

Grape expectations: climate change impacts, viticulture and socio-economic systems



Three Choirs Vineyard. Photo: B M Reyniers

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This thesis is submitted in partial fulfilment for the requirements of the MPhil Environmental Policy.

Statement of originality

This is to declare that, to the best of my knowledge, this thesis is an outcome of my independent and original work. This thesis has not been submitted elsewhere for any degree or any other purposes.

I certify that the intellectual content of this work is my own, and I have duly acknowledged all the sources from which information, data and ideas have been taken.

B M Reyniers

28/02/2024

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Abstract

This research investigates impacts of climate change on viticulture, with consideration for English and Welsh vineyards, and acknowledgement of the complex relationships between the social and environmental system. A systematic map was created to methodically analyse the published scientific literature on observed impacts of climate change on viticulture. This is believed to be the first of its kind on this topic and has revealed novel insights. After screening over 12,000 articles, 158 were included for full text extraction. It was found that temperature is the most observed factor ($n = 147$) that is increasing ($n = 142$) with climate change. Alongside this, timing of phenological events was found to be increasing ($n = 61$) whilst the response to precipitation was either decreasing or ambiguous ($n = 62$). Grapes were found to be increasing in sugar ($n = 25$) and alcohol content ($n = 16$) and decreasing in acidity ($n = 17$). Wine quality and fruit quality were found to be either decreasing or had an ambiguous response ($n = 30$ and $n = 16$ respectively), with yield also decreasing ($n = 17$). This poses a significant threat to grape growers and wine makers who were vastly under-represented in the literature ($n = 19$ and $n = 8$ respectively). The social-ecological system of viticulture is embedded in the concept of *terroir* but is also under-represented in the literature. This poses an opportunity to enhance adaptability and resilience, as viticultural stakeholders already have an appreciation for the interconnected nature of oenology. Given the emergent status of the English and Welsh wine industry, there are pertinent lessons learnt that can be extrapolated from this study that the industry would benefit from exploring further in future research, such as localised studies and further exploration of the social-ecological system.

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Relevant definitions

Some definitions for relevant terms used throughout this piece of work:

Term	Definition
Cultivar	A cultivated variety of grape, selected for characteristics, and propagated using hybrids, grafts or clone
Socio-ecological systems thinking	An approach that emphasises the relationship between people and nature, and the interdependencies they have on each other (Folke et al., 2010; Folke et al., 2016)
Terroir	“Not easily grasped but includes physical elements of the vineyard habitat – the vine, the subsoil, siting, drainage, and microclimate. Beyond the measurable ecosystem, there is an additional dimension – the spiritual aspect that recognises the joys, the heartbreaks, the pride, the sweat and the frustrations of its history” (J. E. Wilson, 1998)
Varietal	The dominant ($\geq 75\%$) grape variety in a wine
Viniculture	The science of wine making
Viticulture	The farming of grapes

Section 1. Project overview

Research aim

The key aim of this research project is to understand the impacts of climate change on viticulture and consider the interactions between the impacts and consequences for the viticultural system, with specific implications for the English and Welsh wine industry. This research thesis will help to gain insight into learnings that can be applied to the emerging sector.

Problem statement

Climate change has resulted in areas that were previously unsuitable for economically successful viticulture to now become viable for production. England and Wales are relevant examples of this, and are undergoing rapid expansion of viticulture, with an emphasis on sparkling wine production.

As the English and Welsh wine industry is in its relative infancy, major knowledge gaps exist within the scientific literature concerning a variety of pertinent topics such as: the impact climate change has had, and will continue to have, on the industry, understanding the socio-economic systems and impacts, as well as the concept of *terroir* in application to English and Welsh viticulture. A complex concept, *terroir* is an 'untranslatable' French word, that includes the physical elements of a vineyards, including climate, geography and soil, as well as social and contributions such as knowledge and guardianship. This concept is inherently embedded in the idea of all the contributing factors used to make wine, which are all impacted by the consequences of anthropogenically induced climate change, which forms the basis of social-ecological systems thinking, and how these are interconnected.

The continued growth and enhancement of the English and Welsh wine industry is intrinsically linked with climate change, as the climate warms and becomes more suitable for a wider range of vine cultivars. By number, the vast majority of vineyards found across England and Wales are small in scale (individually less than five hectares in size). The landscape is a mixture of emerging home-grown talent, as well as key imported knowledge. Smaller producers that

are hobby or part time viticulturalists are competing with large scale and international land purchases and investment. Improved understanding of climate change threats and opportunities will serve to benefit the industry and help prepare for the uncertain future that climate change poses. Additionally, consideration of the wider socio-economic impacts, such as risks and opportunities for producers, will be beneficial to understanding the role and impact the industry can have in the wider landscape. Furthermore, through enhancing these understandings, learning may then be extrapolated to additional emerging regions, which due to climate change are now also viable for wine production, such as new emerging areas in Canada Finland and Norway.

Research objectives

The principal research objectives for this thesis are:

1. Identify and synthesis the published impacts of observed climate change on global viticulture
2. Consider implications of, and impact on, climate change in the English and Welsh wine industry
3. Explore the interactions between climate change impacts and consequences for the viticultural socio-economic system
4. Identify current knowledge gaps to guide future research in this field

Viticulture and climate change

The grapevine, *Vitis vinifera*, is a crop indigenous to the Mediterranean basin, with fruit known as grapes, which are used to make wine (Lereboullet et al., 2013). The grapevine is now found on six continents, and the agriculture of growing grapes, known as viticulture, is a global industry (Schultz, 2016), yet more than 70% of the world's wine is made in Europe (Fraga et al., 2012; Malheiro et al., 2010). Combined, table and wine grapes are ranked the fifth most valuable crop in the world (Anderson et al., 2012; Schultz 2016). The grapevine is a heat demanding plant and different varieties, known as cultivars, require specific temperature ranges or radiation intensity in order for their fruits to fully ripen. In addition to this, there are also requirements for precipitation levels both seasonally and annually, as well as ground moisture levels during particular growing phases of the vine (Malheiro et al., 2010). Due to climate change, patterns in weather, temperature and precipitation are being altered across much of the commercial growing area. These changes simultaneously pose both great threats and great opportunities for global viticulture (Malheiro et al., 2010; Lereboullet et al., 2013; Schultz 2016). An increase in temperature has altered the timing of key phenological events for the grapevine, as well as altering some historic site suitabilities for high quality wine production. Together these lead to potential range shifts and provide opportunities for previously unsuitable regions to develop and expand their viticultural potential (Jones et al., 2005; Schultz and Jones 2010).

Anthropogenically induced climate change has unequivocally caused global mean surface temperatures to rise by 1.1°C, which has been widely accepted to be responsible for adverse impacts related to nature and people, and has been unequally distributed across systems. Furthermore, these impacts have been attributed to economic damage to agriculture, nature, tourism and land (IPCC, 2023). More specifically, climate change is acknowledged widely for having a global impact on grape growing, known as viticulture, and wine making, known as viniculture (e.g. Jones et al., 2005; Schultz and Jones 2010; Santillán et al., 2019). Whilst there are ongoing debates about the specific impacts and implications that will be experienced in different wine making regions around the world, there are many examples of the

consequences of climate change occurring in vineyards and wineries. This in part is due to the climatic requirements that grapes require to appropriately ripen, resulting in optimal fruit quality, to produce quality wines. Temperature based metrics such as mean temperature and degree-days often define the climate-maturity ripening potential that top quality wine regions have traditionally fallen into (Jones, 2007). For example, Pinot Noir is typically grown in regions that are roughly 14.0 – 16.0 °C, which is a cooler and more moderate climate compared to Cabernet Sauvignon which is found in warmer regions that tend to span 16.5-19.5°C. This is why Pinot Noir tends to be found in Burgundy or Northern Oregon, compared to Cabernet Sauvignon which is commonly grown in Bordeaux or Napa (Jones, 2007). Due to climate change, the climate in these areas is warming, altering the mean temperature and growing degree days, pushing the boundaries of optimal production. Some researchers argue that quality is likely to decrease in regions that are exceeding the higher end of optimal temperature isotherms for some grape cultivars as climate change, driving temperatures higher, alters geo-thermal suitability (Jones et al., 2005).

There are several key phenological stages for grapevine growth, which have implications for the health and quality of the vine and wine. The most significant stages are budburst (débourrement), flowering (floraison), veraison (maturation and colour change of grapes) and harvest (maturation of the grape) (Jones and Davis, 2000; Daux et al., 2012). Climate change has impacted the timing of some of these phenological events, such as bud burst, veraison, and harvest and as well as varietal expressions, like aroma and acidity in wine have been widely reported (Malheiro et al., 2010; Cook and Wolkovich, 2016).

Research has found that in Australia, North America and Europe long-term temperature increases are raising sugar concentration and decreasing acidity (Schultz, 2016). For areas such as Champagne, a region in northeastern France famed for sparkling wine, this is particularly pertinent, as their wines are hallmarked by refreshing acidity (Skelton, 2014).

It comes as no surprise that different grape varieties are responding differently to the impacts of climate change. Merlot and Cabernet Sauvignon in Bordeaux are producing higher sugar to acid ratios in a longer growing season (Jones and Davis, 2000). The response of Chardonnay to climate change has been found to be largely positive, with global quality ratings increasing,

yet too much of an increase will likely lead to a decline once optimal thresholds are surpassed (Jones et al., 2005). Bunch sizes of Riesling have been found to increase fourfold with a temperature increase from 20°C to 30°C, yet no changes in bunch size have been observed in Shiraz (Schultz, 2016). Overall, it seems that white grape varieties are more sensitive to temperature changes than red grape varieties, which appear more tolerant. A study which evaluated 24 different viticultural regions across Australia observed that temperature affected vintage variability far more strongly in white wines compared to red wines (Sadras et al., 2007).

Paradigm shifts of environment require a review of viticultural management, as well as consideration for the ramifications on wine quality (Cook and Wolkovich, 2016). Identified as one of the most important climatic factors for determining top-quality vintage wine, growing season temperatures, and any long-term changes to it, demand both review of viticultural practices and vinicultural techniques (Cook and Wolkovich, 2016; Davis et al., 2019). In Priorat, a north-eastern Spanish wine region renowned for balanced and intense wines, there is now a risk of quality being affected due to temperatures being pushed to the upper limits of the optimal isotherm (Bauer, 2008; Ramos et al., 2008). However, in other parts of Western Europe, where drought was historically coupled with higher temperatures, there is now a weakening of this relationship, resulting in earlier harvest whilst maintaining integrity of quality and quantity for some regions (Daux et al., 2012; Cook and Wolkovich, 2016). This divergence of existing patterns is reflective of the stochastic nature of climate change, and its impacts and requires further investigation.

Climate change is both a threat and an opportunity for global viticulture. Climate change is stochastic, and therefore the need for adaptive capabilities is vital if vineyards and wineries are to be able to manage volatile conditions. Yet, there is much variation in attitudes towards climate change in the viticultural industry (Fleming, 2015; Nesbitt et al., 2016; Nesbitt et al., 2018). A study undertaken in Australia found that climate change is ranked as a higher priority for decision makers at wineries compared with growers due to the risk of final product quality. Additionally, there is a correlation between the belief in the reality of climate change and the need to adapt to the consequences of it (Fleming, 2015). Whilst some established regions may be at their upper threshold limits for temperatures, previously unsuitable regions are now

presenting more viable opportunities for viticultural expansion, such as China (Li et al., 2017), England and Wales (Nesbitt et al., 2016; Nesbitt et al., 2018, Biss and Ellis, 2022).

