an easily accessible and freely available inventory for the current wine PDO areas in the EU, comprising geospatial information as well as a set of regulatory information that can be used by researchers and decision makers. The data is freely available through the Figshare data publisher (Candiago et al., 2022).

It includes a geospatial file that contains the boundaries of the analysed PDO and two .csv files that contain the regulatory information aggregated either based on the PDO identifier or based on the category of wine product. The .csv files were saved using commas (“,”) to separate the columns, and a point (“.”) as decimal separator. Both .csv files are saved using utf-8 encoding. The files included in the inventory are:

1. EU_PDO.gpkg: a geopackage file that includes the boundaries for each of the 1177 PDO areas defined in the regulatory documents from eAmbrosia. The join between the spatial features and the other files is guaranteed by the common field *PDOid*.
2. PDO_EU_id.csv: a .csv file that includes the regulatory information outlined in Table 4 aggregated based on the PDO (*PDOid* field).
3. PDO_EU_cat.csv: a .csv file that includes the regulatory information outlined in Table 4 aggregated based on the category of wine product (*Category_of_wine_product* field).

Technical Validation

We spatialized and gathered the regulatory information about wine PDO in Europe based on the official geographical indication register eAmbrosia, that constitutes the legal basis for PDO designation in the EU. In many cases, more than 90% of all the vineyards identified by the Corine Land Cover (EEA, 2022) map are also included in the spatialized wine PDO areas (Table 5). For each PDO, we provide the reference to the official documents from which the data was created, allowing the user to cross check pieces of information with ease. Throughout the spatialization of the PDO and the collection of related regulatory information, spot checks were conducted at various stages of the progress to verify that mistakes had been kept to a minimum.

Usage Notes

Given the amount of information included in our inventory and its coverage, this dataset will be particularly useful for researchers and decision makers in the field of viticulture. For example, the knowledge of regulatory information, such as the planting density, yield, and vine variety, can be used by researchers to calibrate crop models and generate projections of phenology and water stress indicators in PDO areas (Fraga et al., 2016). The results of these models can be compared to the characteristics of the authorized vine cultivars planted in a PDO to develop adaptation solutions for climate change such as the inclusion of new vine cultivars or the authorization of irrigation in the regulatory documents (Santos et al., 2020). Analysing the contents of PDO documents and the related amendments can also improve our understanding of the critical factors that determine the sustainability and reputation of PDO regions. For example, Marescotti et al. (2020), studied the amendments of protected geographical indications in the fruit and vegetable sector and found that there is a strong need to introduce more environmental criteria in the regulatory documents, and Scozzafava et al. (2018), analysed how a change in PDO regulations can promote the premium products from a wine PDO region.

Code Availability

No custom code has been used during the generation and processing of this dataset.

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Chapter 3: climate resilience of European wine regions

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Climate resilience of European wine regions

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Abstract

Over centuries, European vintners have developed profound knowledge about grapes, environment, and techniques that yields the most distinguishable wines. In many regions, this knowledge is reflected in the system of wine geographical indications (GI), but climate change is challenging this historical union. Here, we present the first climate change vulnerability assessment of 1174 wine GIs across Europe and propose climate-resilient development pathways using an ensemble of biophysical and socioeconomic indicators. Results indicate that wine regions in Southern Europe are among the most vulnerable, with high levels also found in Eastern Europe. Vulnerability is driven by the rigidity of the GI system, which restricts the exploitation of suitable bioclimatic conditions and existing grape cultivar diversity, as well as contextual deficiencies, such as limited socioeconomic resources. Building a climate-resilient wine sector will require rethinking the GI system by allowing innovation to compensate for the negative effects of climate change.

Main

The concept of geographical indication (GI) plays an essential role in defining a wine's identity and establishing a strong link between the product's unique characteristics and its provenance (Josling, 2006). Indeed, many of the world's most famous wines are known for their origin and not for their grape variety (White et al., 2009). The system of classifying and regulating wines based on their origin is commonly referred to as *Geographical Indication* or *appellation* (OIV, 2022) and the strictest rules can be found in Europe, where premium GI wines are labelled as *Protected Designation of Origin (PDO)* (European Commission, 2022a). These wines can only be produced in legally defined areas that have been selected based on soil type, climate, and historical or administrative divisions. The presence of both human and natural dimensions in defining wine regulations is related to the historic concept of *Terroir*: an originally French notion that states that the place (both the land and the people) define the product (Leeuwen & Seguin, 2006).

Climate change is increasingly impacting several aspects of viticulture, including vine phenology (Costa et al., 2019; Fraga et al., 2016a; Parker et al., 2020), grape composition (Drappier et al., 2017; Jones & Davis, 2000; Leeuwen & Darriet, 2016a) and growing suitability (Fraga et al., 2013; Fraga et al., 2016a; Hannah et al., 2013). These bio-physical changes require growers and producers to adapt by employing new cultivation techniques, using new varieties, or shifting cultivation locations (Fraga et al., 2018; Leeuwen et al., 2019; Santos et al., 2020; Tscholl et al., 2021). However, the legal rigidity of the GI system significantly impairs the ability of many wine regions to adapt and to preserve traditional wine production in the context of climate change, i.e., GI resilience. For example, Burgundy and Champagne are known for wines made from *Pinot Noir*. If these regions become unable to grow typical *Pinot Noir* grapes at some point, they are under serious threat. A substitute grape candidate would neither qualify for the label, nor would the law permit growers to source grapes from outside the region or introduce new cultivation techniques (European Commission, 2011a, 2011b) without going through a tedious process of amending the wine region's regulations (European Commission, 2019). In many wine regions, increasing resilience will therefore depend upon adaptation strategies that overcome traditional and legislated practices by including more flexibility to better support the sustainable development of wine making in uncertain climates.

Assessing the vulnerability of wine GIs to climate change facilitates the understanding of which regions are threatened the most by climate change and supports the development of potential adaptation pathways to strengthen their resilience. The vulnerability depends on the individual characteristics of each wine region, including the degree of climate exposure and sensitivity and the availability of socioeconomic, natural, and physical resources, which strongly determine how wine appellations can adapt to climate change (IPCC, 2001). The importance of exposure and sensitivity has already been extensively investigated, for instance by relating changes in air temperature or precipitation to relevant vine parameters (Ausseil et al., 2021; Fraga et al., 2016b; Fraga et al., 2013, 2018; Hannah et al., 2013), or analysing how grapevine diversity and variety turnover influence future land suitability (Fraga et al., 2016a; Koufos et al., 2020; Morales-Castilla et al., 2020). However, assessments that consider the adaptive capacity and vulnerability levels of wine appellations have been sparse and thus far, limited to single wine regions (Belliveau et al., 2006; Lereboullet, Bardsley, et al., 2013; Merloni et al., 2018; Nicholas & Durham, 2012; Pickering et al., 2015). The consideration of these characteristics is especially critical for regions that face strong impacts of climate change and need to amend their legal specifications to continue producing GI wines, which requires extensive access to resources and knowledge and may thus not be feasible for appellations with a limited adaptive capacity (Mosedale et al., 2016; Nicholas & Durham, 2012). The future of the GI system under climate change is therefore still poorly understood and our knowledge of how adaptive capacity and climate change vulnerability are related to the resilience of wine GIs is very limited.

In this study, we assessed the climate change vulnerability of 1174 wine regions in Europe by explicitly considering their biophysical and socioeconomic characteristics and their regulatory specifications. We used a novel dataset on European wine appellations (Candiago et al., 2022) coupled with an index-based approach including an ensemble of financial, natural, physical, and social indicators. To assess the climate change vulnerability, we adapted the framework developed by the Intergovernmental Panel on Climate Change (IPCC) in which vulnerability is assessed as a function of exposure, sensitivity, and adaptive capacity. We defined (i) exposure as the expected changes in climatic conditions, including temperature and precipitation, (ii) sensitivity as the degree to which a system is affected by climate related stimuli, based on the biogeographical niche of each wine region, and (iii) adaptive capacity as how well a wine region can adapt to changing climate conditions, considering five distinct dimensions (financial, natural, physical, social, and human) (see Methods). We used a comparative analysis that provides a basis for adaptation planning at different spatial scales, from the European to the national and regional scales, and allowed us to identify potential future pathways related to the climate resilience of the GI system. As such, the results will be valuable to international entities as well as regional decision-makers and represent a first step in evaluating the consequences of climate change for designated appellations across Europe. The results will also be particularly useful to identify priority areas with urgent needs for adaptation and further in-depth studies.

Exposure and sensitivity to climate change

Climate variability has always affected winemaking, but the current rate of climate change is unprecedented, challenging the historical union between favourable site conditions, optimum grape varieties and traditional viticultural practices. We defined exposure as the degree to which climate is projected to change in wine regions. The highest levels of exposure were observed in Slovenia, followed by Croatia, Italy, Greece, and Spain with 29%, 27%, 6%, 6% and 3% of wine regions with an exposure level in the upper percentile, respectively (Figure 13a). Many of these regions are located in mountain terrain, especially in the Apennines, Alps and Carpathian Mountains. In contrast, exposure levels were lower in Portugal and France, where less than 5% of the wine regions had an exposure level over 0.85. Low levels of exposure were also found in Germany, Belgium, and the Netherlands with an average exposure level below 0.3. While there is a trend towards increased temperatures in most regions, precipitation trends are mixed with a tendency towards less precipitation (Figure 13c). The observed trends are consistent with other studies that use the CMIP-6 scenarios (Carvalho et al., 2021; IPCC, 2021). Our results are also in-line with studies analysing climate change impacts on European viticulture, many of which observed high levels of impacts in areas that correspond to high-exposure regions in our study. For instance, strong yield decreases were projected for northern Italy, central Spain, Greece, and Bulgaria (Fraga et al., 2016a) and decreased suitability for Spain, parts of France, central and northern Italy, and large parts of eastern Europe (Hannah et al., 2013).

Climate change is also altering the traditional identity of GIs by moving wine regions either closer to their climate optimum or pushing them further away. As such, the sensitivity level describes the degree to which a system is affected by climate related stimuli based on the climate niche of currently cultivated varieties. We found that regions in southern Europe often tended to have higher sensitivity levels either due to a limited grape variety spectrum or due to warm climatic conditions close to the upper limit of their niche (Figure 13b). However, we also found regions with low sensitivity levels in Southern Europe, e.g., Do Tejo (PT), and regions with increased sensitivity at higher latitudes, e.g., Champagne (FR). Higher sensitivity was often observed in specialized wine regions where only few varieties adapted to local climate conditions are cultivated, while regions with a wider range of varieties tended to have lower sensitivity levels (Figure 13d). Although we calculated the sensitivity based on a detailed database of authorized varieties for each GI, more information about local vine cultivars, especially their climate niche and phenological development, would improve assessments of changes in growing suitability and climate change sensitivity. However, such detailed knowledge is mostly limited to international varieties, which only include approximately 1% of global vine diversity, reducing our capacity to estimate future impacts of climate change in GIs (Morales-Castilla et al., 2020). If climate change is to proceed at the current rate, the GIs as we know them now will necessarily change because the best location for a given variety today might be the best location for a different variety in the future (Wolkovich et al., 2018). The diversity of cultivated varieties will therefore be a critical factor determining the magnitude of future impacts (Morales-Castilla et al., 2020). Specifically, regions with a high sensitivity should work towards increasing the diversity of cultivated varieties to reduce their vulnerability to climate change.

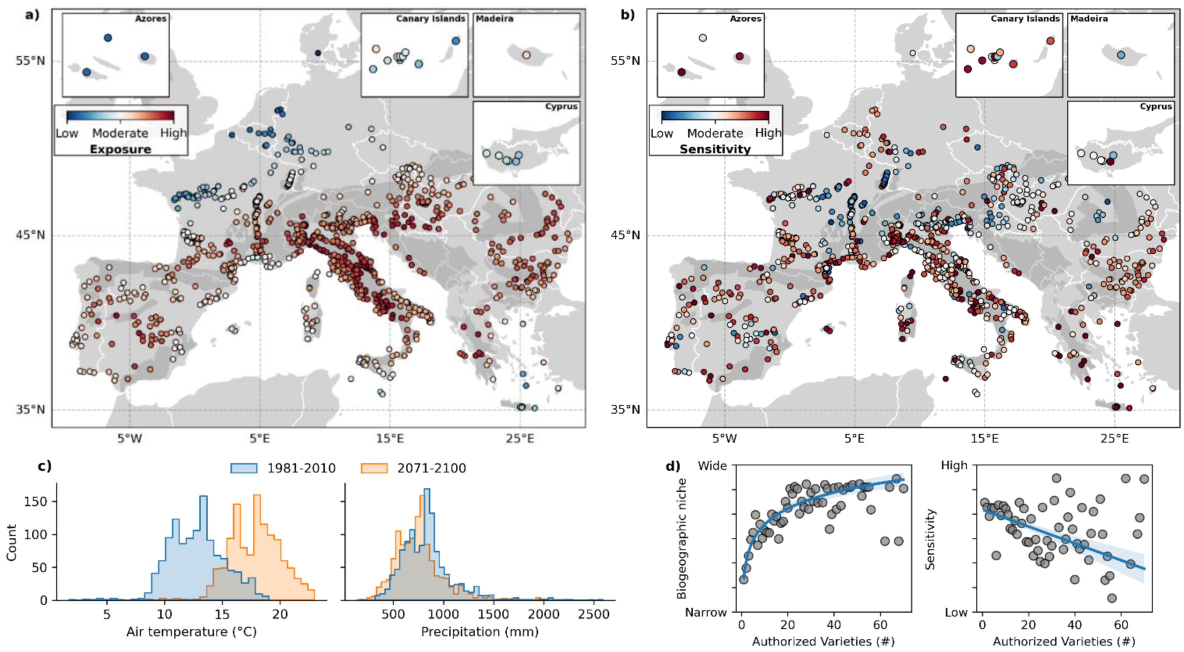

Figure 13. Exposure and sensitivity to climate change of European wine GIs. a,b) Map of climate change exposure and sensitivity of the European wine appellations. The regions are indicated by their centroid. Dark grey areas refer to mountain regions. c) Histogram showing the distribution of annual average air temperature and precipitation for the periods 1981-2010 and 1971-2100 under the ssp585 scenario of all wine regions. d) The biogeographical niche

and sensitivity of European wine GIs related to the number of primary varieties. The blue line shows a logarithmic model between the two variables for the biogeographic niche and a linear model for the sensitivity. Points for each x-value have been summarized using the mean function to reduce the number of points in the plot.

Adaptive capacity to climate change

To adapt and cope with climate change and compensate for high exposure or sensitivity levels, GI regions need access to resources which enable and facilitate the execution of adaptation strategies. We therefore considered 15 indicators of adaptive capacity (Table 6) to analyse the potential of wine regions to adjust to climate change, i.e., their adaptive capacity.

Table 6. Indicators of adaptive capacity.

Dimension	Indicator	Description
Social	Aging index	Ratio between old and young population
	Dependency ratio	Ratio between dependent and working population
	Population density	Population density per agricultural area
Physical	Road length	Total length of roads potentially usable for viticulture
	Mechanization Index	Value of machinery & equipment of wine farms
	Naturalness	Share of natural and semi-natural areas in winegrowing areas
Natural	Shift in Space	Available areas with cooler climatic conditions suitable for viticulture
	Water availability	Excess precipitation available in winegrowing areas
	Temperature variability	Variability of mean temperature
Human	Labour force	Ratio between regular and total farm labour force
	Education Level	Education level of farm managers
	Research accessibility	Proximity to closest research centre on wine and vine
Financial	Debt ratio	Liability percentage of total assets of wine farms
	Return on assets	Profitability in relation to total assets of wine farms
	Subsidy dependence	Net income percentage coming from subsidies of wine farms

Some European wine regions with the highest adaptive capacity were found within or near the European Alps and along the Apennines (i.e., on the west coast of the Italian peninsula) (Figure 14a), for example, Conegliano Valdobbiadene Prosecco (IT) and Alto Adige (IT) (Figure 14c). Slovenia and Italy were the countries with the highest share of regions with an adaptive capacity level in the upper quartile (65% and 14%, respectively), followed by France with less than 10%. In contrast, regions in central Spain and eastern Europe such as Slovakia, Greece, Romania, Bulgaria, and Hungary, had low adaptive capacity levels with average values below 0.3. The regions in Spain tended to have a high financial capacity; however, they had low scores for all the other dimensions, especially the physical and natural capacity, resulting in a low overall adaptive capacity (e.g., La Mancha (Figure 14c)). Winegrowing regions at higher latitudes, including some regions in France, Germany, Denmark, Belgium, or the Netherlands, mostly had moderate adaptive capacity levels around 0.5 (e.g., Rheinhessen (DE) and Alsace (FR) (Figure 14c)). These differences in adaptive capacity across wine GIs in Europe strongly determine how individual regions can adapt to climate change (Mosedale et al., 2016).

However, despite the growing evidence that the adaptive capacity plays a central role for future climate change impacts (Lereboullet, Beltrando, et al., 2013; Moore & Lobell, 2014), regional viticulture-specific data are not available on a European scale for many dimensions of adaptive capacity. The focus of previous studies on climate change adaptation in viticulture and agriculture in general was primarily on bioclimatic pressures, while the social part has often been neglected (Davidson, 2016). Future climate change adaptation and our understanding of the climate change vulnerability of wine regions could therefore benefit extensively if studies accounted for differences in adaptive capacity, especially regarding their socioeconomic characteristics (Barnes et al., 2020).

Pathways to climate-resilient wine growing

The development of a climate-resilient wine sector requires the consideration of all factors that determine vulnerability to climate change, i.e., exposure, sensitivity, and adaptive capacity (Figure 15). This will be important to identify sound adaptation options and increase the resilience of the GI system. Based on a cluster analysis of the characteristics of individual wine regions, three possible pathways for dealing with climate change emerged.

The first development pathway concerns highly vulnerable wine regions that are likely to face strong changes within the next few decades (cluster 6 (Figure 15b)). If these regions are to continue the production of GI wines, they will need to act fast and employ adaptation measures that go beyond vineyard management strategies and include grape diversification (i.e., new varieties) or site relocation (i.e., new climates) (Santos et al., 2020). The most prominent examples of this group of regions can be found in the Iberian Peninsula (e.g., Douro (PT), Rioja (ES)), southern France (e.g., Côtes de Provence), Greece (e.g., Samos) and Bulgaria (e.g., Southern Black Sea coast). Previous studies already highlighted significant changes in growing suitability due to climate change expected in many of these regions (Blanco-Ward et al., 2019; Fraga et al., 2016b; Fraga et al., 2013; Hannah et al., 2013b). Because the scope of the required adaptation measures often entails a partial or complete departure from traditional appellation regulations, early warning and awareness is critical to successful implementation and to providing the necessary support to prepare eventual amendments to production regulations.

The second pathway represents regions with a moderate vulnerability level which are better prepared to face the adverse effects of climate change compared to regions in cluster 6 and belong to cluster 4 and 5. Some of these regions were located in southeast France (e.g., Roussette de Savoie), northern Italy (e.g., Conegliano Valdobbiadene Prosecco), Slovakia (e.g., East Slovak), the Iberian Peninsula (e.g., La Mancha (ES)), Romania (e.g., Cotnari), Bulgaria (e.g., Varna) and in the Apennines. These regions are faced with high exposure and moderate to high sensitivity levels and feasible adaptation strategies will strongly depend on their adaptive capacity. For instance, strategies such as shifting vineyards to higher elevations or exploiting favourable microclimatic niches can be a very effective measure in mountain viticultural areas but may not be geographically possible in other regions (Egarter Vigl et al., 2018). Likewise, expanding the possibility for irrigation can be a promising option, but the high economic burden, intensive labour cost, water, and mechanization requirements, and legal constraints make this option feasible only for a limited number of regions with sufficient socio-economic resources (Fraga et al., 2018). Many regions with a low adaptive capacity, which is especially the case in cluster 5, will therefore likely require resources and external investments to increase their potential for adaptation.

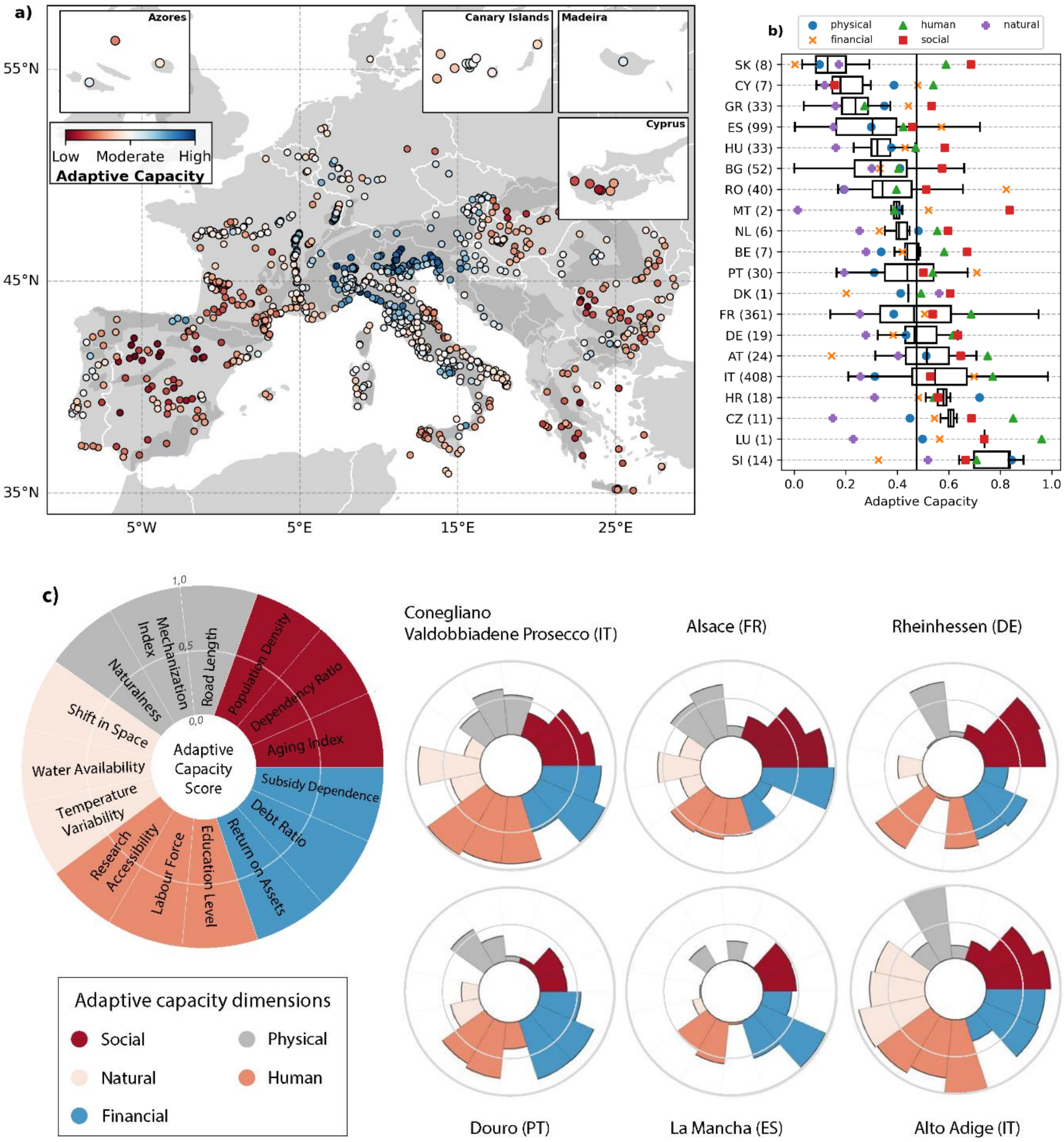

Figure 14. Adaptive capacity of the European wine GIs. a) Map showing the adaptive capacity of European wine GIs. The points refer to the centroids of the regions. Dark grey areas refer to mountain regions. b) The boxplots show the distribution of the adaptive capacity including all wine regions per country. The symbols refer to the average values for the single dimensions of adaptive capacity per country. The vertical line indicates the average adaptive capacity in Europe and the number in brackets indicates the total number of wine regions per country. c)

Petal diagram showing the five dimensions (colours) of adaptive capacity and the related indicators for six selected appellations.

The third pathway describes a scenario for regions with the lowest vulnerability levels representing clusters 1, 2 and 3. These regions generally have moderate to high adaptive capacity levels combined with either low sensitivity or low exposure levels. This gives them the best prospects of maintaining their historic identity and high production standards in the medium to long term. These clusters include some regions at higher latitudes (e.g., Rheinhessen (DE) and Crémant de Wallonie (BE)), in France (e.g., Côtes d'Auvergne, Bordeaux, and Alsace), Czechia (e.g., Moravia), or the European Alps (e.g., Alto Adige (IT)). Because many of these regions have extensive access to resources, including natural, physical, or economic assets as well as necessary knowledge and the appropriate labour force, they have the greatest possibility of implementing and elaborating costly adaptation strategies that would not be feasible in other regions. Although some of these regions are faced with significant changes in climate or have a high sensitivity, their high adaptive capacity makes them less vulnerable to such adverse effects. For instance, in the case of high exposure levels, adjustment of viticultural processes, such as canopy management or pruning techniques, could facilitate adaptation (Leeuwen et al., 2019). In the case of high sensitivity levels, innovation regarding new varieties and blend compositions or ratios could be promising options (Morales-Castilla et al., 2020; Wolkovich et al., 2018). Gradually introducing new varieties and adjusting wine blends might provide an opportunity for these regions to slowly prepare consumers and alleviate concerns about consumer expectations, as is currently occurring for example in the region of Bordeaux (European Commission, 2021).

Conclusion

Many wine regions as we know them today will change. A climate-resilient GI system depends on the adaptive measures that each region can take. If traditional wine production is to survive, many regions urgently need technological and infrastructural advancements as well as the active deployment of human and social resources to compensate for or relax restrictions regarding cultivation sites, grape varieties, and winemaking practices. Our results provide the first overview of the vulnerability levels of traditional wine products in Europe combined with adaptation pathways that provide critical information to build a more climate-resilient GI system. A rigid system for wine production based on single grape varieties or wine styles, fixed management practices, and tight geographical boundaries will likely become obsolete in the next few decades due to the growing impacts of climate change. The GI system must therefore become more flexible while still preserving the connection between terroir and consumers.

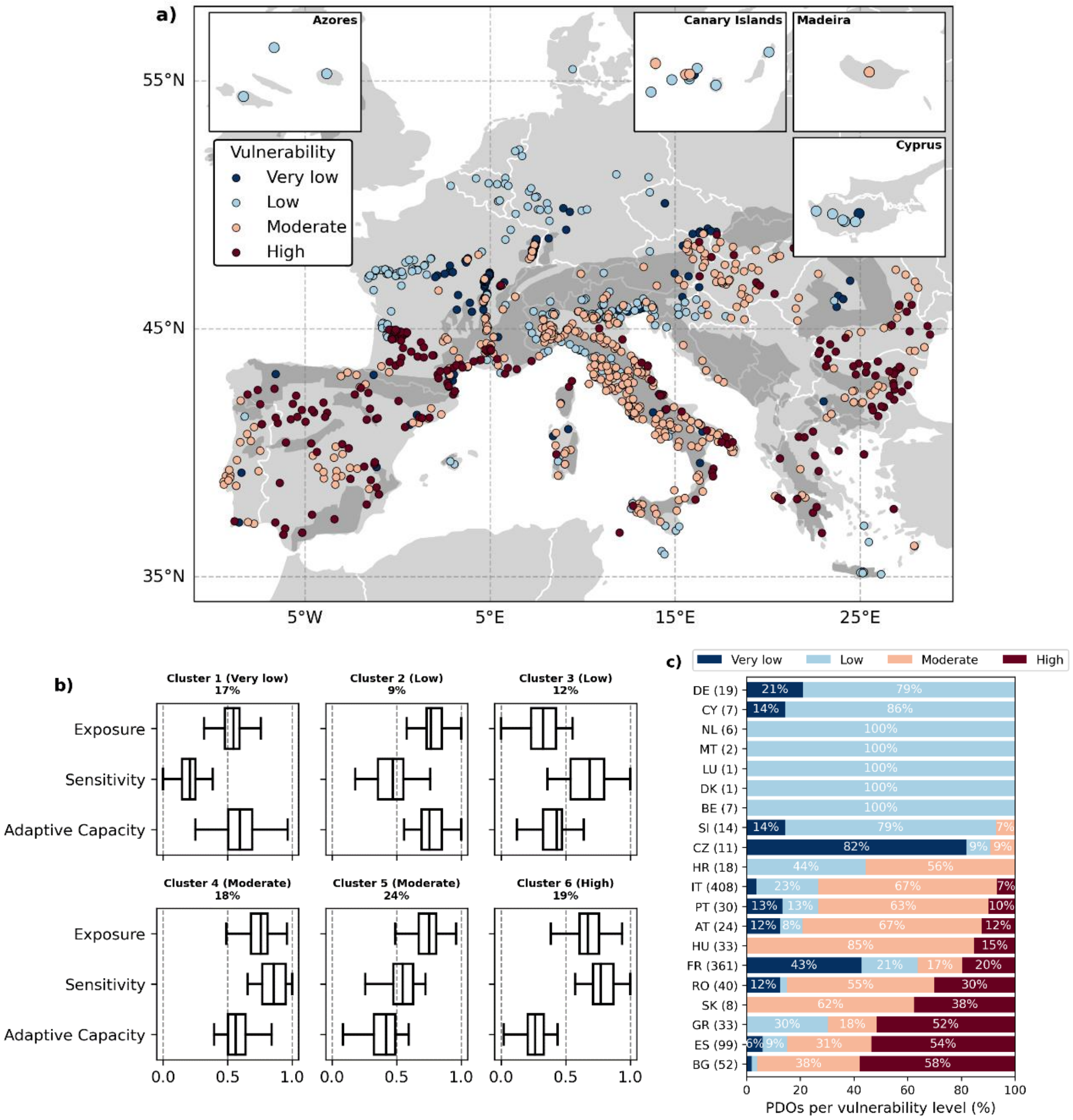

Figure 15. Vulnerability to climate change of European GI regions. a) Climate change vulnerability of the wine GIs in Europe. The regions are represented based on their centroids. Dark grey areas refer to mountain regions. b) Clusters of vulnerability. Each boxplot shows the distribution of exposure, sensitivity and adaptive capacity among the wine regions included in the same cluster. c) Percentage of wine regions per country based on their vulnerability level. The number in brackets next to the country label shows the total number of wine regions for each country. Labels on the bars are only displayed for bars greater than 5%.