English and Welsh viticulture and climate change

Overview

Due to an increase in average temperatures, England and Wales has now become a more suitable location for viticulture (Nesbitt et al., 2016). Climate change has led to an increase in temperatures across the region, as well as increased precipitation levels. These are both set to increase under climate change projections (Met Office, 2024). This poses both threats and opportunities for the expansion of English and Welsh wine (Nesbitt et al., 2018).

However, grape growing for wine making is not completely novel to this part of the world. The origin of grape growing in England and Wales can be traced back to the Romans in the second century, who had several vineyard sites spanning from the Humber to the Severn, and even a northerly site in Lincolnshire (Selley, 2008). Post the collapse of Roman Britain, there was a decrease in wine production, until the Medieval period when there was a shift in culture back to drinking wine as an aspirational drink relative to ales. In addition, the spread of Christianity increased the demand for wine for Holy Communion. There is a record of 42 vineyards across Britain ranging from East Anglia to Somerset found in The Domesday Book in 1087 (Selley, 2008; Skelton, 2019a). Viticulture declined in Britain during the Early Modern period due to several factors. These include: the vineyards of Bordeaux being a part of Eleanor of Aquitaine's marriage dowry to King Henry II which resulted in cheap French wine imports; the Black Death reducing agriculture due to insufficient workers being available to farm the land; and King Henry VIII destroying monasteries which often had vineyards attached (Selley, 2008). Following this decline, viticulture became barely more than a hobby until the turn of the 20th century. The English and Welsh viticulture revival coincides with the industrial revolution and climate warming (Selley, 2008). Castle Coch, outside of Cardiff and the seat of Lord Bute, became the first 'modern' large-scale experiment of British viticulture, however, the re-expansion was halted during the World Wars, as land was prioritised for agriculture. Since the 1950s, vine planting has become more widespread, and scientific studies into British

viticulture began. By 1977, the number of vineyards across England and Wales larger than an acre was 124, and this number has continued to increase (Selly, 2008; Skelton 2019a).

Today, the English and Welsh viticultural industry is booming. As of 2022, the number of individual vineyards is 943, with over 3,230 hectares in production, seeing a 70% increase in the last five years (see figure 1) (WineGB, 2023). Whilst most vineyards are less than five hectares in size, there are 62 that are more than ten hectares in size, and the largest is nearly 90 hectares (Skelton, 2019b).

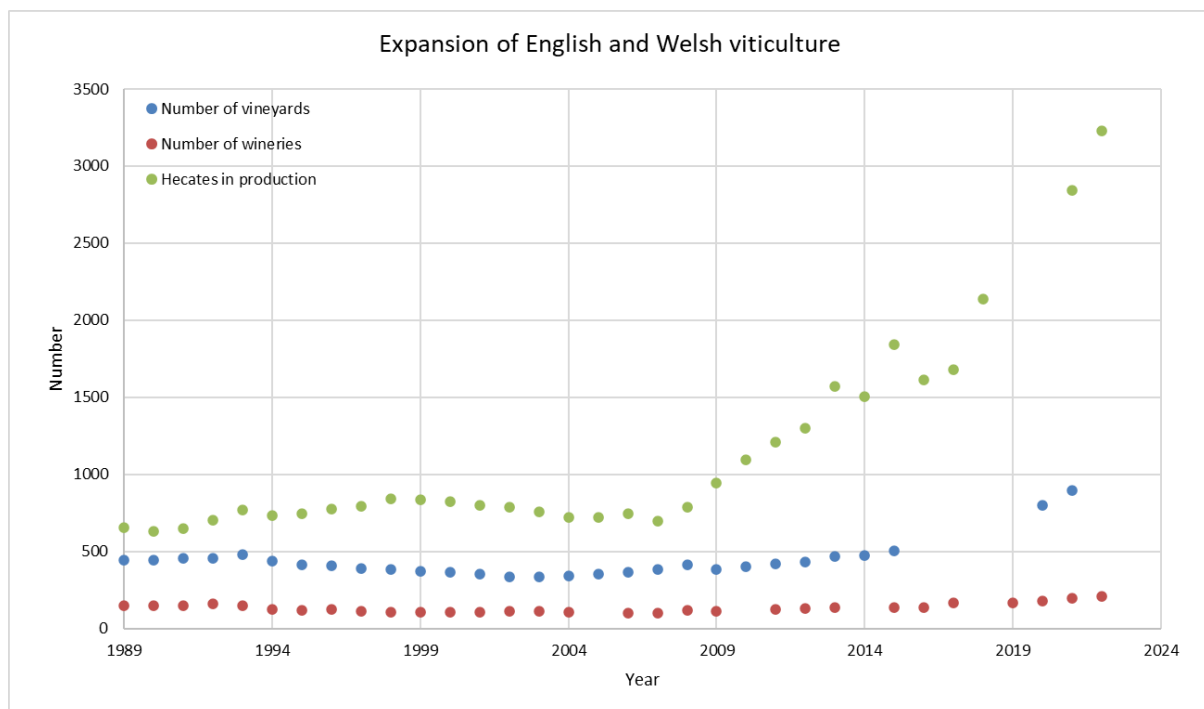


Figure 1: English and Welsh vineyards from 1989 – 2022, data taken from WineGB, 2023. Total hectares in production (green) have grown rapidly since 2005. The number of vineyards (orange) have increased since 2005. Note there are some gaps due to data availability.

The 2018 harvest was the largest recorded to date, with over 13 million bottles produced, and 12 million bottles were produced in 2022 (WineGB, 2023). The variety of grape grown varies by region, but the majority in England and Wales are Chardonnay, Pinot Noir and Pinot Meunier (WineGB, 2023). These three varieties are often known as the ‘holy trinity’ of Champagne grapes and are predominantly used to make Champagne style sparkling wines, which account for 69% of all English and Welsh wine production (Selley, 2008; WineGB, 2023). Kent (1,033 Ha) remains the largest regional producer of English wine, followed by West

Sussex (570 Ha), East Sussex (493 Ha) and Hampshire (380 Ha) (WineGB, 2023). These wines are also garnering international recognition for the quality of production, with more awards being won than ever before; even beating traditional Champagnes in blind tasting competitions (Allen, 2016). The success of this burgeoning industry has sought the attention of the Grand Marque Champagne houses of Taittinger and Pommery, who have both established vineyards in Kent and Hampshire respectively (Eads, 2018).

The potential for the English and Welsh wine industry is vast. As average season temperatures increase, this improves both quality and quantity of the grape harvest. An estimated 1.75 million vines were planted in 2023, which is equivalent to 400 Ha, and nearly 4,000 Ha in total are planted across the country, including around 600 Ha waiting to come into commercial production, that is, planted but not ready to harvest from (WineGB, 2023). With the addition of these plantings, more people will be needed to manage the vines and work in vineyards and wineries. WineGB (2023) has also reported there are 2,300 people in full-time equivalent jobs now working the UK wine sector, with a 50% growth rate forecasted by 2025. This expansion creates opportunities for rural economy development not only directly in vineyards, but with knock on opportunities for development of local tourism, wine trails, administration and boosting demands for hospitality, restaurants, and accommodation due to more people visiting an area. Furthermore, many English and Welsh vineyards are themselves developing additional sources of income, such as hosting weddings, pop-up restaurants, and family events. These social impacts for rural communities are important to consider when evaluating the consequences of English and Welsh viticultural development and is an example of nature-human interactions expanding and developing across the region in a socio-ecological system. With these factors in mind, it is important to evaluate the implications of continued expansion that allow for optimum growth whilst maintaining environmental integrity.

Climate change and English and Welsh viticulture

Climate change has been observed in England and Wales, with an increase in temperatures, changes in precipitation, and extreme weather events recorded (Met Office, 2024a), which has had an impact on English and Welsh viticulture (Nesbit et al., 2016). The Central England Temperature series, through collation of early instrumental temperature series, is the longest

running instrumental temperature series globally, dating back to 1659 (see figure 2) (Met Office, 2024a). This allows climate scientist to clearly see the increase in temperatures, aligned with anthropogenically induced climate change. In England, the ten warmest years in the series have occurred since 1990, and the top five all since 2006.

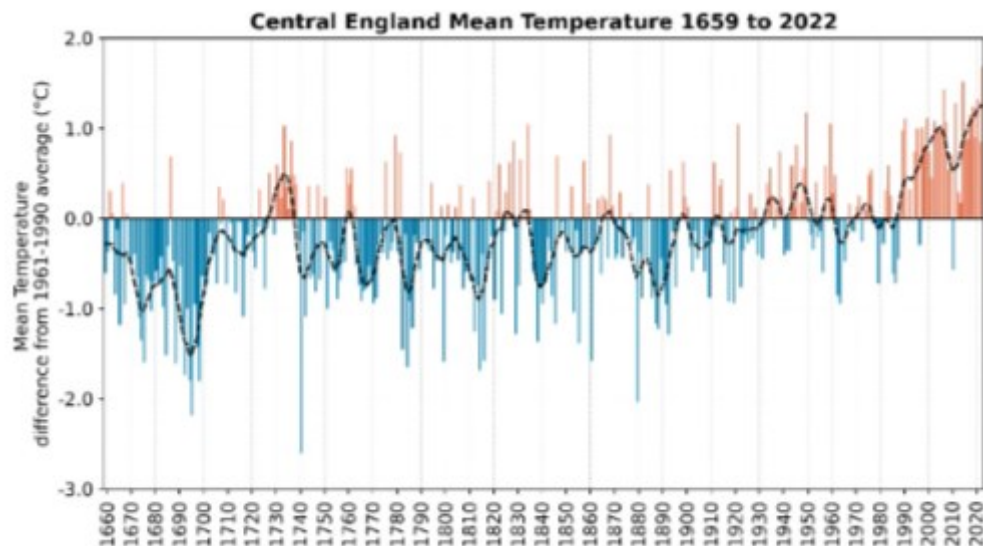
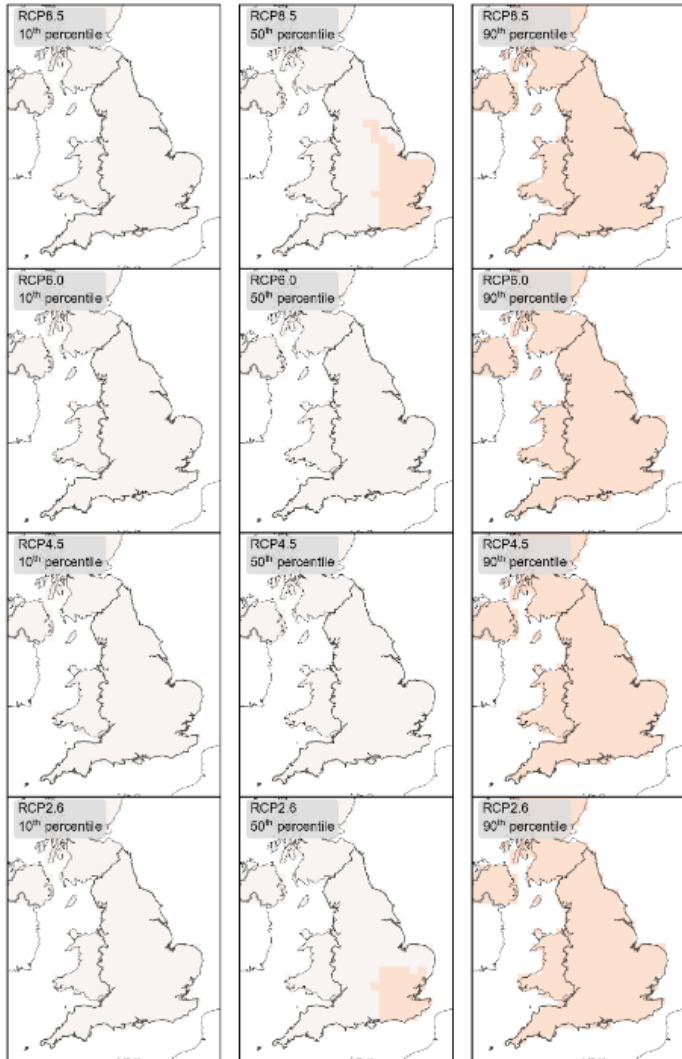