Methods

Wine geographical indications

We assessed the vulnerability to climate change of 1174 wine GIs (also referred to as *appellations*) in the European Union. All 1174 regions are recognized with a protected designation of origin (PDO). We focused on these regions because the wine products labelled PDO have the strongest link to the production area, i.e., the entire production, processing and preparation process must take place in a specific region (European Commission, 2021). Additionally, the regulatory scope also covers viticultural and oenological practices, including yield regulations, pruning techniques or irrigation, as well as authorized varieties and blend ratios. The majority of the considered GIs were located either in Italy (35%) or in France (31%), followed by Spain (8%), Bulgaria (4%), Romania (3%), Hungary (3%) and Portugal (3%). The boundaries of the selected regions were taken from Candiago et al. (Candiago et al., 2022) and are shown in Figure 20.

General Framework

Grapevines are perennial crops that last for many decades. Successful adaptation strategies therefore require long preparation, extensive planning, and careful implementation, as their effects will be apparent for several years. The current capacity for adaptation is therefore a critical factor determining whether a wine region can adapt in time to future impacts of climate change. To combine the current capacity for adaptation with projected climate scenarios, we adapted the vulnerability framework developed by the Intergovernmental Panel on Climate Change (IPCC, 2007). Vulnerability was assessed through exposure, sensitivity, and adaptive capacity (Figure 21). Exposure and sensitivity refer to the expected impacts of climate change on the human and natural systems of a region. Adaptive capacity refers to how a region can adapt to changing climatic conditions and includes biophysical as well as socioeconomic aspects. We calculated exposure, sensitivity and adaptive capacity using an index-based approach that has been widely applied in the current literature on climate change (Parker et al., 2019; Reimann et al., 2018) and developed our indicators based on publicly available statistical and geospatial data. The resulting vulnerability describes the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, also taking into account available resources for adaptation (IPCC, 2007). The vulnerability level of a wine region is directly related to its resilience, as highly vulnerable regions will be less capable to preserve the production of high-quality wine products. By using a clustering approach, we identified potential future pathways to strengthen the climate resilience of wine regions throughout Europe.

Exposure

Exposure measures the degree of climate change in a region. We assessed the exposure of wine GIs by calculating the change in annual mean temperature and precipitation between the present (1981-2010) and future (2071-2100) reference periods. We focused on these two variables because they play a central role in the phenological development of vines as well as ripening and grape composition (Ramos & Toda, 2022). To estimate future climatic conditions, we used the ensemble mean of 5 global climate models under the ssp585 scenario ('GFDL-

ESM4' 'IPSL-CM6A-LR', 'MPI-ESM1-2-HR', 'MRI-ESM2-0' and 'UKESM1-0-LL'). The models were retrieved from the CHELSA dataset with a 1 km horizontal resolution (Karger et al., 2017, 2018). This very high resolution was achieved through a statistical downscaling approach, which has been shown to be very accurate compared to observational temperature and precipitation data (Karger et al., 2017). We focused on the ssp585 scenario to consider the worst-case scenario in a future climatic pathway (O`Neill et al., 2016). Moreover, because we used an index-based approach which is based on relative differences between the considered wine regions, there were no significant differences in the results between the ssp585 and other scenarios. We also used an ensemble of models to reduce the uncertainty inherent to future climatic projections (O`Neill et al., 2016). To calculate the exposure for each GI, the change in temperature and precipitation was first calculated for each grid cell. Any change in temperature or precipitation was considered to have negative effects because these changes alter the specific biophysical conditions that are needed to produce a certain GI wine, and which are described in detail in the related regulations. Next, all grid cells within an appellation were averaged to obtain a representative value, which was then scaled from 0 to 1 using linear min-max normalization.0 represents GIs with the smallest changes in climatic conditions and 1 GIs with the greatest changes. Finally, exposure levels were calculated by averaging the scaled values for temperature and precipitation changes for each GI.

Sensitivity

The sensitivity describes the degree to which a system is affected by climate-related stimuli and is based on the biogeographical niche of each GI. Since traditional wine products can only be produced by certain vine varieties under specific climatic conditions, appellations that fall outside their niche are increasingly likely to face altered vine performance and consequently different product characteristics and wine styles (Leeuwen & Darriet, 2016). We calculated the sensitivity of each appellation in two steps:

1. *Definition of the biogeographical niche*: we estimated the biogeographical niche of each GI by linking their primary varieties to the climatic conditions under which they are cultivated. Primary varieties are the traditional vine cultivars of a region that are primarily used for making the wine products of a GI. In most cases, they were clearly defined in the product specification, however, if there was no specification of primary and additional varieties, we considered all the authorized varieties as primary varieties (European Commission, 2022b). To define the biogeographical niche of each GI, we first classified them into 17 groups based on the Huglin Index (HI), the Cool Night Index (CNI) and the Dryness Index (DI) during the period 1981-2010, applying the categorization developed by Fraga *et al.* (Fraga et al., 2016b). These three bioclimatic indices are widely known to be strongly tied to grape berry quality attributes and yields (Tonietto & Carbonneau, 2004). Indicators were calculated at 1 km grid resolution using monthly climate data from the CHELSA database (Karger et al., 2017, 2018) and then averaged over all grid cells within each appellation. This categorization allowed us to identify GIs with similar growing conditions. Next, we characterized the climate requirements of each primary variety separately for each of the 17 groups by linking

the bioclimatic indices of all the appellations within a group that grew a specific variety to that variety. We then identified the biogeographical niche of a GI by combining the climatic ranges of all its main varieties.

2. *Calculation of the sensitivity*: we calculated the sensitivity based on the difference between current climatic conditions within a GI and the upper limit of the biogeographical niche. We assumed that once climatic conditions within an appellation move outside its biogeographic niche, the region is increasingly likely to be faced by significant changes in grape composition and wine characteristics. The appellations where current climatic conditions were near the upper limit of their niche therefore had a higher sensitivity, as a relatively small change in climatic conditions may affect their capacity to produce traditional wines. In contrast, regions where current climatic conditions were further away from the upper limit of their niche had a lower sensitivity. We scaled the sensitivity levels from 0 to 1 using linear min-max normalization, with 0 representing GIs with the lowest sensitivity and 1 representing those with the highest sensitivity.

Adaptive capacity

To assess the adaptive capacity of the GIs, we calculated 15 indicators related to their individual characteristics. These characteristics were related to 5 dimensions of adaptive capacity to which each region can have access (Ellis, 2000; Williges et al., 2017): the financial dimension, such as dependence on subsidies; the natural dimension, such as the climatic diversity within a region; the physical dimension, such as the availability of road infrastructure; and the social and human dimensions, such as the aging index and the level of education of farm managers. We collected and harmonized three indicators per dimension that are all related to adaptive capacity in the context of viticulture. For the full list of considered indicators, their source and calculation method, please refer to Table 15 and Supplementary Methods 1. To calculate the adaptive capacity of each appellation, all the considered indicators were first scaled to a range between 0 and 1 using the 5th and 95th percentiles as lower and upper thresholds to reduce the influence of outliers (Chen et al., 2015). The adaptive capacity was then calculated by averaging the scores of the indicators and then scaled again to range between 0 and 1 using linear min-max normalization, with 0 representing appellations with the lowest adaptive capacity and 1 representing those with the highest adaptive capacity:

$$AC_i = \frac{X - Q_5}{Q_{95} - Q_5} \quad (1)$$

$$AC = \frac{1}{n}\sum_{i-1}^{n} AC_i \quad (2)$$

where AC_i represents the adaptive capacity score of indicator i, X is the indicator value for a particular GI, Q_5 and Q_{95} are the 5th and 95th quantiles, respectively, and AC is the final adaptive capacity indicator.

Vulnerability to climate change

We analysed the vulnerability of each GI using k-means clustering based on exposure, sensitivity, and adaptive capacity. A similar approach was used in several previous studies (Calil et al., 2017; Izaguirre et al., 2021) and it allowed us to group the winegrowing regions into 6 different clusters, each of them consisting of regions with comparable characteristics. The optimum number of clusters was selected using a sensitivity analysis to assess how the resulting clusters changed under different numbers of groups (Supplementary Methods 2). To assign each cluster to a vulnerability level, we considered the centroid values for the three dimensions exposure, sensitivity, and adaptive capacity for each cluster and transformed them into a scale ranging from very low to very high vulnerability (Table 14). First, we aggregated the centroid values for the three dimensions which yielded an indicator describing the severity of the vulnerability of the corresponding cluster, i.e., the vulnerability index (VI). Because exposure and sensitivity are positively correlated with increased vulnerability while for adaptive capacity higher values indicate a lower vulnerability, we calculated the VI as follows:

$$VI = Exposure + Sensitivity - AC \quad (3)$$

Next, we classified the VI into five vulnerability levels corresponding to very low, low, moderate, high, and very high vulnerability. The maximum possible value for the VI was divided into five equal ranges within which the VI was then classified. The maximum possible value for the VI was 2 (exposure and sensitivity were both 1, and adaptive capacity was 0), and the vulnerability levels were therefore assigned as follows: 0-0.4 = very low, 0.4-0.8 = low, 0.8-1.2 = moderate, 1.2-1.6 = high, and 1.6-2.0 = very high. The advantage of the clustering approach is that it provides detailed information on the different combinations of exposure, sensitivity, and adaptive capacity among the GIs and how they relate to the resulting climate change vulnerability. Additionally, the clustering approach allowed us to characterize and compare distinct groups of appellations to derive future pathways related to their climate resilience.

Data availability

The dataset containing the primary and additional varieties cultivated in each PDO is available at https://doi.org/10.5281/zenodo.7257126.

Code availability

Data processing was conducted using the Python programming language as well as QGIS and ArcGIS. The Python code for the clustering and vulnerability calculation can be found at the following link: https://doi.org/10.5281/zenodo.7341521.

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Appendix A – Supplementary materials for chapter 2

Tables

Table 7. Strings used for the search papers with a focus on: (i) climate change effects on ecosystem conditions in vineyard landscapes and (ii) the ecosystem services provided by vineyard landscapes.

Focus	Search strings
(i) Climate change effects on ecosystem conditions in vineyard landscapes (keywords are based on the indicators suggested for agroecosystems in Maes et al. (2018)	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (*nitrogen OR "heavy metal" OR fragmentation OR diversity OR rotation OR density OR connectivity OR "semi-natural" OR seminatural OR fallow OR "high nature value*" OR organic OR livestock* OR bird* OR mammal* OR amphibian* OR reptile* OR pollinator* OR habitat OR "protected area*" OR "soil organic carbon" OR "soil pH" OR "soil erodibility" OR "bulk density" OR "soil biodiversity" OR "water availability" OR "gross primary production" OR "water capacity" OR "soil nutrient*"*))
(ii) Ecosystem services in vineyard landscapes	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND (*"ecosystem service*"*))

Table 8. Strings used for the search of the articles regarding climate change effects on ecosystem services provided by vineyard landscapes and the influence of ecosystem conditions. In this study we considered ecosystem services classes from the CICES classification v5.1, adapted from (Haines-Young & Potschin-Young, 2018), CC BY 4.0). For the selection of the 28 CICES classes to be studied for vineyard landscapes and the related keywords used in the search we referred to (Winkler et al., 2017).

Ecosystem service searched	**CICES 5.1 code**	**Search string**
Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes	1.1.1.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*yield* OR "grape leaves" OR "grapevine leaves" OR crop* OR "table grape*" OR "crop load*" OR "grape berr*" OR "berry growth" OR "grape maturity" OR "yield component*" OR "fruit composition" OR "cultivated crops*" OR "wine grape*" OR "grape juice" OR wine OR "sugar content"*))
Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)	1.1.1.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*pruning OR "grape seed*" OR "grape skin*" OR MegaPurple OR "color additive*" OR wood OR "Ravaz index"*))
Fibres and other materials from reared animals for direct use or processing (excluding genetic materials)	1.1.3.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR

		"global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*pomace*))
Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	2.1.1.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("carbon storage" OR "carbon sequestration" OR filtration OR sequestration OR storage OR accumulation OR GHG OR "greenhouse gas" OR N2O OR "nitrous oxide" OR sulfur OR "nitrogen deposition*" OR fertilizer* OR spray OR pesticide* OR salinization OR "soil salinity" OR "salt accumulation"*))
Smell reduction	2.1.2.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("spatial planning" OR "land use planning" OR "smell impact" OR smell OR "sulfur smell" OR harvest OR "crush smell"*))
Noise attenuation	2.1.2.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*"spatial planning" OR "land use planning" OR "noise impact" OR "tractor noise" OR "sound cannon*" OR highway*))

Visual screening	2.1.2.3	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*"spatial planning" OR "land use planning" OR zoning OR reflector OR "visual impact" OR landscape OR viewshed OR preservation OR aesthetics*))
Control of erosion rates	2.2.1.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("soil conservation" OR "soil loss*" OR "cultivation practice*" OR "mass stabilization" OR erosion OR "erosion rate" OR "erosion model" OR "alternate row cultivation" OR "row cultivation" OR disking OR mowing OR ripping OR liming OR "tree removal" OR "run off" OR erosivity OR "land terrac*" OR "native vegetation removal" OR "vegetation removal" OR "cover crop" OR "mass flow" OR tractor* OR machinery OR steep slope*))
Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	2.2.1.3	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("fraction of transpirable soil water" OR FTSW OR infiltration OR "water deficit" OR "water relations" OR hydraulics*

		OR "run off" OR soil moisture OR irrigation OR (fish AND flows) OR "ecolog flow*" OR "water security" OR "water stress" OR flooding OR landscape OR "buffer zone" OR setback OR "flood control" OR "flood protection" OR "wet feet" OR drainage*))
Pollination (or 'gamete' dispersal in a marine context)	2.2.2.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*insect* OR pollination OR bee OR finch* OR "cover crop" OR "wind pollination" OR arthropod*))
Seed dispersal	2.2.2.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("seed dispersal" OR bird* OR starling* OR turkey* OR "sound cannons*"*))
Maintaining nursery populations and habitats (Including gene pool protection)	2.2.2.3	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*diversity OR biodiversity OR "nursery population" OR habitat OR germplasm OR "biological resource" OR "gene pool"*))

Pest control (including invasive species)	2.2.3.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("cover crop" OR pest* OR "pest control*" OR "rodent control*" OR "beneficial predator*" OR "bird box*" OR "owl box*" OR "raptor box*" OR "nest box*" OR "integrated pest management*" OR IPM OR "native plant*" OR "natural enemy" OR "pest management" OR pesticide OR "biological control" OR arthropod OR rodent* OR insecticide* OR phylloxera OR nematode**))
Disease control	2.2.3.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("red blotch" OR botrytis OR fungal OR herbicide OR phomopsis OR disease* OR fungicide*OR disorder*OR eutypa OR "biological control" OR fanleaf OR mulch OR leafroll OR "corky bark"*))
Weathering processes and their effect on soil quality	2.2.4.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("soil fertility" OR nutrient* OR "soil structure" OR "in situ soil" OR "soil biological activity" OR "nutrient uptake" OR*

		mineral OR "soil quality" OR "weathering process*"*))
Decomposition and fixing processes and their effect on soil quality	2.2.4.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*microbe* OR fungi OR "soil arthropod*" OR arthropod OR mulch OR worm* OR legume* OR "nitrogen fixing" OR "soil quality" OR decomposition OR "fixing process*"*))
Regulation of temperature and humidity, including ventilation and transpiration	2.2.6.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("latent heat" OR transpiration OR "climat* regulation" OR shade OR "hydrologic cycle" OR "micro climate" OR "regional climate" OR evapotranspiration OR ventilation OR photosynthesis OR ecophysiology*))
Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	3.1.1.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("wine tasting" OR picnic* OR "eating grape*" OR "drink* wine" OR dolmade* OR birding OR "bird watch*" OR*

		employment OR "hot air" OR "balloon ride" OR "limousin tour*" OR "gourmet tourism" OR "cable car"*))
Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	3.1.1.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*biking OR hiking OR "horseback rid*" OR padding OR walking*))
Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	3.1.2.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("climate change" OR enology OR trial OR "precision viticulture" OR scientific*))
Characteristics of living systems that enable education and training	3.1.2.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*winemaking OR winegrowing OR "wine seminar" OR school OR university OR college OR education OR "tasting room" OR "environmental education"*))
Characteristics of living systems that are resonant in terms of culture or heritage	3.1.2.3	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR

		"temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("family winery" OR tradition OR charm OR traditional OR historical OR identity OR "sense of place" OR "social capital" OR heritage OR "local food cultural"*))
Characteristics of living systems that enable aesthetic experiences	3.1.2.4	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*beauty OR scenery OR landscape OR winescape OR "vineyard row" OR aesthetic OR mustard OR poppies OR inspiration OR wildflower OR "seasonal change" OR "leaf change" OR "foliage change" OR art OR gallery*))
Elements of living systems that have symbolic meaning	3.2.1.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*representation OR appellation OR symbolic OR "social cohesion" OR terroir OR uniqueness OR AVA OR "American Viticultural Area" OR DOC OR "denomination origine controlle" OR "denominazione di origine controllata" OR AOC OR "Appellation d'origine contrôlée" OR emblem**))

Elements of living systems that have sacred or religious meaning	3.2.1.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*wedding* OR yoga OR meditation OR retreat OR spiritual OR sacred OR religious OR religion OR "mother earth" OR inspiration*))
Elements of living systems used for entertainment or representation	3.2.1.3	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*wedding* OR entertainment OR "bachel* part*" OR "winery tour" OR "wine tasting" OR concert OR theater OR music OR movie* OR "film festival" OR festival OR "harvest festival" OR contest OR "vintage festival" OR "wine queen" OR "wine event*" OR tourism OR agritourism OR agrotourism OR "wine cave" OR "wine tourism" OR "wine tour*" OR visit OR "day trip"*))
Characteristics or features of living systems that have an existence value	3.2.2.1	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND (*view OR "land use" OR "option value" OR existence OR "nature conservation" OR landscape*))

Characteristics or features of living systems that have an option or bequest value	3.2.2.2	((vineyard OR viticulture OR "grape* grow*" OR wine*) AND ("climat* change*" OR "global change" OR "environmental change" OR "climat* warm*" OR "global warm*" OR "temperature rise" OR "extreme event*" OR "extreme weather" OR "greenhouse gas*" OR "global emissions") AND (winemaker* OR winegrower* OR farmer* OR producer* OR vintner*) AND *("family farming" OR "family winery" OR "inter-generational" OR stewardship OR "land ethic" OR bequest*))

Table 9. Inclusion and exclusion criteria used during the paper selection. The focus of the articles to be excluded were defined by the authors while screening the titles, abstracts, and keywords of the papers in our sample.

Inclusion criteria
(1) Article published in a peer-reviewed journal (2) Paper type is research article or review (3) Article's language is English (4) Focus on past, present, or future conditions (5) Focus on vineyard landscapes (6) Papers that study, in both a qualitative or a quantitative perspective, with or without the support of specific data, and including significant and non-significant correlations from empirical studies either: the relationships between climate change and ecosystem conditions; or the relationships between ecosystem conditions and ecosystem services; or the relationship between climate change, ecosystem conditions and ecosystem services.
Exclusion criteria
(1) Focus only on theoretical methodological approaches/technologies/frameworks not explicitly including the relationships from inclusion criteria (6) (2) Focus on sustainability/energy/waste/economic assessments (life cycle assessment, SWOT, GHG emissions, energy requirements and production, water, firm performance, waste management) not explicitly including the relationships from inclusion criteria (6) (3) Focus on oenology, berry composition, sensorial profile of wines, analysis of vine genotype, characteristics and specific physiological traits, effects of abandonment on vine and vineyard, experiments performed in mesocosms without any results measured in situ, in vitro/laboratory analysis (4) Focus on policy, conceptual frameworks, vulnerability, adaptive capacity, adaptation strategies (5) Study focus is not on vineyard landscapes, or it is neither on a relevant ecosystem condition nor on a relevant ecosystem service for VL

Table 10. Options used to answer the structured questions of our review.

Question Id	Options for answer
Q1	Type of article: ▪ **Research paper** o **Model =** a method based on a numerical model to analyse VLs. o **Field experiment =** an experiment that include the manipulation of some field conditions. o **Field observation =** a method based on in situ observations. o **Questionnaire =** a method that include the compilation of a survey. ▪ **Review** o **Literature review =** a review of the available literature on a certain field.
Q2	▪ **Local** = study focuses at big geographical scale including one or a few vineyard plots nearby. ▪ **Regional** = study focuses on a larger number of vineyard plots in the same region, or on vineyard plots in different regions from the same country, or it includes a whole viticultural region. ▪ **National** = study focuses on the different vineyard regions in a country. ▪ **Transnational** = study focuses on very small geographical scale or it includes plots from different countries. ▪ **NA** = used for review papers.
Q3	▪ **Observed** = study focuses on observed features of the analysed phenomenon. ▪ **Future** = study includes future projection of the analysed phenomenon. ▪ **NA =** used for review papers.
Q4	▪ **Yes** = the study included only *ecosystem conditions* → *ecosystem services* links. ▪ **No** = the study included *climate change* →*ecosystem conditions*, or a *climate change* → *ecosystem conditions* → *ecosystem services* links.
Q5	▪ **Yes** = the study included *climate change* →*ecosystem conditions*, or a *climate change* → *ecosystem conditions* → *ecosystem services* links. ▪ **No** = the study included only *ecosystem conditions* → *ecosystem services* links.
Q6	The list of disciplines involved in the study of ecosystem conditions and

	services that were included in this study is provided in **Table 12**.
Q7	The list of disciplines involved in the study of climate change variables that were included in this study is provided in **Table 12**.
Q8	The list of normalized ecosystem conditions considered in this study is provided in **Table 11**.
Q9	The list of ecosystem services considered in this study is provided in **Table 8**.
Q10	The *ecosystem conditions* → *ecosystem services* links studied in our sample are presented in **Figure 5**.
Q11	The general climate change effects considered in this study are related to temperature, precipitation, CO_2 concentration or extreme events (as defined in the study).
Q12	The *climate change* →*ecosystem conditions*, or *climate change* → *ecosystem conditions* → *ecosystem services* links are presented in **Figure 5**.

Table 11. Ecosystem conditions classes considered in this review. To determine the ecosystem conditions studied in each article, we analysed the paper listing the cropland agroecosystem conditions as defined by the framework developed for the mapping and assessment of ecosystem and their services (MAES) (Maes et al., 2018). Specific ecosystem conditions related to vineyard landscapes found during the screening of the articles, e.g., vine variety and vine pruning technique, were added to the list of ecosystem conditions addressed. We grouped ecosystem conditions into homogeneous classes to reconcile different terminologies used to describe the same ecosystem conditions in different fields and to simplify the integration of knowledge with respect to climate change and ecosystem services.

Ecosystem conditions from	**Normalized**
Degree of bird functional	Animals and fungi
Host density	
Presence of pests	
Presence of A. Pseudococci	
Presence of arbuscular mycorrhiza	
Presence of arthropods	
Presence of bats	
Presence of birds	
Presence of C. Montrouzieri	
Presence of carabids	
Presence of H. Dimidiatus	
Presence of diseases	
Presence of dominant invasive predator	
Presence of fungi	
Presence of insects	
Presence of L. Abnormis	
Presence of L. Botrana	
Presence of E. Ambiguella	
Presence of natural enemies	
Presence of spiders	
Suitability for grape growing	Climatic suitability
Suitability for viticulture	
Degree of berries growth	Gross primary production
Grapevine vigor	
Presence of buds	
Status of buds and trunk development	
Status of vegetative development	
Quantity of biomass	
Presence of bare inter-rows	Ground cover
Presence of biochar	
Presence of compost	
Presence of cover crops in inter-row space	
Diversely structured inter-row vegetation	
Diversity of cover crops	
Extensive inter-row management	
Availability of floral resources in inter-rows	
Presence of flower driven cover crop	
Presence of grass cover	
Presence of green cover crop	
Ground cover diversity	
Presence of inter-row grass cover	
Presence of inter-row herbaceous cover	
Presence of mulched P. Tanacetifolia and ryegrass	
Presence of mulch	
Presence of native cover crop	
Presence of native ground vegetation	
Presence of natural green cover	
Presence of amendment	
Presence of compost	
Presence of cover crops	
Presence of extensive inter-row vegetation	
Presence of sediment barriers	
Use of service crops	
Presence of tilled inter-rows	
Presence of spontaneous cover crop	
Presence of heat stress	Heat and water stress
Presence of water stress	
Increase of artificial areas	Landscape composition
Diversity of agricultural crops	
Land cover diversity	
Land cover heterogeneity	
Land cover type	
Land use change	
Landscape complexity	
Landscape diversity	
Landscape fragmentation	
Land use changed to hay crop	
Land use changed to grassed	

vineyard	
Land use changed to pasture	
Land use changed to semi-natural system	
Land use changed to tilled vineyard	
Presence of natural habitat	
Presence of oak woodland	
Presence of other agricultural areas	
Presence of remnant vegetation patches	
Presence of riparian zones	
Presence of semi-natural habitat	
Presence of shrub	
Presence of vineyards	
Presence of wildlands	
Presence of woodlands	
Proportion of vineyard	
Presence of wetlands	
Presence of agroecosystem	Local scale habitat conditions
Forage availability	
Presence of grass cover in specific vineyard areas	
Grass height	
Presence of habitat for natural enemies	
Habitat heterogeneity	
Presence of flowers strips	
Presence of hedgerows and vegetation strips	
Length of hedgerows	
Presence of native buckwheat strips	
Presence of native habitat	
Presence of ecological infrastructure in vineyards	
Presence of nest site for birds	
Presence of oak trees	
Presence solitary trees	
Vineyard block design	

Use of agroforestry practices	Management regime
Degree of crop productivity	
Use of irrigation	
Use of nitrogen fertilization	
Use of conventional farming	
Adoption of organic farming	
Presence of organic vineyards	
Copper transport	Nutrients and metals
Nitrogen availability	
Presence of nitrates	
Nitrogen deposition	
Nitrogen transport	
Nutrient competition	
Phosphorus transport	
Degree of herbicide use	Pesticide use
Degree of pesticide application	
Reduction of fungicide application	
Reduction of pesticide application	
Growing season length	Phenology
Length of phenological stages	
Degree of vegetative growth	
Type of canopy management	Vine pruning
Use of minimal pruning	
Use of vertical shoot	
Use of local vine varieties	Vine variety
Use of optimal vine variety	
Presence of suitable vine varieties	
Type of vine variety	
Use of soil amendment	Vineyard soil
Soil depth	
Soil erosion	
Soil organic carbon	
Soil respiration	
Soil structure	
Soil water availability	
Soil water content	
Degree of evapotranspiration	Water availability
Water availability	
Water evaporation	

Table 12. Classes used to define the disciplines of the articles and links in our review. We studied the disciplines that considered ecosystem conditions and services based on the research areas defined for the publishing journals included in our sample. We did this analysing the disciplines defined for each article, that were also used to classify the single links between ecosystem services and ecosystem conditions found in the paper. If an article was assigned more disciplines, we considered all of them. To select the disciplines' classes, we adapted the classification used by Scopus. We did this after checking the consistency between the disciplines assigned by Scopus and Web of Science to the publishing journals included in this review.