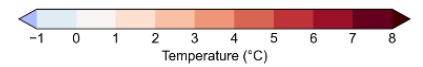
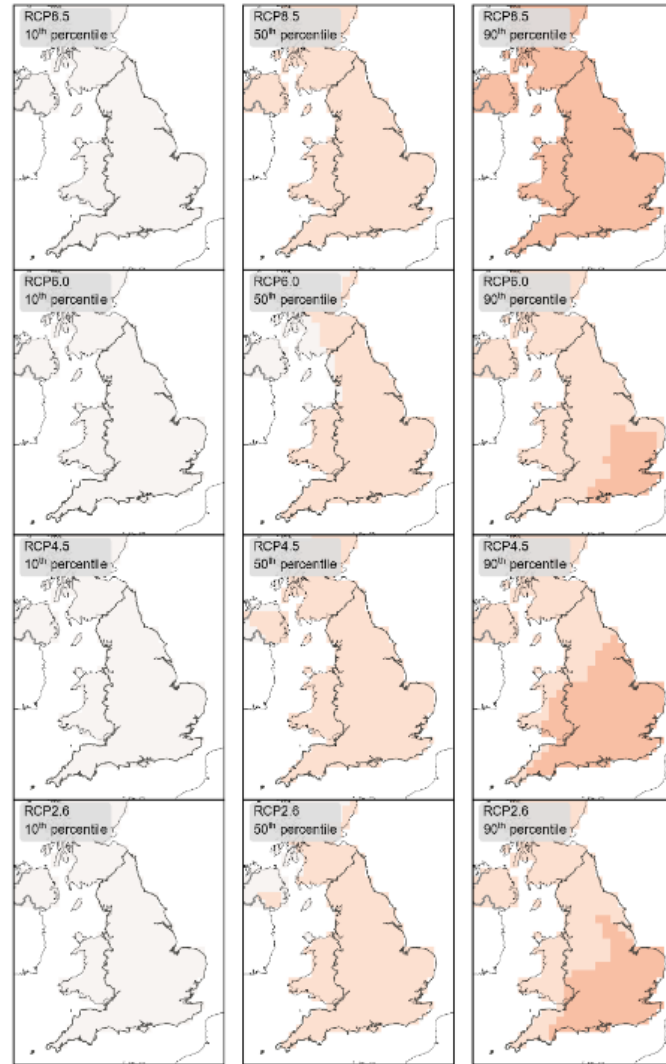
Figure 2: Temperature changes recorded by the Central England Mean Temperature. The longest running temperature series in the world, the Central England Mean Temperature series shows the continued upward trend of temperatures caused by anthropogenically induced climate change. (Source: Met Office, 2024.)

Findings from Nesbit et al., (2018) highlight the site suitability of areas in England and Wales has changed in recent years, in part driven by the change in climate. Additionally, perceptions of climate change are also important to note, as Nesbit et al., (2016) found that 64% of English and Welsh producers saw climate change as a threat, whilst 29% saw it as a threat and an opportunity, and just 7% saw it as an opportunity. However, there has been a shift in perceptions more recently, with more stakeholders seeing it as an opportunity (Gannon et al., 2023).

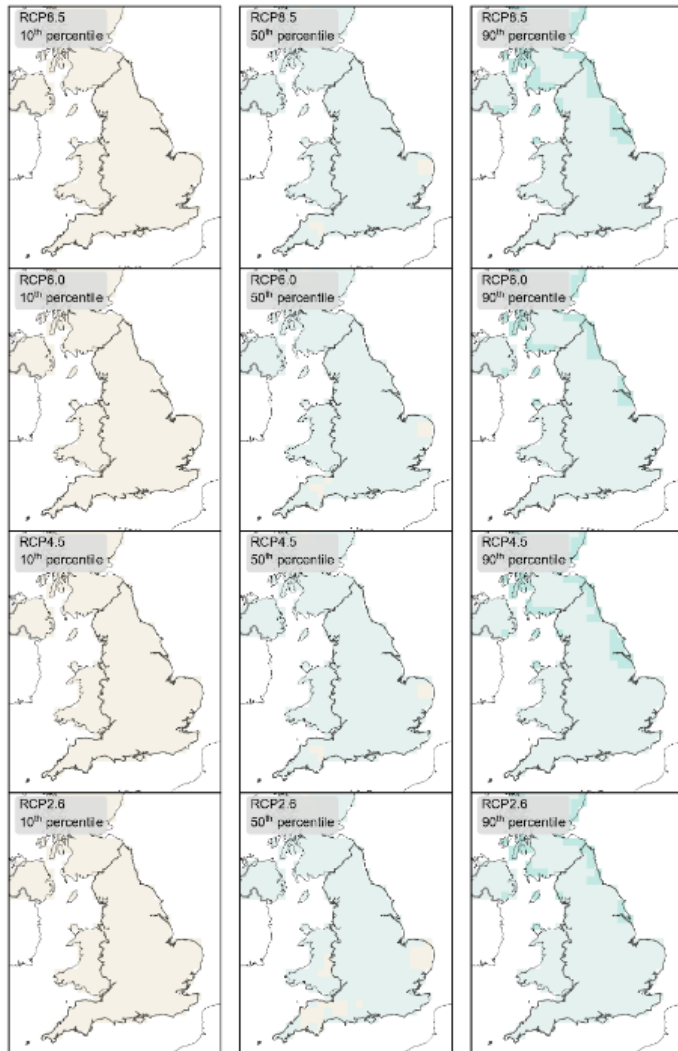
3.a) Annual mean temperature anomaly in
England for 2020-2039 minus 1981-2000



3.b) Annual mean temperature anomaly in
England for 2040-2059 minus 1981-2000



3.c) Annual precipitation anomaly in England
for 2020-2039 minus 1981-2000



3.d) Annual precipitation anomaly in England
for 2040-2059 minus 1981-2000

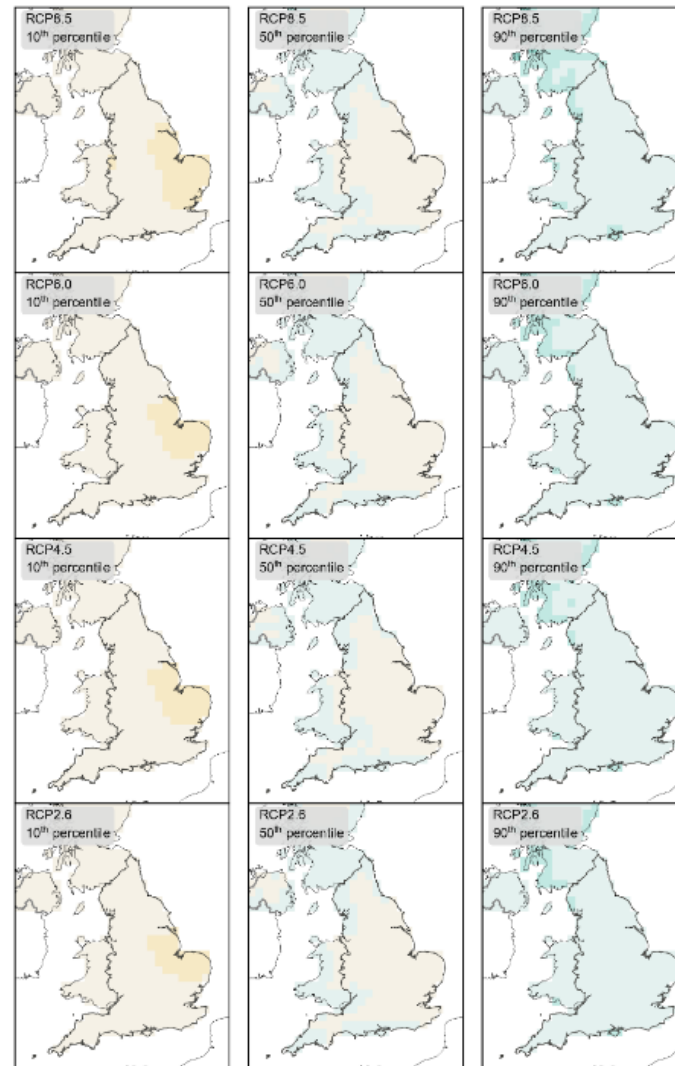
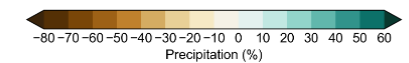


Figure 3. a-d) Climate change projections in England and Wales generated using the UKCP18 model. Climate change projections show that, to varying degrees depending on the Representative Concentration Pathway (RCP) scenario, across England and Wales temperatures and precipitation levels are set to increase. (Source: Met Office, 2024b)



As temperatures continue to rise, growers have need to remain mindful of their varietal choices for planting. It is possible that red wines may become viable in England and Wales, and whilst some research has explored the possibility of commercial viticulture in Scotland under high end climate change scenarios, which appears to be unlikely (Dunn et al., 2019), a practical approach needs to be taken, that considers the holistic impacts of climate change. It is reasonable to postulate that if the United Kingdom is experiencing the realities of RCP 8.5, establishing hard to mature red vines, such as Malbec, will be an unlikely priority. However, as the majority of vineyards are located in the south-east of England (see figure 4), which overlaps with where UKCP anticipates higher temperature and precipitation levels (see figure 3 a-d)). This may be of concern to growers, and it would be beneficial for research efforts to focus on this area to identify further threats, opportunities, and what appropriate risk management strategies may look like.

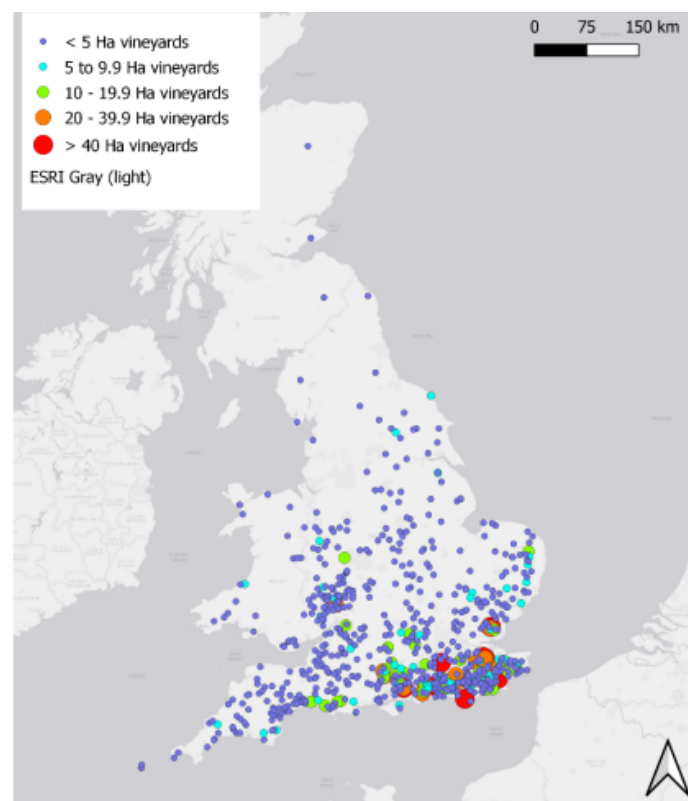


Figure 4. Map showing the distribution of vineyards around the United Kingdom. There is a significant range in size of vineyards, from less than a hectare to over 90 hectares. The majority of vineyards are less than 5 hectares, and most are found in the south and south-east.