Disciplines
Agricultural and Biological Sciences
Biochemistry, Genetics and Molecular Biology
Business, Management and Accounting
Earth and Planetary Sciences
Economics, Econometrics and Finance
Energy
Environmental Sciences
Neuroscience
Medicine
Social Sciences
Chemistry
Materials Sciences
Engineering
Multidisciplinary

Table 13. Representation of the share (%) of how much the relationship between ecosystem condition, ecosystem service or climate change variables were studied in: (a) Figure 19a, (b) Figure 19b and (c) Figure 19c.

(a)

Source	Target	Value
Animals and fungi	Crop production	1.45
Animals and fungi	Erosion control	0.36
Animals and fungi	Disease control	0.36
Animals and fungi	Filtration and storage by organisms	1.09
Animals and fungi	Populations and habitats	0.72
Animals and fungi	Pest control	3.99
Climatic suitability	Crop production	1.09
Gross primary production	Decomposition and fixing	0.36
Gross primary production	Filtration and storage by organisms	0.72
Ground cover	Aesthetic	0.36
Ground cover	Crop production	1.45
Ground cover	Erosion control	2.54
Ground cover	Disease control	0.72
Ground cover	Decomposition and fixing	9.06
Ground cover	Fibers and materials	0.36
Ground cover	Filtration and storage by organisms	1.45
Ground cover	Water regulation	2.9
Ground cover	Populations and habitats	11.96
Ground cover	Pest control	4.35
Ground cover	Pollination	1.09
Ground cover	Climate regulation	1.81
Landscape composition	Aesthetic	0.72
Landscape composition	Erosion control	0.72
Landscape composition	Heritage	0.72
Landscape composition	Disease control	0.36
Landscape composition	Decomposition and fixing	1.81
Landscape composition	Filtration and storage by organisms	0.72
Landscape composition	Water regulation	0.36
Landscape composition	Populations and habitats	7.97
Landscape composition	Pest control	2.9
Local scale habitat conditions	Aesthetic	0.36
Local scale habitat conditions	Erosion control	0.36
Local scale habitat conditions	Heritage	0.36
Local scale habitat conditions	Scientific investigation	0.36
Local scale habitat conditions	Disease control	0.72
Local scale habitat conditions	Decomposition and fixing	1.09
Local scale habitat conditions	Filtration and storage by organisms	0.72
Local scale habitat conditions	Water regulation	0.72
Local scale habitat conditions	Populations and habitats	5.07
Local scale habitat conditions	Pest control	3.26
Local scale habitat conditions	Climate regulation	0.72
Management regime	Decomposition and fixing	0.72
Management regime	Filtration and storage by organisms	0.72
Management regime	Populations and habitats	3.26
Management regime	Pest control	1.81
Nutrients and metals	Crop production	0.36
Pesticide use	Crop production	0.36
Pesticide use	Populations and habitats	1.09
Pesticide use	Pest control	0.72
Phenology	Populations and habitats	0.36
Vine pruning techniques	Crop production	0.36
Vine pruning techniques	Disease control	0.36
Vineyard soil	Crop production	1.45
Vineyard soil	Decomposition and fixing	3.99
Vineyard soil	Filtration and storage by organisms	0.36
Vineyard soil	Water regulation	0.36
Vineyard soil	Populations and habitats	1.81
Vineyard soil	Climate regulation	0.36
Water availability	Crop production	2.9
Water availability	Filtration and storage by organisms	0.36

(b)

Source	Target	Value
CO2 concentration	Gross primary production	0.82
CO2 concentration	Phenology	0.82
CO2 concentration	Nutrients and metals	0.82
CO2 concentration	Animals and fungi	0.82
Extreme events	Gross primary production	4.92
Precipitations	Animals and fungi	4.92
Precipitations	Phenology	4.92
Precipitations	Water availability	4.1
Precipitations	Climatic suitability	4.1
Precipitations	Nutrients and metals	4.1
Precipitations	Vineyard soil	3.28
Precipitations	Vine variety	3.28
Precipitations	Gross primary production	2.46
Precipitations	Ground cover	0.82
Precipitations	Pesticide use	0.82
Precipitations	Heat and water stress	0.82
Temperature	Phenology	20.49
Temperature	Climatic suitability	9.84
Temperature	Vine variety	7.38
Temperature	Animals and fungi	6.56
Temperature	Water availability	5.74
Temperature	Gross primary production	3.28
Temperature	Vineyard soil	2.46
Temperature	Nutrients and metals	1.64
Temperature	Heat and water stress	0.82

(c)

Source	Target	Value
Animals and fungi	Pest control	7.69
Animals and fungi	Crop production	1.28
Climatic suitability	Crop production	3.85
CO2 concentration	Gross primary production	2.56
Extreme events	Gross primary production	1.28
Gross primary production	Crop production	5.13
Heat and water stress	Crop production	1.28
Landscape composition	Decomposition and fixing	6.41
Phenology	Crop production	3.85
Precipitations	Water availability	8.92
Precipitations	Vineyard soil	3.85
Precipitations	Climatic suitability	3.85
Precipitations	Landscape composition	6.41
Temperature	Water availability	8.97
Temperature	Vineyard soil	2.56
Temperature	Animals and fungi	1.28
Temperature	Phenology	3.85
Temperature	Heat and water stress	1.28
Temperature	Climatic suitability	3.85
Temperature	Gross primary production	1.28
Temperature	Landscape composition	6.41
Vineyard soil	Decomposition and fixing	2.56
Vineyard soil	Crop production	1.28
Water availability	Crop production	10.26

Figures

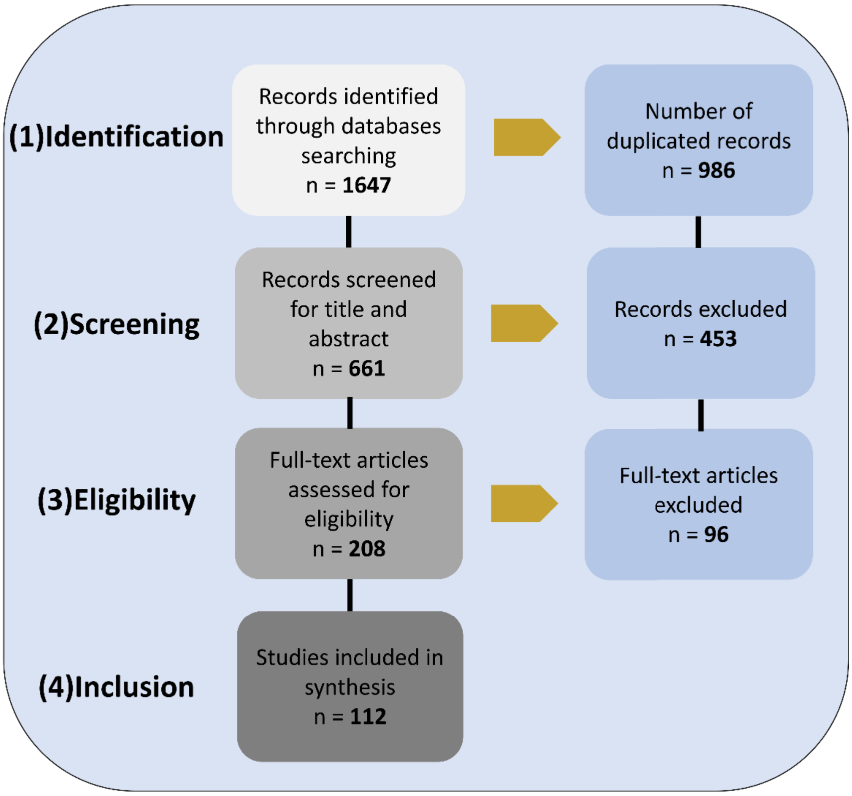

Figure 16. Flow diagram representing the use of the preferred reporting items for systematic reviews and meta-analyses, adapted from (Moher et al., 2009), CC BY 4.0) for the selection of the peer-reviewed literature in this review. For each step, we report the number of papers analysed and those excluded. We excluded from our review duplicated papers and papers not matching with our inclusion criteria (Table 9).

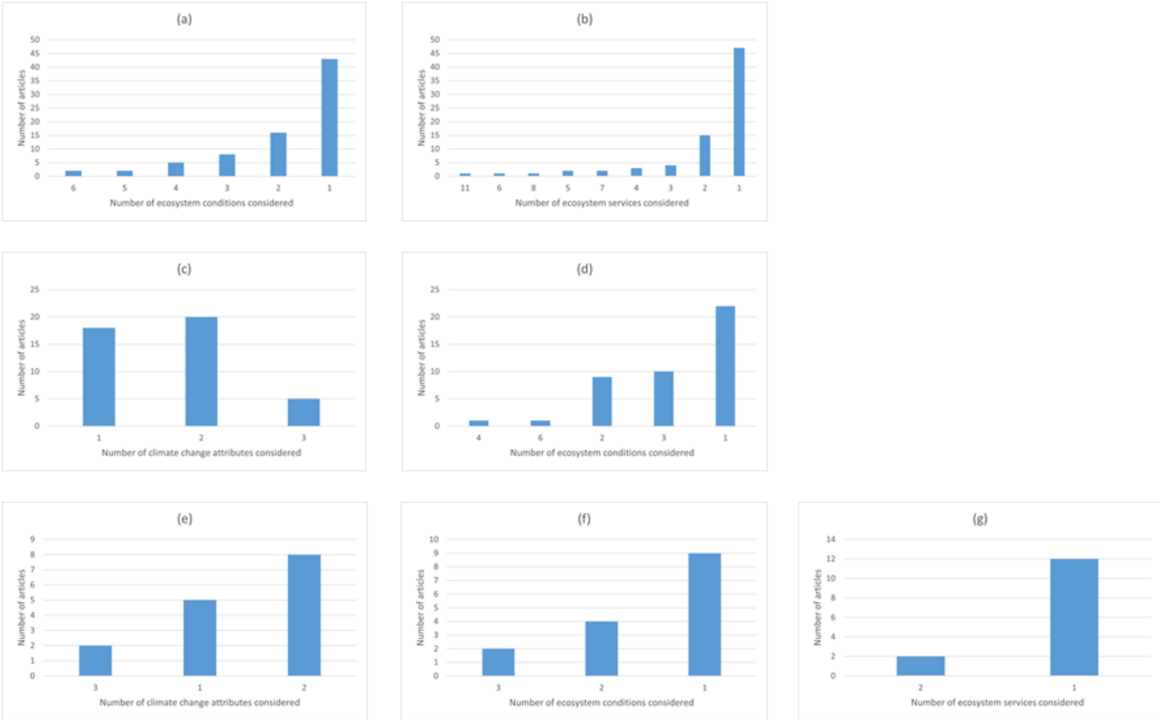

Figure 17. Frequency in the consideration of climate change attributes, ecosystem conditions and ecosystem services in articles that included: (a,b) *ecosystem conditions→ecosystem services* links; (c,d) *climate change→ecosystem conditions* links; (e,f,g) *climate change→ecosystem conditions→ecosystem services links*.

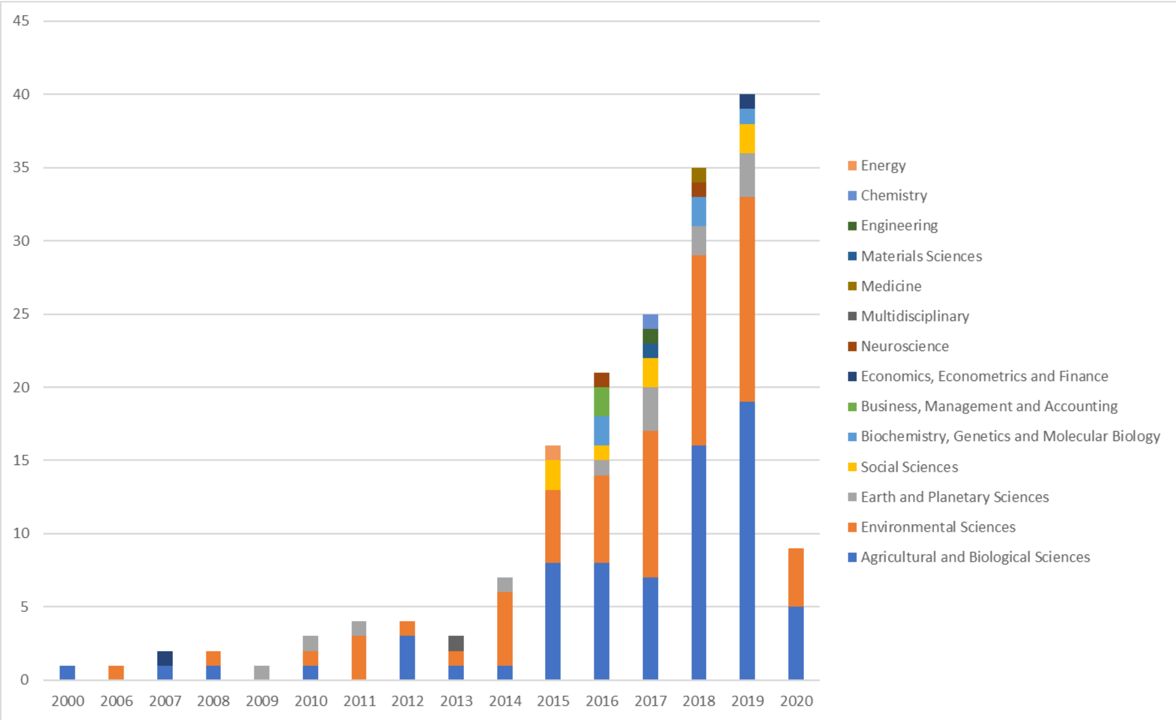

Figure 18. Temporal perspective on the disciplines of the papers of our sample.