It has been acknowledged that climate change impacts are hitting the planet in a faster rate than previously anticipated (Tollefson, 2022; IPCC, 2023) and remaining mindful of this when considering the adaptative capacity of the industry, as well as future proofing, is pertinent. Extreme weather events are likely to occur in a higher frequency (IPCC, 2024). Whilst frost events maybe decreasing in frequency globally, the risk of a late frost event to damage vines during budburst remains high; in 2022, nearly a third of producers in the United Kingdom reported that spring frosts had affected their yield. Yet this number reduced drastically down to only 6% of producers in 2023 (WineGB, 2023b). As discussed previously, the challenge lies in appreciating where inter-annual variation stops, which would be considered par for the course in viticultural practices, and where climate change impacts begin, which requires adaptability and resilience.

Warmer and wetter weather, which is expected to increase in England and Wales (see figure 3 a-d) also poses a greater challenge of pests and pathogens (Nesbit et al., 2016). The 2023 Harvest Report found that over 40% of producers in the United Kingdom lost some crop to *Botrytis*, and 27% lost some crop to mildew. Both figures were higher than reported in 2022 (WineGB, 2023b). This presented another layer of complexity and risk that producers need to shoulder, which can have economic implications in terms of lost revenue and could damage their business prospects.

Social-ecological systems

Social-ecological systems are complex, and using this system perspective allows for the emphasis of the relationship between people, societies, cultures, economies, and the biosphere that they are embedded in. Simultaneously, social-ecological systems thinking acknowledge that these people, societies, cultures, and economies are shaped by, depend upon, and must evolve with the biosphere (Folke et al., 2016). Resilience thinking encompasses the complexity and dynamics of social-ecological systems, and has three central aspects: resilience, adaptability, and transformability (Folke et al., 2010). Walker et al., (2004) defined resilience as “the capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks”. Adaptability is seen as the capacity of actors in a social-ecological system to

influence resilience, which is essentially management (Walker et al., 2004). Transformability refers to the capacity of crossing thresholds whilst developing new trajectories, and when this occurs at smaller scales it allows for resilience at larger scales (Folke et al., 2010). Whilst this is a complex construct, this perspective addresses the challenge of “stewardship of development” in the context of long-term sustainability and human interaction and development (Folke et al., 2016).

It has been acknowledged that environmental governance is most effective when ecological processes are partnered with the institutions that are managing human-environment interaction (Leslie et al., 2015). Viticulture is a process that has a strong connection to the concept of human environment interaction, due to *terroir*. Dating back to fourteenth century Burgundy, France, it is claimed by some that the word is untranslatable, originating from an experience-based knowledge and understood only by the *vigneron*, a French ‘wine grower’ (Haynes, 1999; Wilson, 2001). Pioneering researcher, J. E. Wilson was one of the first non-French speakers to explore the term in a more modern context, and defined *terroir* as:

“...not easily grasped, but includes physical elements of the vineyard habitat – the vine, subsoil, siting, drainage, and microclimate. Beyond the measurable ecosystem, there is an additional dimension – the spiritual aspect that recognises the joys, the heartbreaks, the pride, the sweat and the frustrations of its history” (Wilson, 1999).

At its essence, *terroir* is the interrelationships and interactions between all the factors involved in making wine, which can be divided into five main categories; geological (relating to geology), pedological (relating to soil), physiographic (relating to land form), meteorological (relating to weather and climate), and vinicultural (relating to grape growing and wine making practices, and often including the human element) (Haynes, 1999). In a modern context, the term is frequently misunderstood but forms the backbone of much oenological conversation. Most modern use of the term is limited predominantly to mainland Europe, and it is used as the foundations for the appellation system, which designates protected viticultural regions, and is often closely linked to quality (van Leeuwen et al., 2004). Additionally, in modern usage many factors of *terroir* end up being combined or grouped together and sometimes the human

aspect is completely disregarded, despite its role being an important dimension (Haynes, 1999; Wilson, 2001). The traditional spiritual and human aspects of *terroir* demonstrate the importance of the relationship between a wine grower and their land. This poses an opportunity to apply a socio-ecological systems thinking lens onto a system that is forged in the close interplay between social and environmental interactions.

Considering that *terroir* is a concept with deep roots in human-environmental interactions, applying the lens of social-ecological systems thinking as an approach to resilience, adaptability and transformability within the viticultural industry presents a unique opportunity to develop the dialogue of sustainability. Winemakers are a group that are inherently adaptable and must manage inter- and intra- annual variation of weather whilst maintaining quality and vintage integrity. Environmental issues are already testing the limits of current management approaches, and there is demand for innovative and integrative approaches across disciplines. Theoretically, social-ecological systems thinking offers a persuasive approach for environmental management (Virapongse et al., 2016).

Knowledge gap identification

In a global context viticultural research has been focused on investigating and predicting the impacts of climate change, as well as anticipating variability that may emerge within the industry (Holland and Smit, 2010; Roehrdanz and Hannah, 2020). Research to date has also considered how different warming scenarios may affect viticulture on different spatial and temporal scales (e.g. Webb, Whetton and Barlow, 2007; Duchêne et al., 2010; Santillán et al., 2019; Droulia and Charalampopoulos, 2021). However, a systematic review of the literature is lacking, as well as consideration of how impacts vary, and a review of how they vary between regions. Furthermore, knowledge concerning the vulnerability of the global wine industry is minimal, as well as how climate change impacts may look in practical scenarios. In order to reduce overall vulnerability to climate change, these research gaps need to be addressed (Holland and Smit, 2010).

To date, research has largely been focused on commercially large scale, historic and economically significant wine producing regions. Regions that are considered 'emerging' and

are expanding in production and viability due to climate change are lacking in scientific research. Concerning English and Welsh viticulture in particular, research has been predominantly limited to site suitability models, and there are still knowledge gaps concerning climate resilience (Nesbitt et al., 2016; Nesbitt, Dorling and Jones, 2019).

Research in context

Famously sensitive to climate, viticulture is a global industry that is rooted in the impacts of global warming. It has been generally acknowledged in the literature that climate change is impacting viticulture on global (e.g. Anderson, 2017; Jones et al., 2005; Mozell & Thachn, 2014; Schultz, 2016), regional (e.g. Moriondo et al., 2011; Fraga et al., 2012; Chen et al., 2016; Maciejczak and Mikiciuk 2019) and local scales (e.g. Ashenfelter and Storchmann 2010; Holland and Smit 2014; Boselli et al., 2016; Roehrdanz and Hannah 2020). Whilst grapes are able to withstand a range of temperatures, they are inherently sensitive to the climate they are grown in, with slight changes in temperature, precipitation, sun exposure and frost events affecting fruit and subsequent wine quality (Malheiro et al., 2010; Hannah et al., 2013; Arceño, 2022; Arias et al., 2022)

The climate is changing, and anthropogenic induced climate change is causing an increase in intensity and frequency of events (IPCC, 2023). Whilst agricultural productivity has increased (IPCC, 2023), global wine production is at risk due to changes effecting a variety of factors including fruit quality, yield, and wine quality (Jones et al., 2005; Fraga, 2019; Arceño, 2022). As the planet continues to face uncertainty and perturbations in the climate system, understanding changes that have been observed and recorded is vital to enhance our current knowledge in order to improve adaptive capacity. Whilst there is a range of scientific literature acknowledging the impacts of climate change, there is yet no review of this literature which presents a holistic review of these impacts that have been observed. Understanding the relationships between impacts and how they vary is crucial for developing knowledge of the relationship between climate change and viticulture. Without this solid foundation, mitigation, management, and adaptation will not be sufficient or have practical utility. By reviewing observed impacts in the literature, insights can be seen into what has happened to date, and what consequences may be reasonably anticipated in the short-term

in nearby regions. The intention of using observed data only, rather than modelled information, is so that lessons can be learned from regions that have experienced these effects of climate change. Whilst models are helpful in providing insights into potential scenarios, real world, observed data was selected as the experiences in these regions can potentially then be applied to England and Wales. To sufficiently explore the literature, a meta-data set of the information needs to be generated for analysis. A method of doing this is systematic mapping.

In recent decades, the viticultural industry in the England and Wales has rapidly expanded due to improving growing conditions for grapes (Nesbitt et al., 2016), with the area under vine expanding 74% in the last five years (WineGB, 2023). Viticulture in the England and Wales will continue to grow, benefiting from the higher temperatures during the growing season which are projected under future climate change scenarios (Mosedale et al., 2016). Yet, despite this rapid expansion, the English and Welsh wine sector remains a vastly under-researched topic (Skelton, 2014).

Viticulture is a social-ecological system, with strong relationships between people, the environment, and the wine produced. The consequences of climate change will affect this system, which is embraced through the concept of *terroir*. Whilst viticulture and *terroir* have not been explicitly considered as a social-ecological system in academic research before, it is the intention that outputs from this research can help shed light on the complexity of the interconnectivity of impacts and highlight research gaps for future scientists to explore. Furthermore, these lessons can be applied to the English and Welsh wine industry to help support the embedding of resilience into the system, to enhance its adaptability to climate change.

Systematic mapping is a methodology that was developed in response for a need to describe existing literature across a broad subject and is a way of describing literature across a broad subject through the generation of a meta-data set (James, Randall and Haddaway, 2016). A systematic map was conducted as it was deemed the most effective methodology for identifying the impacts of climate change on viticulture. By assessing the existing literature in a structured and systematic way, knowledge gaps and knowledge clusters could be properly

identified, extrapolated, and analysed. Methodologies like systematic mapping follow a rigorous, transparent, and objective process that aims to reduce selection and publication biases. They allow the reader to view the decisions made in the inclusion or exclusion of research, as well as showing the process of how conclusions are reached (James, Randall and Haddaway, 2016). It Systematic aims to collate, describe, and catalogue available evidence. Once a set of meta-data has been produced these results can be analysed, visualised, and described (James, Randall and Haddaway, 2016). The systematic map was developed as a way of identifying impacts, whilst also detailing any management strategies and identifying key themes that require further research and exploration (James, Randall and Haddaway, 2016), and this was applied to climate change and viticulture to develop this understanding.

This research aims to address the question of how observed climate change is impacting global viticulture. This project uses a systematic mapping methodology to conduct a review of how climate change is observed to be impacting viticulture globally, which is understood to be the first systematic map on this topic. Key themes that are identified in these findings are then considered in the context of English and Welsh viticulture, with consideration of areas for future research. The research also considers the complex interactions between impacts of climate change, and some of the challenges this poses to the social-ecological system of viticulture.