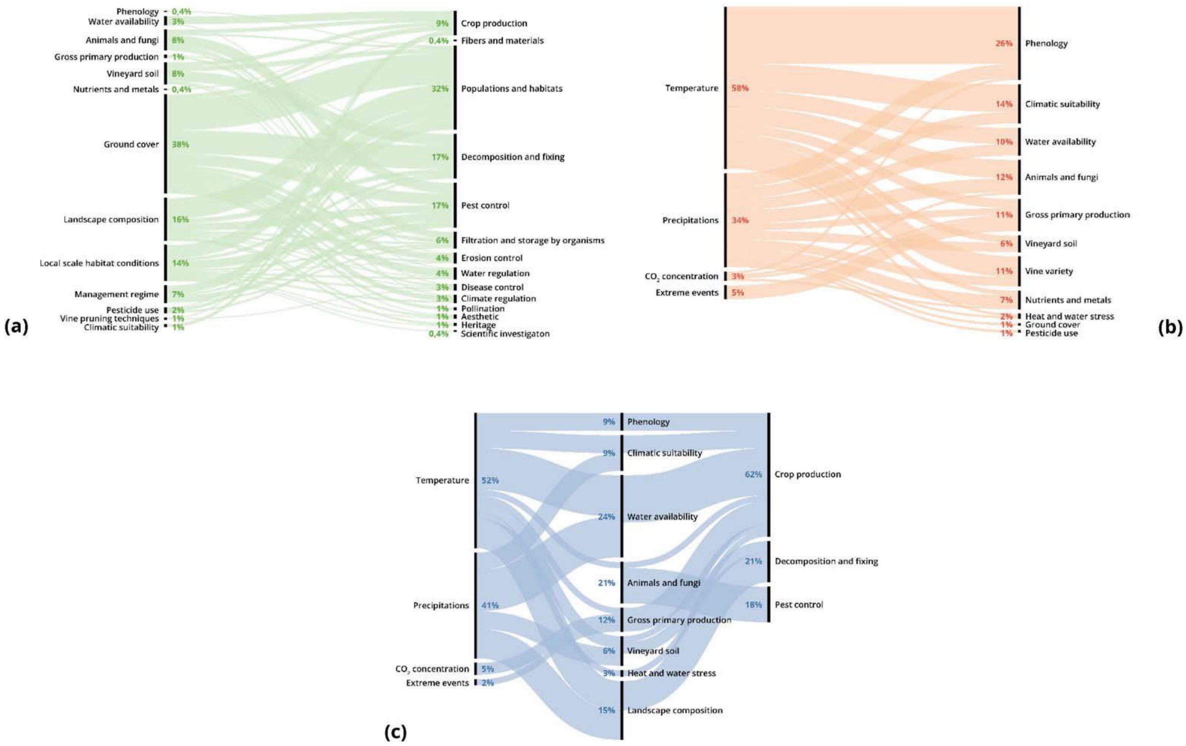

Figure 19. Sankey diagrams representing: (a) the *ecosystem conditions* → *ecosystem services* links; (b) *climate change* → *ecosystem conditions* links; (c) *climate change* → *ecosystem conditions* → *ecosystem services* links retrieved in our review. The thickness of the lines is proportional to the total number of links. The percentages in the diagram represent the share of how much the single links' components and their relationships were studied (see also Table 13). Percentages have been rounded and may not equal 100%.

Papers

List of the 112 articles analysed in this study.

1.Delpuech, X. & Metay, A., 2018. Adapting cover crop soil coverage to soil depth to limit competition for water in a Mediterranean vineyard. Eur. J. Agron. 97, 60–69.

2.Cameron, W. et al., 2019. Advancement of grape maturity: comparison between contrasting cultivars and regions. Aust. J. Grape Wine R. 26, 53–67.

3.Leeuwen, C. V. et al., 2019. An Update on the Impact of Climate Change in Viticulture and Potential Adaptations. Agron. 9, 514.

4.Gaitán-Cremaschi, D., Palomo, I., Molina, S. B., Groot, R. D. & Gómez-Baggethun, E., 2017. Applicability of economic instruments for protecting ecosystem services from cultural agrarian landscapes in Doñana, SW Spain. Land Use Policy. 61, 185–195.

5.Muñoz-Rojas, M., Doro, L., Ledda, L. & Francaviglia, R., 2015. Application of CarboSOIL model to predict the effects of climate change on soil organic carbon stocks in agro-silvo-pastoral Mediterranean management systems. Agric. Ecosyst. Environ. 202, 8–16.

6.Crescimanno, G., Morga, F. & Ventrella, D., 2012. Application of the swap model to predict impact of climate change on soil water balance in a Sicilian vineyard. Ital. J. Agron. 7, 17.

7.Trouvelot, S. et al., 2015. Arbuscular mycorrhiza symbiosis in viticulture: a review. Agron. Sustain. Dev. 35, 1449–1467.

8.Winkler, K. J., Viers, J. H. & Nicholas, K. A., 2017. Assessing Ecosystem Services and Multifunctionality for Vineyard Systems. Front. Environ. Sci. 5, 15.

9.Biasi, R., Brunori, E., Ferrara, C. & Salvati, L., 2019. Assessing Impacts of Climate Change on Phenology and Quality Traits of Vitis vinifera L.: The Contribution of Local Knowledge. Plants. 8, 12.

10.Williams, J. N. et al., 2011. Assessment of carbon in woody plants and soil across a vineyard-woodland landscape. Carbon Balance Manag. 6, 11.

11.Barbaro, L. et al., 2016. Avian pest control in vineyards is driven by interactions between bird functional diversity and landscape heterogeneity. J. Appl. Ecol. 54, 500–508.

12.Assandri, G., Bogliani, G., Pedrini, P. & Brambilla, M., 2018. Beautiful agricultural landscapes promote cultural ecosystem services and biodiversity conservation. Agric. Ecosyst.

Environ. 256, 200–210.

13.Genesio, L., Miglietta, F., Baronti, S. & Vaccari, F. P., 2015. Biochar increases vineyard productivity without affecting grape quality: Results from a four years field experiment in Tuscany. Agric. Ecosyst. Environ. 201, 20–25.

14.Jiménez-García, L., García-Martínez, Y. G., Marco-Mancebón, V., Pérez, I. & Jiménez-García, D., 2019. Biodiversity analysis of natural arthropods enemies in vineyard agroecosystems in La Rioja, Spain. J. Asia-pac. Entomol. 22, 308–315.

15.Thiéry, D. et al., 2018. Biological protection against grape berry moths. A review. Agron. Sustain. Dev. 38, 15.

16.Hoffmann, C. et al., 2017. Can Flowering Greencover Crops Promote Biological Control in German Vineyards? Insects 8, 121.

17.Francaviglia, R. et al., 2012. Changes in soil organic carbon and climate change – Application of the RothC model in agro-silvo-pastoral Mediterranean systems. Agr. Syst. 112, 48–54.

18.Schultz, H. R., 2000. Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV-B effects. Aust. J. Grape Wine. R 6, 2–12.

19.Fernandez, L., Seixas, F., Oliveira, P., Leitao, S. & Moura, J., 2012. Climate change impacts on nitrogen in a hydrographical basin in the north-east of Portugal. Fresenius Environ. Bull.

20.Fraga, H., Pinto, J. G. & Santos, J. A., 2019. Climate change projections for chilling and heat forcing conditions in European vineyards and olive orchards: a multi-model assessment. Clim. Change. 152, 179–193.

21.Lazoglou, G., Anagnostopoulou, C. & Koundouras, S., 2018. Climate change projections for Greek viticulture as simulated by a regional climate model. Theor. Appl. Climatol. 133, 551–567.

22.Roehrdanz, P. R. & Hannah, L., 2016. Climate Change, California Wine, and Wildlife Habitat. J. Wine. Econ. 11, 69–87.

23.Hannah, L. et al., 2013. Climate change, wine, and conservation. Proc. National Acad. Sci. 110, 6907–6912.

24.Fraga, H. et al., 2015. Climatic suitability of Portuguese grapevine varieties and climate change adaptation. Int. J. Climatol. 36, 1–12.

25.Brambilla, M., Ilahiane, L., Assandri, G., Ronchi, S. & Bogliani, G., 2017. Combining habitat requirements of endemic bird species and other ecosystem services may synergistically enhance conservation efforts. Sci. Total Environ. 586, 206–214.

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Appendix B – Supplementary materials for chapter 3

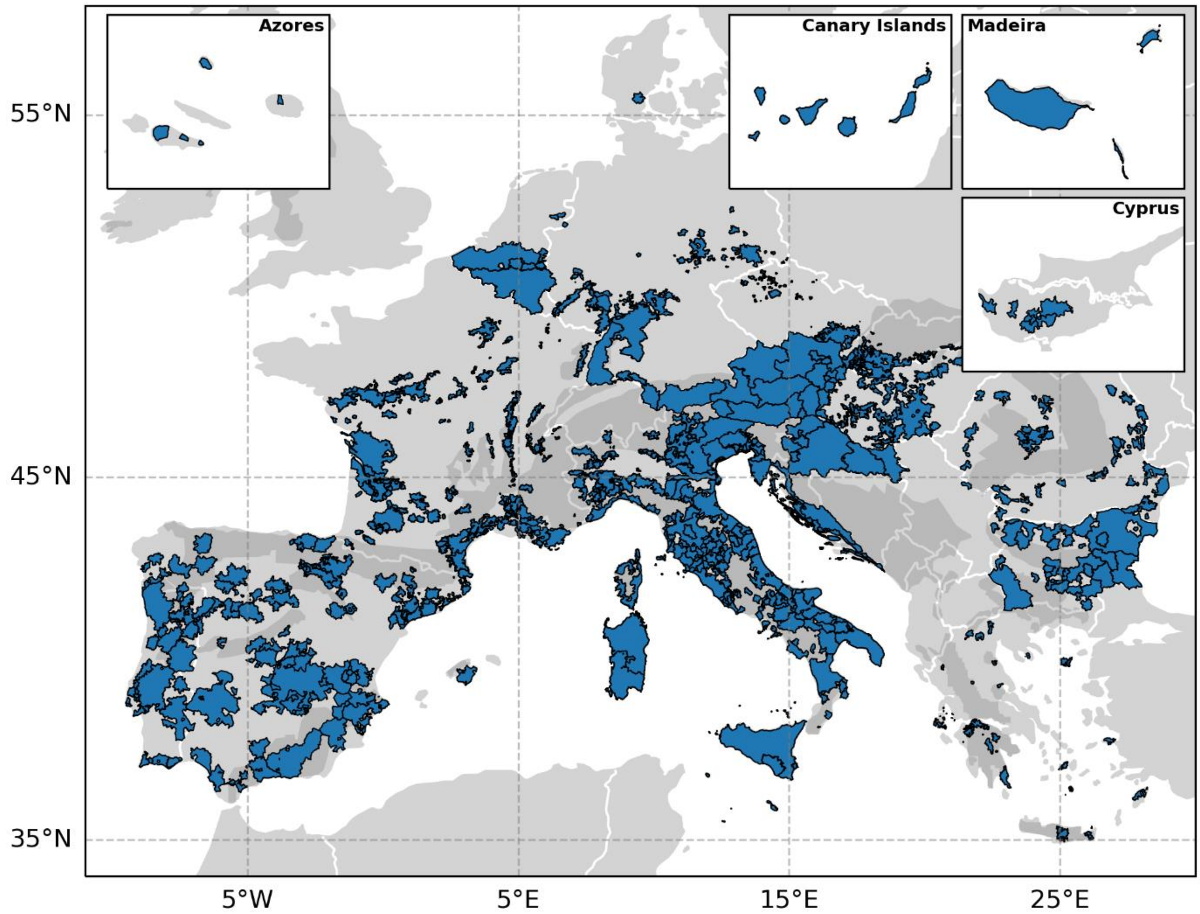


Figure 20. European wine PDOs adapted from Candiago *et al.* (Candiago et al., 2022). Dark grey areas refer to mountain regions.

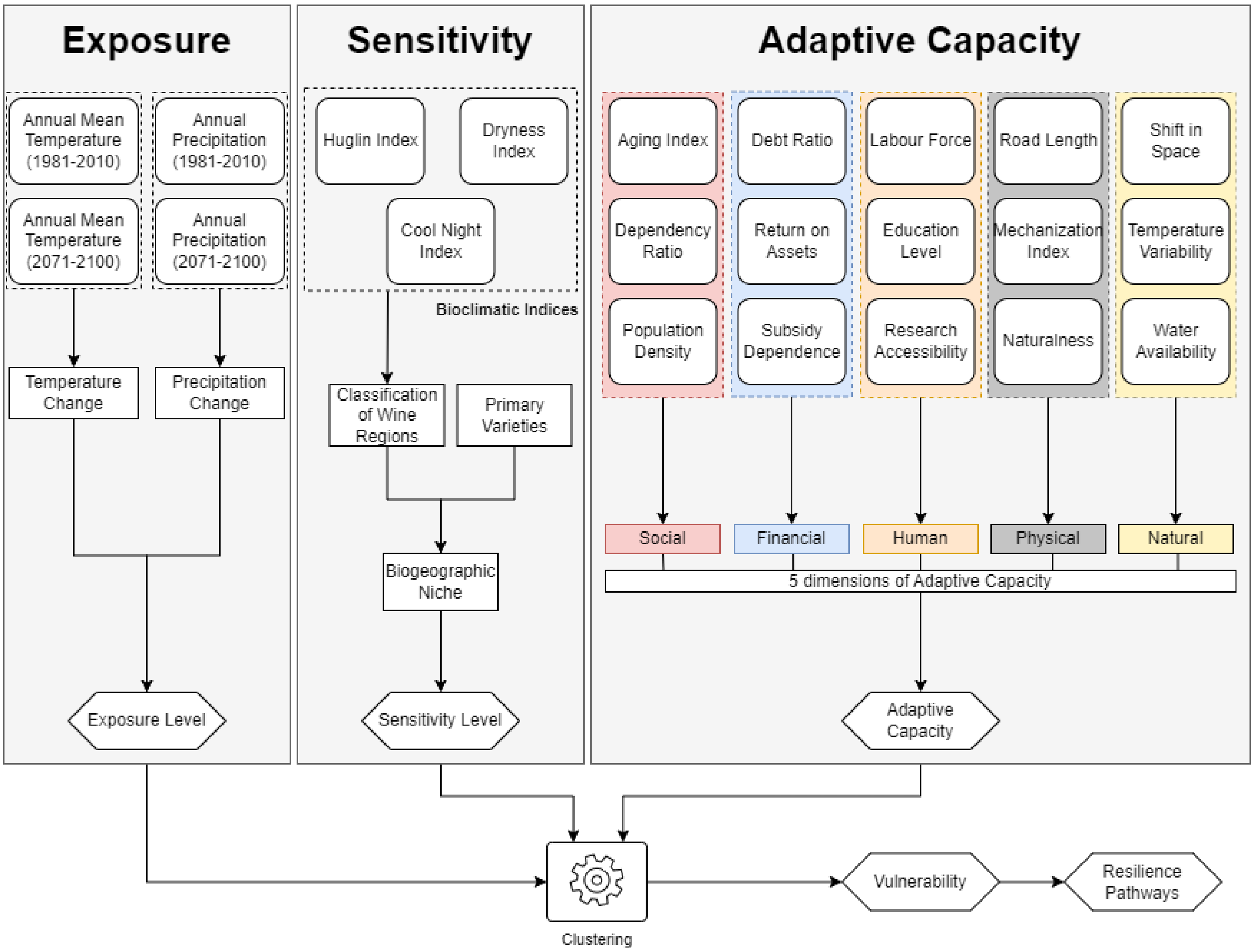


Figure 21. Methodological overview. The three grey boxes show the steps and the indicators used to calculate exposure, sensitivity and adaptive capacity.