Section 2. Research Methods

Systematic map

A systematic map was carried out based on the methods described by Collaboration for Environmental Evidence (CEE) Systematic Review guidelines (CEE, 2013) and James, Randall and Haddaway, (2016). Information was collated on study details, environmental impacts, social impacts, economic impacts, vinicultural impacts, and any adaptation suggestions.

The systematic map was based on the following primary research question:

How is observed climate change impacting viticulture?

After an initial scoping search to identify and validate the methodology and key search terms, search string was developed using SCOPUS which was applied to title, abstract, and key words in the advanced search function. This was adapted and used Boolean operators, including a wildcard (*) in order to search for multiple word endings. The final search string used was:

("global warming" OR "global heating" OR "temperature change" OR
"weather change*" OR "climat* change*" OR "climate-change" OR
"climat* warm*" OR "climat* vari*" OR "vari* climat*" OR "climat* crisis"
OR "climat* alter*" OR "climat* adapt*" OR "climat* fluct*" OR "climate
hazard*" OR "extreme weather" OR "natural hazard*" OR "disaster*" OR
"flood*" OR "sea level rise" OR "precipitation" OR "rainfall variability" OR
"rain* vari*" OR "temperature increase*" OR "temperature decrease*" OR
"water-stress*" OR "water stress*" OR "drought*" OR "water defic*" OR
"frost*" OR "spring frost" OR "spring-frost" OR "early-frost" OR "early
frost*" OR "soil erosion" OR "soil degraded*" OR "soil chang*")*

AND

("viticulture" OR "vini" OR "viti*" OR "viniculture" OR "wine grape" OR
"vine" OR "grapevine" OR "wine" OR "oen*")*

This search string was applied to the academic data bases of SCOPUS and Web of Science to ensure as many relevant sources were included. A grey literature search was not conducted,

as the aim of this research was to explore scientific literature only. The academic records found from the search string were collated in EndNote X9 and Microsoft Excel. The articles were then screened using specific inclusion and exclusion criteria at stages of title, abstract and full text (see figure 5; see table 1). The initial download took place in May 2020, and an update of literature occurred in August 2022, following the same methodology, to ensure that the systematic map included more recent publications.

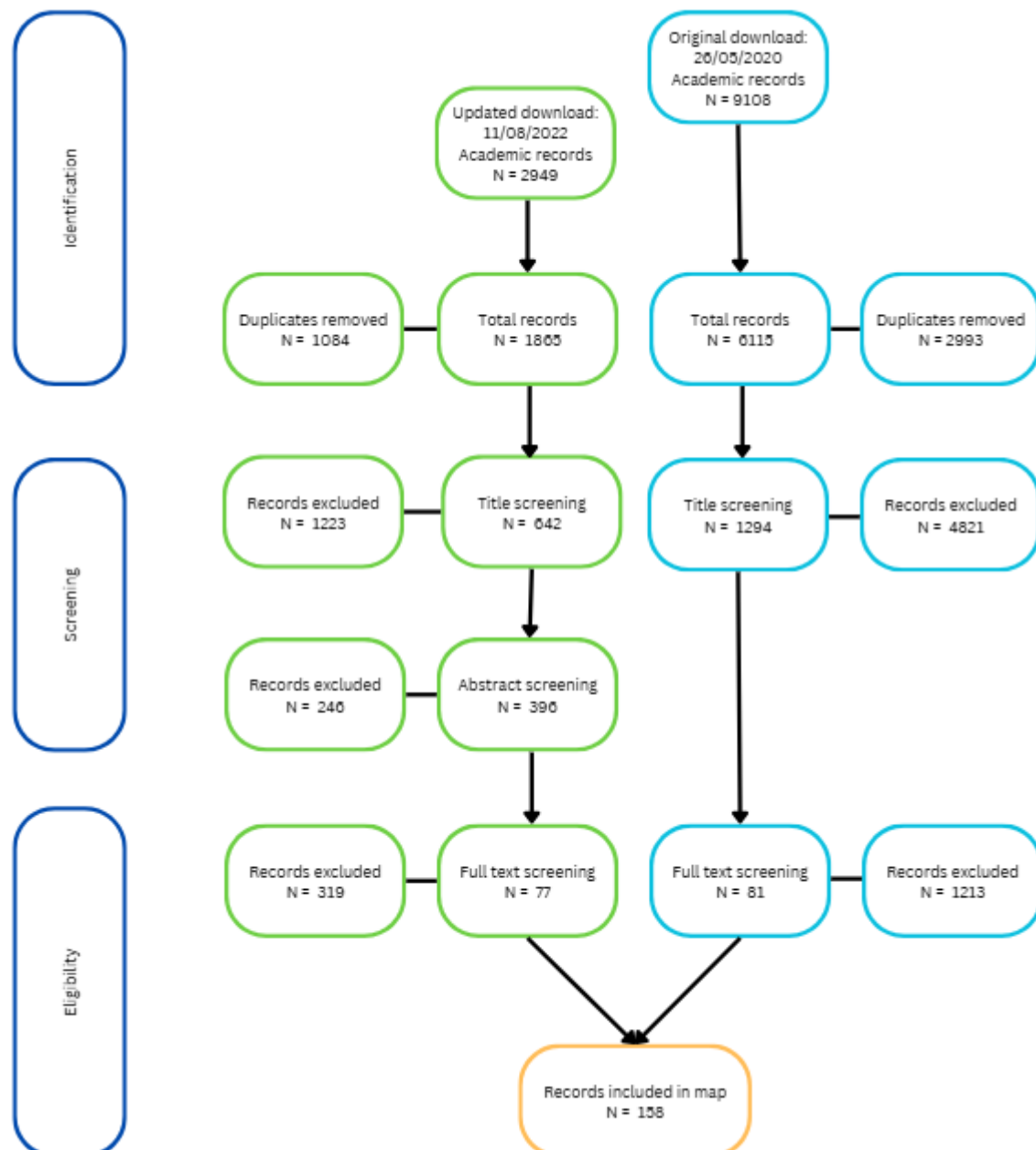


Figure 5: Number of records at each screening level for the systematic map. The combined downloads contained 12,057 records. Once duplicates were removed, there were a total of

7,980 records that were screened for eligibility against the criteria. A total of 158 records were included in the final full text extraction used to generate the meta-data set.

Table 1: Systematic mapping criteria. Criteria used to determine the inclusion and exclusion of records for the systematic map.

Include	Exclude
Papers in English	Papers not in English
Full text available	Full text not available
Main scope of article is on climate change impacts of viticulture	Articles that acknowledge climate change, but it is not the focus of the research, or findings not placed in a climate change context
Records on grapes used for wine making	Records on grapes not grown for winemaking, such as table grapes, raisins or pisco
Observed studies	Experiments conducted in greenhouses, in vineyards pot grown vines, or laboratory settings
Records that are based on historic or present data	Records that are based on modelled or future scenarios
Discussion of observed and recorded impacts of climate change on viticulture	Mitigation, adaptation, sustainability, or other focus not on observed climate change impacts
Records that attribute the impacts of climate change to the observed impacts to climate change	Records that discuss the impacts of climate change, e.g. temperature increase, but do not attribute the impact to climate change

The criteria were developed with the intention of ensuring the correct records were captured that could be used to develop a meta-data set that would sufficiently answer the specific research question. As the research was focused on observed impacts of climate change, papers that used projections or climate models were excluded from the screening process. This was due to the aim of this research to focus on real world observation to provide tangible lessons learned to emerging sectors, and those undergoing the adverse effects of climate change. Attribution of climate change was deemed essential criteria as the theme of the

research is on the observed impacts of climate change, so articles that did not attribute increasing temperatures, or other elements that are commonly attributed to climate change, were excluded. Whilst this approach is subjective, papers were included if they specifically linked the impacts discussed in the research to climate change in order for it to be considered evidence of the real world, observed impacts.

The coding was developed with both deductive and inductive approaches. A list of aspects was determined to be coded for in the data extraction, based on key aspects determined in the literature review. Additionally, as more papers were read, further themes emerged, so an inductive approach was used to include these. A Kapa analysis was undertaken to check for consistency and clarity in the criteria and inclusion-exclusion process (James, Randall and Haddaway, 2016), as per the methodology in the CEE (2013) guidance. Articles accepted after full text screening were then extracted into a coded data sheet on Microsoft Excel. Information that was extracted was broken down into categories of study details, including whether papers were from an old world or new world region, or if they were a review paper, and impacts on vineyard, social, economic, and wine factor. The impacts were identified as either observed to be increasing, decreasing, or having an ambiguous response, and input as code. Ambiguous responses were recorded for articles that did not make it clear whether factor considered were increasing or decreasing due to climate change. Once coded, the results were then synthesised and analysed, then subsequently presented into figures and tables using Microsoft Excel. The results are subsequently considered in the context of the English and Welsh wine sector.

Section 3. Research Results and Discussion

A meta-data set was created through a systematic mapping process, which resulted in information from 158 papers being extracted and analysed. The meta-data set provides insight into trends and directions of research in published literature, whilst also allowing for the identification of data gaps. The trends from the meta-data set are then considered through the lens of implications of climate change in England and Wales. The results and discussion sections are combined to allow for a more continuous flow of narrative, and with consideration of the interconnectedness of factors.

Data set and included academic records

A total of 12,057 records were download, and after the full screening process, 158 records remained which were fully extracted to produce the meta-data set. A Kapa analysis, a test for inter-review reliability, was undertaken to ensure clarity and consistency of the screening process (see table 2). This found that agreement between the two reviewers was 90%, and likelihood of agreement by chance was 71%. The Cohen's Kapa coefficient, k , is 0.65 which is considered a 'substantial agreement' as per the CEE methodology guidelines (CEE, 2013).

Table 2: Kapa analysis results. The P_o shows agreement of 90%, and a likelihood of agreement by chance, P_e , at 71%. The Cohen's Kapa coefficient, k , is 0.65 which demonstrates substantial agreement.

Kapa Analysis	
P_o	0.90
-	0.71
k	0.65

The papers included in the systematic map were plotted by year and show a continued upward trend over time (see figure 6). The trend starts to increase notably from 2012 ($n = 5$) until 2021 ($n = 34$), with a steepening curve. The year 2022, coloured orange, is not an

accurate representation of the total number of papers that may have been published in that year. This is due to the systematic download update occurring in August 2022, and therefore subsequent publications from that year were not included.

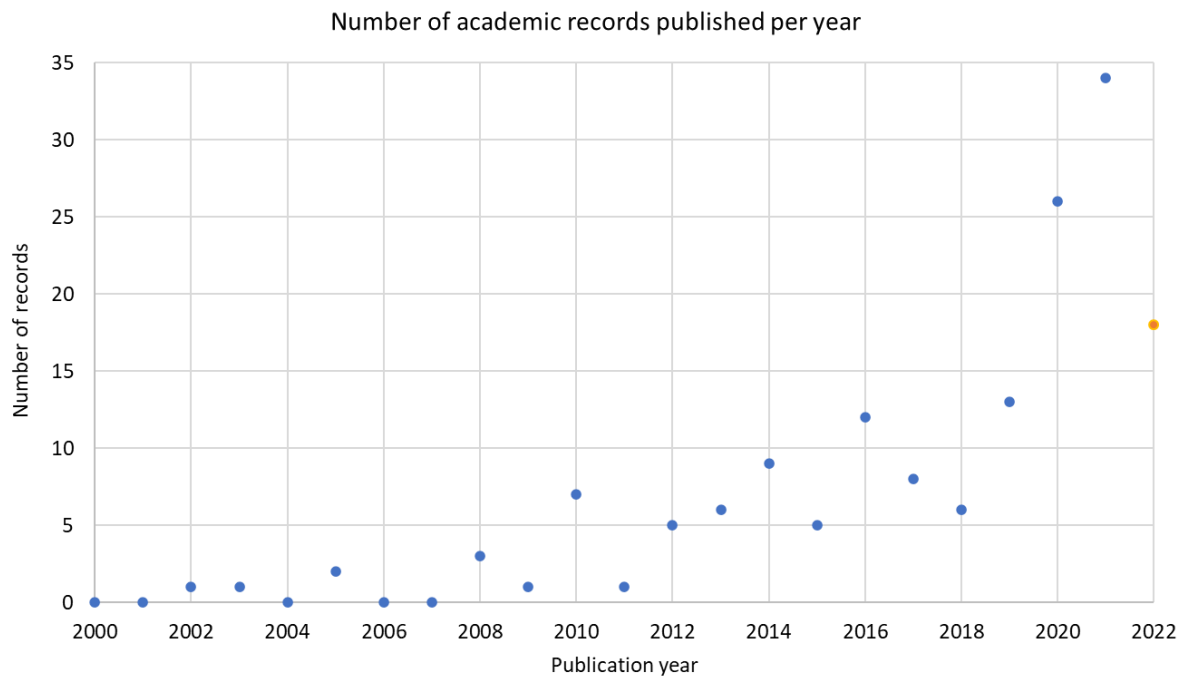


Figure 6: The number of papers published per year. A total of 158 papers were included from the systematic mapping process. The year with the highest number of papers included is 2021, with 34 records. The year 2022, coloured in orange, is not representative of a full year of publications, as the sample was collated in August of that year.

A contributing factor that may account for some of the increase in publications over time is the increased awareness, social engagement, and academic interest in climate change (Donnelly & Yu, 2017). Impacts of climate change on the environment and people has become more evidence, and therefore research interest has increased significantly. This is due in part to the effects being felt more prevalently, and scientific consensus in the reality of anthropogenically induced climate change (IPCC, 2023). This necessitates interest to understanding these impacts, particularly in an industry such as viticulture which dates back the dawn of civilisation.

It was found during the screening process that there were many academic records that were insightful on the topic of increased temperatures, variability in climate patterns, and changes

to historic weather, that could be reasonably ascribed to the consequences of anthropogenically induced climate change. However, these articles did not make this link explicit in their work, and as such, the record was excluded on the basis it did not meet the inclusion-exclusion criteria established above. This was also noted during the Kapa analysis, where the reviewer also expressed the challenge in rejecting a paper, despite the fact that it would be beneficial to include in the extraction, due to the lack of attribution to anthropogenically induced climate change. This will be discussed further in the limitations section of the discussion.

The included records were grouped into wine making regions. Distinguishing wine production between 'old world' and 'new world' is traditional phrasing, linked with the spread of winemaking globally, although some Sommeliers are moving away from this distinction, towards more specific categories grouped by temperature. In this context, 'old world' is used to refer to traditional wine making countries, which contributed to the establishment of modern winemaking methods. The grapes, wines, winemakers, and traditions were then exported to other countries. Examples of 'old world' countries include France, Spain, Italy, Portugal, and Greece (WineFolly, 2024). Sometimes, the phrase 'Ancient World' is used to describe wines that originate from the very first countries that started wine making, thousands of years ago, and were the cradle of wine civilisations. These are countries such as Türkiye, Georgia, Greece, Cyprus, Iraq, Iran, and Israel (WineFolly, 2024). For the simplicity of this analysis, the 'ancient world' countries have been grouped with 'old world.' 'New world' refers to countries and winemakers that, whilst developing their own approach, shared in traditions and grapes from the 'old world' region. Commonly, this development occurred alongside colonisation. Examples of 'new world' countries include North America, South America, New Zealand, Australia, and South Africa (WineFolly, 2024).

Of the included academic records, over double the number of papers studied the impacts of climate change in old world regions ($n = 79$), compared to new world regions ($n = 34$), (see figure 7). Review papers were records that were reviews of literature on a topic, or covered multiple regions, and are therefore categorised separately. An explanatory factor towards the bias in old world research could be that given nearly 70% of the world's wine production comes from Europe, which is old world, and therefore the research is accounting for where

most of the grapes are found yet more than 70% of the world's wine is made in Europe (Fraga et al., 2012; Malheiro et al., 2010). However, as new world wines continue to expand, with climate change posing threats and opportunities for both regions, it is worth researchers considering expansion of research into more new world regions. Additionally, new world regions may be benefiting from climate change, as previously unsuitable areas now become more viable for commercial production, such as parts of Europe like England and Norway, and new regions in Canada emerge such as Niagara.

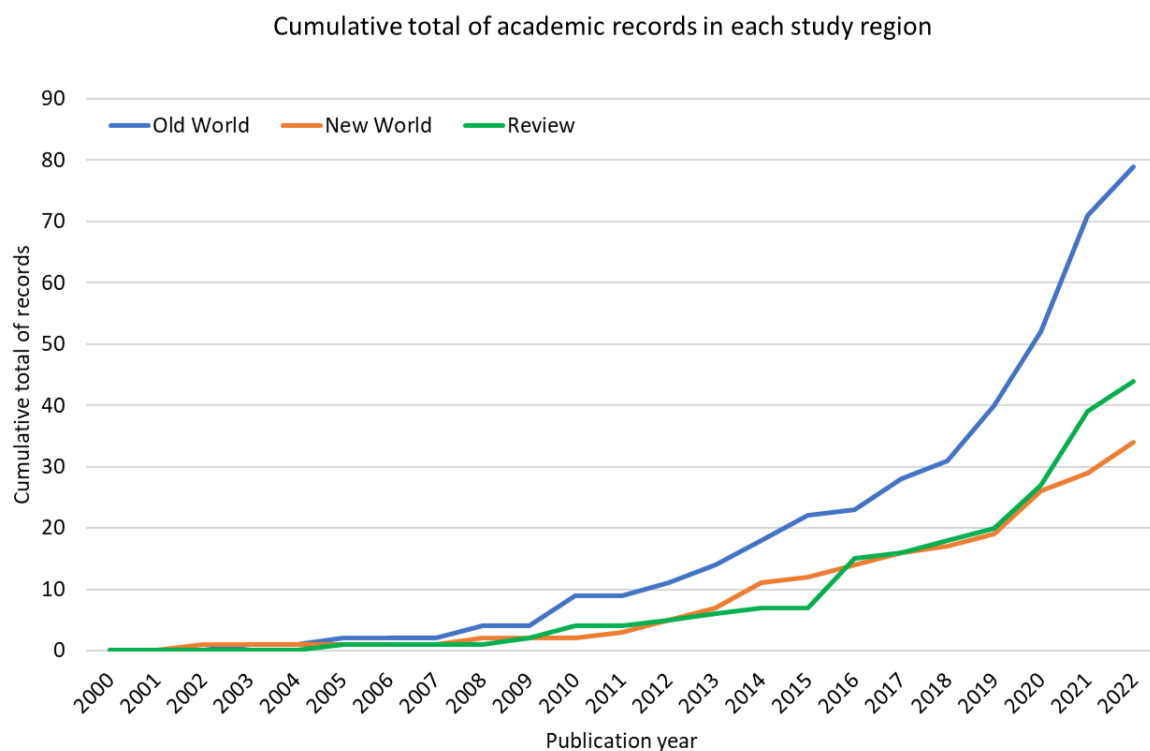


Figure 7: Cumulative total of academic records in each study region. The total number of old world papers ($n = 79$) is more than double the total of new world papers ($n = 34$). Review papers ($n = 44$) have a similar trend to new world records but have recently spiked in popularity. The total number of records reviewed was 158.

Review papers ($n = 34$) are of a similar trend to new world, though there is a slightly greater upward trend. This could be explained by the increase in publications overall, which provides more content for review authors to analyse. However, review papers would be expected to be lower as these often take more time produce and are a less common category of paper.

Impact of climate change in vineyards

Whilst there is extensive literature acknowledging the climate change has an impact on viticulture, this meta-analysis is believed to be the first full systematic map to review the factors of observed climate change. The impact of climate change on environmental factors in vineyards was categorised (see figure 8). Temperature was the most frequently noted factor ($n = 147$), which is unsurprising, given it is one of the most notably observed impacts of climate change globally.

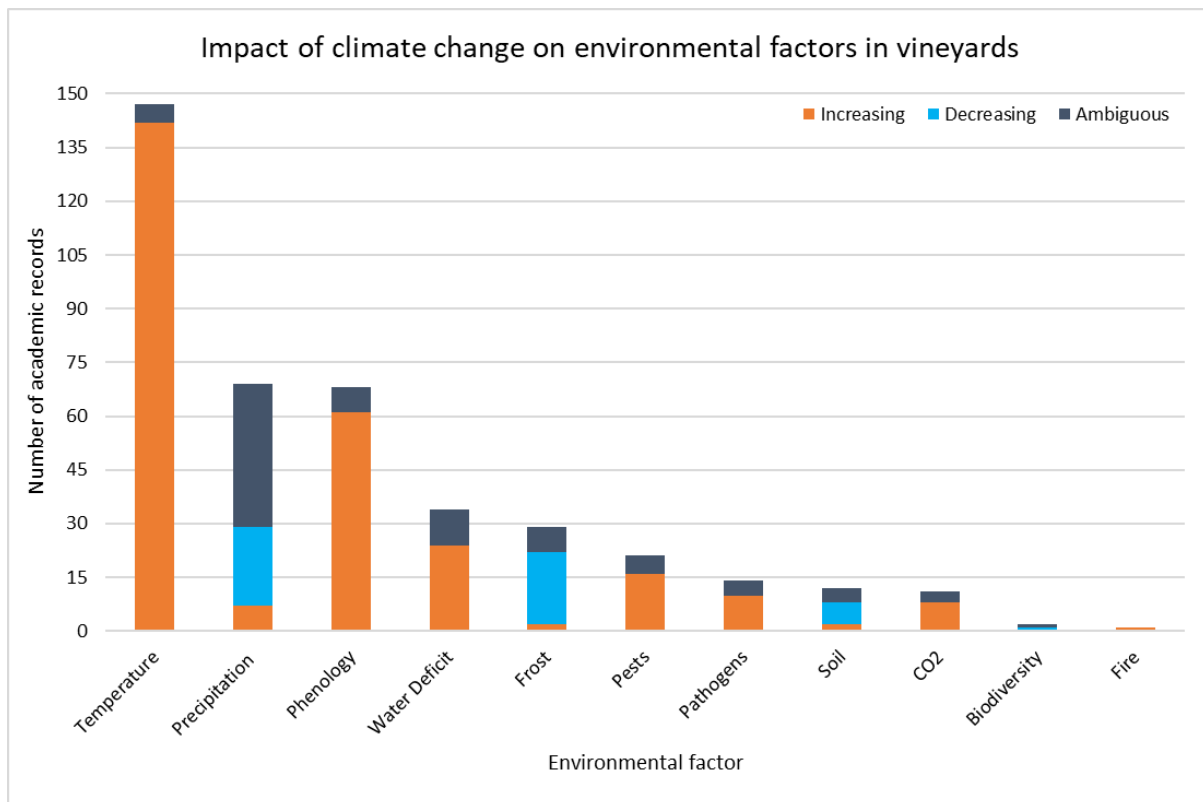


Figure 8. Impact of climate change on environmental factors in vineyards. The impact of different environmental factors in the academic records ($n = 158$) were classified as either increasing, decreasing, or having an ambiguous effect. Temperature ($n = 147$) was the most commonly recorded impact. Whilst precipitation was the second most frequently recorded impact ($n = 69$), the consequence of the impact has a mixed response ($n = 40$).