Table 14. Vulnerability levels of the clusters, their corresponding centroid values and the vulnerability index (VI).

Cluster	Exposure	Sensitivity	Adaptive Capacity	VI	Vulnerability Level
1	0.55	0.20	0.59	0.16	Very low
3	0.79	0.43	0.77	0.45	Low
2	0.33	0.69	0.41	0.60	Low
5	0.74	0.54	0.41	0.88	Moderate
4	0.75	0.85	0.60	0.99	Moderate
6	0.67	0.80	0.26	1.21	High

Supplementary Methods 1: Adaptive Capacity Indicators

Table 15. Exposure, sensitivity and adaptive capacity indicators used to assess the vulnerability of winegrowing regions. All the indicators were standardized to the level of individual wine regions during the calculations.

Dimension	Dimension	Indicator
Exposure		Change in annual mean temperature Change in annual precipitation
Sensitivity		Huglin index Cool night index Dryness index
Adaptive capacity	Social	Aging index Dependency ratio Population density
	Physical	Road length Mechanization Index Naturalness
	Natural	Shift in Space Water availability Temperature variability
	Human	Labour force Education Level Research accessibility
	Financial	Debt ratio Return on assets Subsidy dependence

Indicators: Exposure

Change in annual mean temperature

General description The change in annual mean temperature under climate change, (C°).
Rationale Air temperature is a key determinant of vine development. Several wine regions have already observed altered phenological development and grape composition caused by increased air temperature(Leeuwen et al., 2019; Santos et al., 2020). Changes in air temperature are therefore strongly related to the climate change impacts that can be expected in a wine region.
Input data Chelsa high resolution monthly temperature data (present time 1981-2010 and future projection 2071-2100) for the ssp858 scenario from a 5-model ensemble(Karger et al., 2017, 2020).
Calculation process Annual mean temperature during 2071-2100 minus the annual mean temperature during 1981-2010
Standardization 0 = lower increase in temperature; 1 = higher increase in temperature.

Change in annual precipitation

General description The change in annual precipitation under climate change, (mm).
Rationale A decrease in precipitation can have negative consequences for wine regions by exposing vines to increased drought, which impacts vine growth and berry composition(Santos et al., 2020). In established wine regions, that traditionally optimized plant material and viticultural techniques to their local conditions, a change in the precipitation pattern may require specific adaptations(Leeuwen et al., 2019).
Input data Chelsa high resolution monthly precipitation data (present time 1981-2010 and future projection 2071-2100) for the ssp858 scenario from a 5-model ensemble(Karger et al., 2017, 2020).
Calculation process Annual precipitation during 2071-2100 minus annual precipitation during 1981-2010
Standardization 0 = lower decrease in precipitation; 1 = higher decrease in precipitation.

Indicators: Sensitivity

Huglin index

General description

The Huglin index describes the thermal conditions in a wine region during the vegetation period, which is related to the potential grape sugar content(Fraga et al., 2014), (C°).
Rationale Thermal conditions during the vegetation period play a critical role for vine phenology and grape ripening(Fraga et al., 2013). They strongly determine viticultural suitability(Fraga et al., 2016) and have been used to forecast required adaptation efforts for several regions(Santillán et al., 2019). Changes in thermal conditions therefore have significant impacts on the wine style that can be produced in a region as well as which varieties can be cultivated and where they can be grown.
Input data Chelsa high resolution monthly temperature data (1981-2010) (Karger et al., 2017, 2020).
Calculation process $\sum_{April}^{Sept.} \frac{(T-10)+(Tmax-10)}{2} d$ T=Mean air temperature (C°) Tmax=Maximum air temperature (C°) D=Length of day coefficient, from 1.02 to 1.06
Standardization 0 = lower Huglin index; 1 = higher Huglin index.

Cool night index

General description The cool night index accounts for minimum temperatures during September, providing an estimate of temperature conditions during the ripening stage(Fraga et al., 2014), (C°).
Rationale Minimum temperatures during grape ripening are critical for grape composition at harvest and influence wine style and quality. As a consequence, increased air temperature during this period can result in decreased wine quality(Santos et al., 2020). For instance, if minimum air temperatures during night become too high, sugar consumption in the berries increases which in turn affects the concentration of flavour compounds(Santos et al., 2020).
Input data Chelsa high resolution monthly temperature data (1981- 2010)(Karger et al., 2017, 2020).
Calculation process Average daily minimum temperature during September (C°).
Standardization 0 = lower cool night index; 1 = higher cool night index.

Dryness index

General description The dryness index evaluates soil water availability for vine development, by estimating soil

water reserves, precipitation, and potential evapotranspiration(Fraga et al., 2014), (mm).
Rationale The available water is a critical factor that influences vine growth and berry ripening. For instance, a decrease in precipitation or an increase in temperature in areas with dry conditions (low dryness index) can put the vines under water stress and negatively impact vine vigor(Santos et al., 2020). In contrast, areas with moist conditions (high dryness index) might even experience positive consequences from a decrease in the dryness index, such as lower pathogen pressure(Bois et al., 2017).
Input data Chelsa high resolution monthly temperature and precipitation data (1981- 2010) (Karger et al., 2017, 2020).
Calculation process $$\sum_{April}^{Sept.} (\mathrm{Wo} + \mathrm{P} - \mathrm{Tv} - \mathrm{Es})$$ Wo=Initial available soil water reserve (mm) on the first month / DI on the following months P=Precipitation (mm) Tv=Potential vineyard transpiration (mm) Es=Direct evaporation from the soil (mm) Tv; Es are assessed using the Thornthwaite method
Standardization 0 = higher dryness index; 1 = lower dryness index.

Indicators: Adaptive capacity

Aging index

General description The ratio between the old and the young population in a municipality, (n°).
Rationale This indicator is a measure of aging population indicating how many persons at retirement age there are for every child. It shows the demographic trend that a municipality can expect. An unfavourable ratio (high indicator values) may indicate an exodus of young people and families, showing a negative outlook for the regional labour market which may also impact future agricultural activities in the area(Borsdorf et al., 2008).
Input data Population number at the LAU2 (municipality) level (Eurostat, 2022a).
Calculation process $$\frac{Residents\ age\ > 65}{Residents\ age\ 0 - 15}$$
Standardization

0 = high aging index; 1 = low aging index.

Dependency ratio

General description The ratio between the dependent population and the working population per municipality, (n°).
Rationale This indicator shows the socioeconomic burden on the active population, which must support the non-active population through taxes. It gives insight into structural weaknesses of regions, such as emigration of the economically active population, or their economic attractiveness.
Input data Population number at the LAU2 (municipality) level (Eurostat, 2022a).
Calculation process $\frac{Residents\ age < 15\ and\ > 65}{Residents\ aged\ 15 - 65}$
Standardization 0 = high dependency ratio; 1 = low dependency ratio.

Population density

General description The population density per agricultural area and municipality, (n°/ha).
Rationale This indicator gives insight into the rural-urban gradient of each municipality. Dense population clusters generally coincide with urban or metropolitan areas, while lowly populated areas are associated with the countryside. A high population density positively impacts the value of farmland and the availability of labour force, thereby facilitating the continuation of agricultural activity. Very low values on the other hand show a low attractiveness of the region with negative demographic and socioeconomic trends.
Input data GISCO population dataset (Eurostat, 2022d), Corine Land Cover (EEA, 2022), EUcropmap(d'Andrimont et al., 2021).
Calculation process Calculation of the ratio n° of people/total agricultural area. To calculate the agricultural area per municipality we used the Corine Land Cover classes related to agriculture as a primary source. We used the EUcropmap to obtain information in municipalities for which no agricultural areas were present in the Corine Land Cover.
Standardization 0 = lower population; 1 = higher population.

Road length

General description The total length of the roads per municipality (m).
Rationale The availability of transport infrastructure is critical for the adaptive capacity (IPCC, 2001). In the context of viticulture, the available road network is related to the capacity to effectively supply and manage vineyards, for instance when altering varieties or relocating plantations. An increased availability of roads is therefore related to increased adaptive capacity, as many structural changes in vineyards, which may be critical for climate change adaptation, can be performed more effectively.
Input data Road shapefile from Open Street Map (OpenStreetMap, 2022).
Calculation process Calculation of the total length of the roads classified as primary, secondary, tertiary, and tracks (up to the 5^{th} grade) in the Open Street Map dataset within a municipality in areas below 1200m of elevation.
Standardization 0 = lower road length; 1 = higher road length.

Mechanization index

General description The value of machinery & equipment per total utilised agricultural area.
Rationale A low value indicates regions with low necessity for machinery or very extensive vineyards per farm in which case the depreciations should be easy to manage. High indicator values show machine intensive viticulture in small farm areas.
Input data Statistical data about machinery and equipment and total utilised agricultural area for viticultural farms in Europe (codes in brackets in the calculation process description identify the statistics that have been used to calculate the indicator)(*European Commision, Farm Accountancy Data Network, 2022.*, n.d.)
Calculation process $\frac{\text{Machinery and equipment (€)}}{\text{Total Utilised Agricultural Area (ha)}}$ Machinery and equipment (SE455) in € = Tractors, motor cultivators, lorries, vans, cars, major and minor farming equipment. Total Utilised Agricultural Area (SE025) in ha = Total utilised agricultural area of holding. It consists of land in owner occupation, rented land, land in share-cropping (remuneration linked to output from land made available).
Standardization 0 = high mechanization index; 1 = low mechanization index.

Naturalness

General description The natural and semi-natural areas in % of the total area of the municipality.
Rationale Natural and seminatural areas play an important role for viticulture because they provide habitats for natural predators that can support pest and disease control(Winkler et al., 2017). Because a shift in climatic conditions can change patterns of crop pathogens and pests(Caffarra et al., 2012), these areas are of critical importance for adaptation purposes, as they support the resilience of vineyards.
Input data Corine Land Cover (EEA, 2022), European DEM(*EU-DEM v1.1, Copernicus Land Monitoring Service, 2022.*, n.d.)
Calculation process To calculate the percentage of natural and seminatural areas, we used the Corine Land Cover classes related to forest and seminatural areas, wetlands and water bodies, below 1200m of elevation.
Standardization 0 = low amount of natural and seminatural areas; 1 = high amount of natural and seminatural areas.

Shift in space

General description The potential of a municipality to relocate vineyards to areas with cooler climatic conditions to adapt to increasing temperature, (km^2).
Rationale Relocating vineyards to areas with cooler climatic conditions can be an effective adaptation strategy in the context of climate change(Santos et al., 2020). For instance, a shift to higher elevations allows to maintain cool climatic conditions during grape ripening under climate change and can thus preserve varietal composition and traditional wine style in a region(Egarter et al., 2018). The more potential new area is available within the boundaries of a region, the higher its adaptive capacity.
Input data Chelsa high resolution monthly average temperature data (present time 1981-2010 and future projection 2071-2100 using the ssp858 scenario and a 5-model ensemble)(Karger et al., 2017, 2020), European DEM (*EU-DEM v1.1, Copernicus Land Monitoring Service, 2022.*, n.d.) , Corine Land Cover (EEA, 2022), boundaries of wine regions in Europe.
Calculation process Calculation of present and future Huglin index. All areas that are: too cool for viticulture in the present (Huglin<1200), suitable for viticulture in the future (Huglin>1200) and classified as agricultural or forest areas are considered as potential new areas for viticulture[25–27].
Standardization

0 = lower capacity to shift in space; 1 = higher capacity to shift in space.

Water availability

General description The water available through precipitation in a municipality, (mm).
Rationale Artificial irrigation might not be feasible in all areas and can pose significant challenges to the natural water reserves of a region. The available water from precipitation (after accounting for evapotranspiration) is therefore critical to the adaptive capacity of a region. A higher availability of water is related to lower risk for drought and lower dependence on irrigation and may therefore protect regions from negative impacts of climate change.
Input data Climate moisture index over the period 1981-2010 from the CHELSA database(Karger et al., 2017, 2020), boundaries of wine regions in Europe (Candiago et al., 2022)
Calculation process The difference between evapotranspiration and total precipitation.
Standardization 0 = lower water availability; 1 = higher water availability.

Temperature variability

General description The number of climatic niches present in each municipality based on the variability of temperature (°C).
Rationale The availability of climatic niches plays an important role for viticulture, since varieties typically have a very narrow range of climatic conditions where they can produce optimum quality(Parker et al., 2020). A high variability of climatic conditions within a region thus allows the cultivation of a greater number of varieties and facilitates potential climate change adaptation through relocation of vineyards(Tscholl et al., 2021).
Input data Chelsa high resolution monthly average temperature data (1981-2010) (Karger et al., 2017, 2020), boundaries of wine regions in Europe (Candiago et al., 2022)
Calculation process Standard deviation of the mean temperature values.
Standardization 0 = lower temperature variability; 1 = higher temperature variability.