Global temperatures continue to rise in line with anthropogenically induced climate change (IPCC, 2023) with climate change impacts being experienced at a rate faster than anticipated by climate scientists (Tollefson, 2022). Temperature is widely acknowledged to have an impact on the growing conditions for grapes (Malherio et al., 2010; Shultz 2016), but considering it alongside other factors experienced in the vineyard and in wines (see figure 7), it is a novel approach to consider the consequences of climate change and the knock-on effect this has on other aspects of the viticultural system.

Despite phenology and temperature being inherently linked, it is interesting to note that whilst temperature is featured 147 times, phenology is mentioned over 50% less ($n = 68$). The closely interconnected relationship between temperature, phenological events and climate change is widely discussed in scientific literature (Donnelly & Yu, 2017). Given that temperature is a key aspect in defining phenological timings, increases in temperature will impact phenological events. Given the significance and strong relationship between the two factors, it is worth noting the difference in frequency. Phenological timings in vineyards are significant to wine makers, as bud burst and harvest time can shift between years, which is an important factor of inter-annual variation, leading to vintage variation which is a culturally significant aspect of wine making. However, significant shifts in phenological timings can result in a shift in site suitability. This shift in suitability has been a factor in the development and expansion of the English and Welsh wine industry, as warmer weather means previously unsuitable varieties are now commercially viable. In existing regions however, this can result in a shift of what was originally commercially successful and require changes to wine making practices or even grape blends. Additionally, there is a risk of earlier phenological events and higher temperatures impacting acidity, alcohol, sugars, as well as the grapes themselves being at risk from sun damage.

Furthermore, CO₂ levels were noted to be increasing ($n = 8$), and CO₂ fertilisation in crops is acknowledged as an impact of climate change (IPCC, 2023), yet this seems under-represented in the literature. A potential explanation could be the reticence of attribution to link cause and effect. As mentioned previously, many papers were excluded from the systematic map on the basis that they failed to explicitly mention 'climate change,' and instead discussed the consequences of it, e.g. temperature rising, changes in extreme weather events and weather

frequency. The reluctance in consequence attribution may be a contributing factor, and in the rest of the research presented, thus findings should be considered with this in mind.

Precipitation events are the second most commonly noted impact ($n = 69$), though this is split between the precipitation levels seeming to be increasing ($n = 7$), decreasing ($n = 22$), or an ambiguous response ($n = 40$), that is, both increasing and decreasing. Precipitation levels are seen to be increasingly globally with climate change, as warmer air can hold more water. Although, in some regions, droughts are also increasing, because changes in wind patterns, as well as other climatic factors, are impacted by climate change (Met Office, 2024a). These aspects are reflected in water deficits being noted as increasing ($n = 24$) and having an ambiguous response ($n = 7$). Grapes have specific water requirements seasonally and annually (Malheiro et al., 2010), and so changes to this could be attributable as a contributory factor to change in the quality and quantity of yield (see figure 8) (Fraga, 2020; Lamonaca, Santeramo and Seccia, 2021). Precipitation patterns are expected to continue to change, with extreme events of flooding and drought increasing in frequency and unpredictability (IPCC, 2023), this is likely to have further compounding impacts on the viticultural system, affecting yields, quality of fruit and wine, as well as pests and pathogens. The unpredictability of changes to precipitation is a significant challenge in climate change modelling, and the fact that an ambiguous response (both increasing and decreasing) is perhaps reflective of this. Pest and pathogen management would be more likely to be required, but this is mentioned much less frequently. As with temperature and phenological links, published literature is not necessarily reflective of the well-known synergies in the industry; increased rainfall will increase risks of pathogens like mildew, reduce yield and can impact quality of wine.

Pests and pathogens both are recorded to be on the rise ($n = 16$ and 10). Given the damage that pests can have on crops, and the associated economic losses, it is surprising that whilst 76% of academic articles stated an increase in pest risk, this account for only 10% of all academic records included. It would not be unreasonable to anticipate a higher percentage of papers, given the significance of the implications of pest and pathogen increase. It has been noted that pest and pathogen life cycles, migratory patterns, and distribution are impacted by climate change, and are likely to be a higher risk due to the unpredictability of changes due to climate change impacts (Lena et al., 2013; Reineke and Thiery, 2016). As noted in academic

articles (e.g. Reineke and Thiery, 2016), it would be beneficial to undertake modelling approaches to understand some of the potential risk. However, there is some suggestion that due to changes in phenology of the vine, this could decrease the impact of some pests such as the European grapevine moth during peak times (Di Lena et al., 2013). Furthermore, this is likely to have social knock-on impacts, in terms of risk factors and worry for growers, as well as economic damages. This is discussed further in the social impacts section of the discussion.

Both number of frost events ($n = 29$) and soil quality ($n = 12$) had proportionately large numbers of decreasing responses recorded ($n = 20$ and $n = 6$ respectively). Due to temperatures rising, and therefore milder weather, it is unsurprising that frost events are reported to be decreasing. However, it is worth noting that in some regions this is variable, and some report less frost events overall, but some later frosts which pose a risk to the budburst of vines such as cool climate viticultural regions like Ontario (Shaw, 2017). Soil quality has been noted to be decreasing with climate change, due to changes in precipitation and combined with agronomical practices. Recent research has highlighted that changes in agronomic practices can influence the aroma composition of wines, which is strongly associated with quality (Cataldo et al., 2021; Schultz, 2022). There has also been a surge in popularity of organic and biodynamic wines, which utilises methods that can help improve the soil (Vinissimus, 2023). Given this is an emerging trend, it would be insightful to consider this in future research. These practices are also associated with supporting biodiversity, which was only considered twice in the academic literature. Large, commercial scale vineyards are more likely to follow conventional agronomical practices and are generally more likely to be studied. Exploring more artisanal producers and their methods, which are often overlooked, may provide useful lessons that could be applied across the industry. Furthermore, given that grape growing has relatively minimal impact on the landscape once established in comparison to other crops which require more intensive spraying and disruption to the land through methods such as tillage, it would be constructive to explore soil and biodiversity health in vineyards in more detail with a climate change lens, as well as considering other factors that affect soil and biodiversity, such as fire ($n = 1$), which appears to be overlooked in much of the existing literature.

Impacts of climate change on wine

The systematic map also explored the observed impact of climate change on a variety of factors relating to the wine produced. It is interesting to note than when compared with the observed impact of climate change in the vineyard, many more of the factors relating to wine have produced ambiguous responses than clearly increasing or decreasing (see figure 9). This could be partially explained by the fact that many aspects of wine are subjective, and therefore people are reluctant to ascribe somethings as clearly increasing or decreasing. It should also be considered whether those observing the impacts would consider them ambiguous, or if this has been ascribed by those authoring the articles. Nevertheless, it has been widely acknowledged in the literature that climate change is impacting factors in wine, such as acidity and quality (Jones, 2005; Shultz 2016, Venios et al., 2020). These novel results are still beneficial in identifying which attributes are most commonly discussed, or not, within existing literature, and what would be most beneficial for future research to fill knowledge gaps.

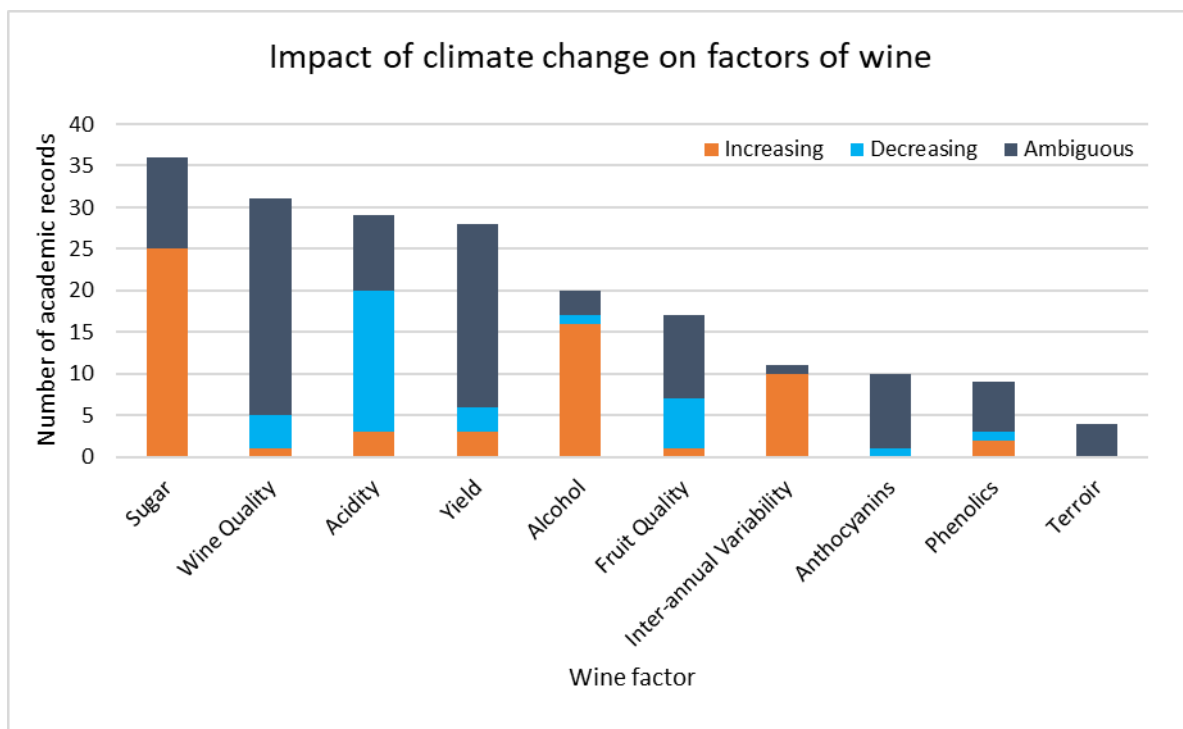


Figure 9. Impacts of climate change on factors affecting wine. The sugar content of wine was the most frequently recorded ($n = 36$) impact of climate change on factors affecting wine, in

the data set (n = 158). Wine quality was the second most frequently recorded (n = 31), although most (n = 26) articles were ambiguous and did not give a clear indication if quality was increasing or decreasing with climate change. All factors apart from sugar, acidity, alcohol, and inter-annual variability were recorded to have an ambiguous response to climate change

The most frequently recorded wine factor impacted by climate change was sugar (n = 36). This is unsurprising, given that it is commonly acknowledged that increased temperatures from climate change increase the ripeness of the fruit, which in turn leads to higher levels of sugar, and this is a notable trend in studies (Schultz, 2016; Venios et al., 2020; Navrátilová et al., 2021). This is often coupled with rising alcohol levels (n = 16), as during the fermentation process, yeasts convert sugar to alcohol, and so increases in sugar levels will increase alcohol content. However, it is interesting to note that alcohol was mentioned in less than half of the academic records compared to sugar content. A potential factor to explain this could be that there are many challenges surrounding an increase in alcohol content, including the classifications of table wine (less than 15% alcohol by volume), and therefore if alcohol levels continue to rise, this creates a challenge for the industry, with potentially large financial repercussions. Increased sugar and alcohols levels are coupled with decreasing acidity levels. Acidity is partially generated through diurnal variation, as well as ripeness of the fruit. Due to the changes in phenology, increased sugar and increased alcohol levels, acidity is decreasing (n = 17). This is a challenge for regions such as Champagne, which are usually hallmarked for their refreshing acidity (Skelton, 2014).