Labour force

General description Farm labour force based on the ratio between regular and total labour force (%).
Rationale Regular labour force usually lives in close proximity to the farm where it works. Areas

with a higher share of regular labour force from total labour have potentially more access to workers that can be used for specific tasks, e.g., to carry out tailored adaptation strategies.
Input data Statistics on labor force in Europe (Eurostat, 2021c)., boundaries of wine regions in Europe (Candiago et al., 2022)
Calculation process $$\frac{\text{Regular labour force}}{\text{Total labour force}}$$ Regular labour force=Labour force that is regularly employed by the farm, and it's not part of the holding family Total labour force= Total labour force employed by the farm
Standardization 0 = lower ratio; 1 = higher ratio.

Education level

General description The training level of farm managers based on their highest education level.
Rationale A higher education can improve adaptive capacity and the identification of adaptation solutions amongst farmers(Williges et al., 2017). Farmers with a higher education level are more likely to find innovative strategies to cope with and adapt to climate change and therefore have a higher adaptive capacity.
Input data Statistics on training of farm managers in Europe (Eurostat, 2022b). boundaries of wine regions in Europe (Candiago et al., 2022).
Calculation process $$\frac{\frac{\text{Farmers with full education} * 2}{\text{Number of total farmers}} + \frac{\text{Farmers with basic education}}{\text{Number of total farmers}}}{2}$$ Farmers with full education = Farmers with full agricultural training Farmers with basic education = Farmers with basic agricultural training Number of total farmers = Total number of farmers in the region
Standardization 0 = lower level of training; 1 = higher level of training.

Research accessibility

General description The distance of each LAU2 polygon included in a winegrowing region to the next major research centre on wine and vine in Europe, (m).
Rationale

Research and technology are important to find new solutions for climate change adaptation(Greiving et al., 2011). A lower distance to major research centres facilitates the transmission of new knowledge and innovative solutions and therefore improves adaptive capacity.
Input data Location of the research centers on wine and vine, boundaries of LAU2 polygons (Eurostat, 2022d), OSM European road network (OpenStreetMap, 2022), boundaries of wine regions in Europe (Candiago et al., 2022).
Calculation process Calculation of the linear distance along the roads from the centroid of each LAU2 polygon included in a winegrowing region to the nearest research centre on vine and wine. The research centres were selected based on a search in the Scopus database: we searched papers published in the last 5 years on the topic of viticulture and spatialized the affiliation of the first authors in the list.
Standardization 0 = low distance to research centres; 1 = high distance to research centres.

Debt ratio

General description The liability percentage of the total assets of farms specialized in viticulture. This indicator shows how much of the farm capital is owned by the farmer and how much is borrowed capital (%).
Rationale Financial readiness is important for farms in the context of climate change, as they might need to adopt new innovative solutions and technologies to cope with the negative impacts(Williges et al., 2017). Lower values of this indicator show regions where farms are less indebted and therefore can acquire additional capital and pay back already borrowed capital more easily in case of needed investments, e.g., to develop strategies for climate change adaptation.
Input data Statistical data about liabilities and total assets for viticultural farms in Europe (codes in brackets in the calculation process description identify the statistics that have been used to calculate the indicator)(*European Commision, Farm Accountancy Data Network, 2022.*, n.d.).
Calculation process $\frac{\text{Total liabilities}}{\text{Total assets closing valuation}}$ Total liabilities (SE485) = Value at closing valuation of total of (long-, medium- or short-term) loans still to be repaid. Total assets closing valuation (SE436) = Fixed assets + current assets.

Standardization 0 = higher ratio; 1 = lower ratio.

Return on assets

General description The adjusted net income of farms specialized in viticulture compared to their total assets (%).
Rationale This indicator is a measure of fiscal health of the farm by showing the real farm profitability. Farms specialised in viticulture are asset intensive so return on assets of more than 3% shows already success. A high value indicates farms that are economically successful and therefore have a higher adaptive capacity to climate change, as it is easier to write off investments or pay for additional labour and still be profitable.
Input data Statistical data about the return on assets for viticultural farms in Europe (codes in brackets in the calculation process description identify the statistics that have been used to calculate the indicator)(*European Commision, Farm Accountancy Data Network, 2022.*, n.d.).
Calculation process $$\frac{(\text{Farm Net Income} - (\text{Unpaid labour input} * (\text{Wages paid}/\text{Paid labour input})))}{\text{Total assets closing valuation}}$$ Farm net income (SE420) in € = Remuneration to fixed factors of production of the family and remuneration to the entrepreneur's risks in the accounting year. Unpaid labour input (SE015) = Refers to unpaid labour expressed in annual work units (AWU) → labour input by the farmer or the farmers family. Wages paid (SE370) in € = Wages and social security charges of wage earners. Paid labour input (SE020) = Refers to paid labour expressed in AWU. Total assets closing valuation (SE436) in € = Fixed assets plus current assets of the farm.
Standardization 0 = lower ratio; 1 = higher ratio.

Subsidy dependence

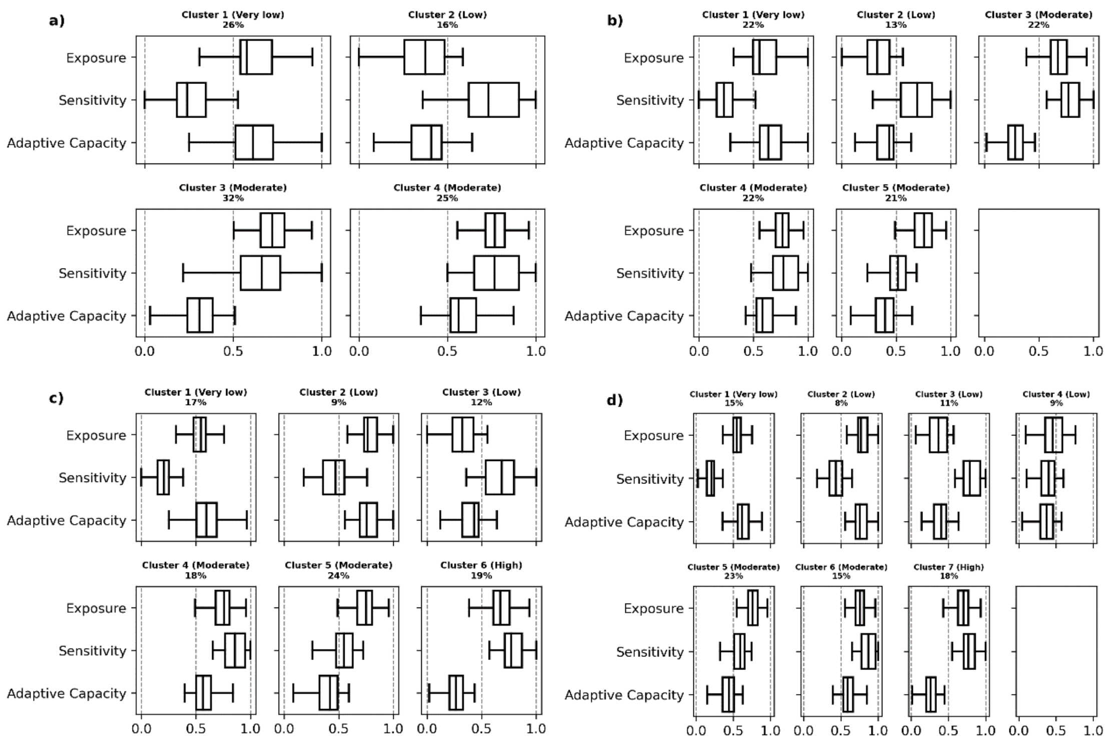
General description Dependency of farms in the viticultural sector on subsidies (%).
Rationale Farms with a low subsidy dependency are economically more viable on their own. The higher the ratio the less profitable are farms if subsidies are discontinued.
Input data Statistical data about the return on percentage of subsidies and net income for viticultural farms in Europe (codes in brackets in the calculation process description identify the

statistics that have been used to calculate the indicator)(*European Commision, Farm Accountancy Data Network, 2022.*, n.d.).
Calculation process $$\frac{\text{Total subsidies } - \text{ excluding on investments}}{\text{Farm Net Value Added}}$$ Total subsidies - excluding on investments (SE605) = Subsidies on current operations linked to production, in €. Farm Net Value Added (SE415) = Remuneration to the fixed factors of production (work, land and capital), whether they be external or family factors.
Standardization 0 = higher ratio; 1 = lower ratio.

Supplementary Methods 2: Sensitivity Analysis

To identify the optimum number of groups k for the clustering, we carried out a sensitivity analysis. We tested the clustering using 4 to 8 groups and analysed the effect of the number of groups on the obtained clusters. Figure 22 shows the characteristics of the resulting clusters for different numbers of groups.

Below a total number of six groups, we only find clusters with very low, low and moderate vulnerability levels, whereby most of the wine regions are allocated to the moderate vulnerability level (57 and 65% when using 4 and 5 groups, respectively). When increasing the number of groups, new clusters appear to include wine regions with exposure, sensitivity, and adaptive capacity characteristics in the high vulnerability level, while reducing the number of wine regions with a moderate vulnerability level. For instance, when using 6 groups, 19% of the wine regions are allocated to the high vulnerability cluster, while the number of wine regions that are classified as moderate vulnerability is reduced to 42%. This new cluster with a high vulnerability is a key group because it is the one that has poor scores for all three components. Similar results were observed when using more than 6 groups: 18 and 19% of the wine regions are allocated to a high vulnerability cluster when using 7 or 8 groups, respectively. Working with less than 6 groups therefore would produce an underestimation of present vulnerability because regions with a high vulnerability are clustered together within groups of moderate vulnerability. Increasing the number of groups further leads to a more fine-tuned separation of the clusters, for instance a new cluster with a low vulnerability level appears when using 7 groups and a new cluster with a moderate vulnerability level when using 8 groups. However, the overall share of appellations in the different vulnerability levels remains very similar, for instance 21, 28 and 27% of the appellations fall into the low vulnerability level and 42, 38 and 40% into the moderate vulnerability level using 6, 7, and 8 groups, respectively.



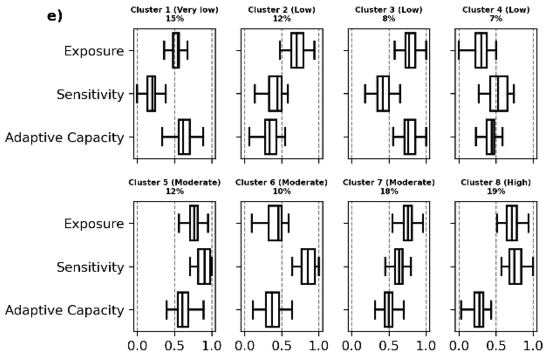


Figure 22. Characteristics of the clusters using a) 4, b) 5, c) 6, d) 7 and e) 8 groups for clustering.

We also analysed the percentage of wine regions that are assigned to the same vulnerability level across different numbers of groups (Table 16). Results with 6 or more groups are all very similar to each other, with at least 75% of the regions assigned to the same vulnerability level. In contrast, results with fewer than 6 groups are very different from those with 6 or more groups, which is mostly related to the fact that no regions are assigned a high vulnerability when using less than 6 groups.

Based on the sensitivity analysis presented here, we conclude that the best number of clusters for the study is 6. The use of 6 groups makes it possible to identify wine regions with a high vulnerability level but avoids an increased disaggregation with a large number of groups. Meanwhile, it assures that up to 87% and 75% of the regions obtain the same scoring as when using 7 or 8 groups, respectively.

Table 16. Percentage of wine regions with an equal level of vulnerability for different number of clusters.

Number of groups	4	5	6	7	8
4	-	92	68	64	51
5	92	-	70	64	55
6	68	70	-	87	75
7	64	64	87	-	78
8	51	55	75	78	-

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Relòjo mai stuf de ’n tènp ndat

i travi e le piere i scròca;

tel scur fa pégola

sol che i gat e ’l ciòc

i sarà bòni de ’ndar pian pian

ndé che i sa, ’ndé che i ol[2]

[2] From Luciano Cecchinel, “*burigòt de nòt”*, included in Sanjut de stran, Marsilio, 2011.

Estratto per riassunto della tesi di dottorato

L'estratto (max. 1000 battute) deve essere redatto sia in lingua italiana che in lingua inglese e nella lingua straniera eventualmente indicata dal Collegio dei docenti.

L'estratto va firmato e rilegato come ultimo foglio della tesi.

Studente: Sebastian Candiago matricola: 956407

Dottorato: Science and Management of Climate Change

Ciclo: 34°

Titolo della tesi[1] : Viticulture and climate change: a socio-ecological perspective

Abstract: English version

Vineyard landscapes result from centuries of evolution between humans and nature, in which winegrowers have developed the necessary knowledge about grapes, the environment, and techniques that yield the most distinguishable wines. Nowadays, this equilibrium is threatened by climate change. This thesis explores the benefits of adopting a socio-ecological perspective to study the impacts of climate change on viticulture. The first chapter presents a systematic review that investigates published literature on vineyard landscapes and climate change to identify if and how a socio-ecological perspective was adopted. The second chapter focuses on the production of comprehensive geospatial data to analyse quality winegrowing regions in Europe under climate change. The third chapter presents the first climate change vulnerability assessment of viticulture at the European level. Results show that the adoption of a socio-ecological perspective increases knowledge on the mechanisms that regulate the functioning of viticultural areas, giving insights on possible strategies that can enhance the resilience of these regions.

Abstract: versione in Italiano

I paesaggi viticoli sono il risultato di secoli di evoluzione tra uomo e natura, in cui i viticoltori hanno sviluppato le conoscenze di uve, ambiente e tecniche per produrre i vini migliori. Oggigiorno, questo equilibrio è minacciato dai cambiamenti climatici. Questa tesi esplora i benefici di un approccio socio-ecologico per lo studio degli impatti dei cambiamenti climatici sulla viticoltura. Il primo capitolo analizza la letteratura sui paesaggi viticoli e i cambiamenti climatici, identificando se e come in questo campo sia mai stato adottato un approccio socio-ecologico. Il secondo capitolo è incentrato sulla creazione di dati geospaziali adatti all'analisi delle regioni viticole europee che producono vini di qualità nel contesto dei cambiamenti climatici. Il terzo capitolo presenta la prima analisi di vulnerabilità della viticoltura ai cambiamenti climatici a scala europea. I risultati mostrano come l'adozione di un approccio socio-ecologico faciliti la conoscenza dei meccanismi che regolano il funzionamento delle aree viticole, suggerendo possibili strategie per migliorare la resilienza di queste regioni.

Firma dello studente

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[1] Il titolo deve essere quello definitivo, uguale a quello che risulta stampato sulla copertina dell'elaborato consegnato.