Inter-annual variability was seen to be increasing (n = 10) which may be a cause of concern for producers. Inter-annual variability is the backbone of vintage variation and is what many wine connoisseurs will spend a lifetime studying and collecting. However, if inter-annual variability increases, this poses an increased risk to growers and makers, who may find it challenging to account for aspects that will contribute to this, such as yield and sugar. It would be interesting to explore the factors that are ascribed to inter-annual variability in further research, as this could vary between growers and producers, and vary between regions. Furthermore, to consider the boundaries where inter-annual variability stops, and climate change begins would also be an interesting topic of research to explore.

Phenolics are chemical compounds that affect the feel, taste and colour of wine, an example of which is tannins, found in grape skins and oak barrels (Vinny, 2015). Anthocyanins are chemical compounds that can be grouped with phenolic compounds, and are responsible for the coloured pigment of grapes, and also contribute towards the colour of the fruit and the wine (Kharadze et al., 2018). It was found that climate change had an ambiguous effect on phenolics ($n = 6$) and anthocyanins ($n = 9$). This could be ascribed to a variety of factors, including wine making techniques, quality of fruit, and subjectivity of identification of these compounds in wine. These factors are often associated with quality of wine, which in itself is inherently ambiguous, much like the climate change impacts observed.

Fruit quality and wine quality are interesting to consider, given that the majority of observed impacts were ambiguous in response ($n = 26$ and $n = 10$ respectively) or decreasing in quality ($n = 6$ and $n = 4$ respectively). A factor that may account for this is that wine quality is inherently a very subjective topic, which different consumers and critics can appraise very differently. However, fruit quality can require certain metrics such as sugar and acid levels at harvest, so can be viewed slightly more objectively.

The impacts of climate change discussed, ranging from changes in vineyard environments, composition of wines, as well as the social factors (discussed in further detail in the next section), all feed into the notion of *terroir*. *Terroir* is based on the concept of all the inter-connectivity of factors that go in to creating a unique wine. Whilst often misused in English today to be synonymous with quality (van Leeuwen et al., 2004), it is in fact all-encompassing of geological, pedological, physiographic, meteorological, and vinicultural (Haynes, 1999). These factors, with the exception of physiographic, have been explored in this research, and have been observed to be impacted by climate change. Yet *terroir* was only mentioned in 4 papers out of 158, and was noted to have an ambiguous response to climate change. Whilst there is some research dedicated to exploring the impact of climate change on *terroir*, there is still a limited appreciation for how this concept will be impacted by climate change (Bonfante and Brillante, 2022).

Social impacts of climate change

Viticulture is an aspect of agriculture, entrenched with human-environmental interactions, and yet the social aspect of climate change impacts on viticulture remains vastly understudied. This is highlighted by the lack of studies concerning the social elements of climate change impacts on viticulture. Grape growers were only acknowledged as being impacted by the consequences of climate change 19 times, which is twice as often as wine makers were mentioned (see figure 8). Wine sellers ($n = 4$) and the local community ($n = 1$) were rarely considered. Given that growers are represented more than wine makers, yet wine quality is perceived more ambiguously impacted than fruit quality (see figure 6), this means that wine makers may be having to deal with a more challenging and unpredictable scenario, yet this is not reflected in the published literature.

Considering the economic impacts of climate change on viticulture, this seems to be even more understudied than the social impacts, with only ten papers associating an impact, two acknowledged tourisms as impacted, and only one considered investment (see figure 10). Given that grapes (of both table and wine forms) are the fifth most valuable crop globally, this seems like a major research gap that would benefit from being explored further.

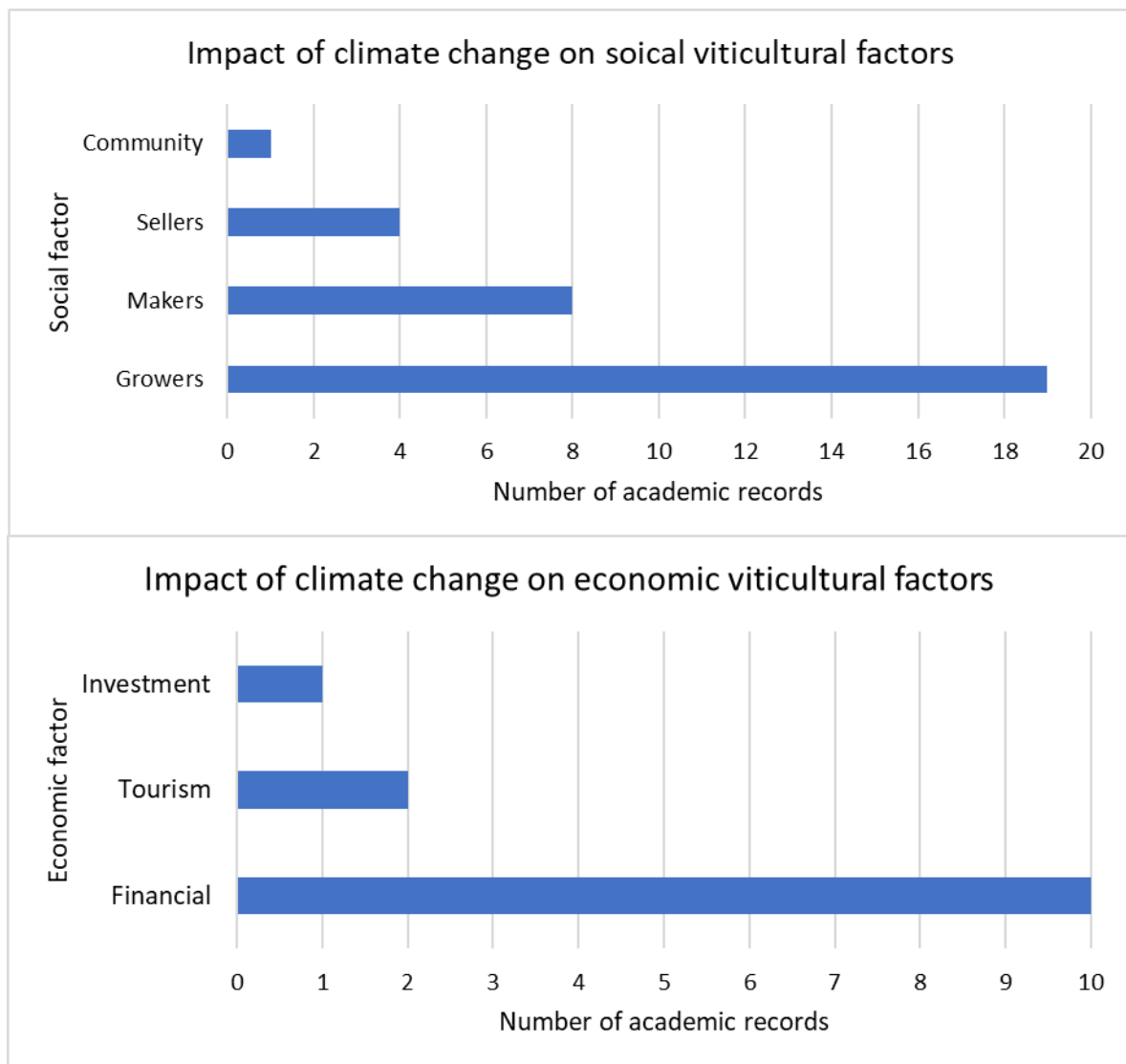


Figure 10. Impact of climate change on social and economic viticultural factors. Social and economic factors are poorly represented in the literature, with maximum references per category are 19 and 10 respectively ($n = 158$). Grape growers ($n = 19$) are represented twice as often as wine makers ($n = 8$). Academic records discussing climate change impacts focus on the potential financial consequences ($n = 10$), without much mention of impacts on tourism or investment.

The inter-connectivity of impacts appears to be under-appreciated in existing literature. The findings from the systematic map show that factors such as temperature rise and reduction in precipitation are impacting sugar and alcohol levels in wine, and overall fruit and wine quality. However, acknowledgement of these connections and their relationships, and subsequent association with social elements are missing. Furthermore, the economic burden

that growers and makers face by shouldering this risk should not be under-estimated, and urgently requires further research. Case studies in Australia found that some grape growers were suffering from depression, anxiety, and even taking their own lives due to the pressure they felt from the impacts of climate change on their vineyards (Bryant and Gamham, 2013; Bryant and Gamham, 2014). If producers are experiencing these feelings in Australia, it is not unreasonable to anticipate that other growers around the world may experience similar. This research gap requires urgent addressing for the welfare and support of grape growers, with insights that are likely to be applicable to other fruit growing and agronomical sectors around the world in the face of climate change.

The impacts of climate change discussed, ranging from changes in vineyard environments, composition of wines, as well as the social factors, all feed into the notion of *terroir*. At its core, the concept of *terroir* is about embracing the social-ecological system, and considering the relationships between people, climate, and crop. However, as discussed, climate change is impacting these factors, and the subsequent gaps in the research concerning issues such as social elements have been identified. The complexity of these relationships cannot be overstated and require further analysis and mapping. An example of this chain of connectivity can be seen in how temperatures are rising, which is increasing pest and pathogen risk. This risk can then impact yield, with subsequent consequences for the producers who have to face uncertainty in the quality and quantity of their yield, which can affect cash flow, the price their wine can be sold for, and their ability to reinvest into the vineyard. The interdependencies of these factors are non-linear and appears to be compounding, and urgently requires further research.

Discussion of impacts and implications

Considering the impact of climate change on vineyards (figure 8) and the impact of climate change on wine (figure 9) holistically, it can be seen that the primary impacts, such as temperature changes and precipitation levels, are acknowledged and discussed more than the secondary impacts, such as the consequences this has for the wines, like changes in acidity and alcohol level. There appears to be a disaggregation of the inherent interconnectivity of these aspects of viticulture. This could, in part, be due to a reluctance to attribute climate

change to having an impact on aspects such as quality of wine, when this could have financial repercussions for stakeholders. However, this lack of acknowledgement is a barrier to understanding, quantifying, and adapting to climate change, as many of the aspects have a complex web of interconnectivity.

Considering rising temperatures, which impact phenology, and therefore leads to earlier ripening and then higher sugar levels, a grape grower may have significant challenges in selling their grapes or making high quality wines. Their wines may have a higher level of alcohol and appear out of balance on the palette. This can have social ramifications for the grower and maker making less profits. Yet this narrative is not necessarily reflected equally in the literature due to the number of papers attributing climate change to each of these factors. The further away from the vineyard the narrative becomes, there is less and less attribution to climate change to these factors.

It is unsurprising that the majority of these papers considered old world regions (see figure 7), given that these account for 70% of global production. It is possible that as these regions may have more resources, this may account for the research area bias. However, it is interesting to note that old world wine regions are famed for embracing the concept of *terroir*, yet this was one of the least mentioned factors when exploring climate change impacts on viticulture. It seems surprising that limited research has been undertaken on the links between climate change and *terroir*, given that *terroir* also helps form parts of the legal definitions of wines, and the protected appellation system which is often used synonymously with quality across most of Europe. Furthermore, some wine critics view the old world as being of higher quality, and equivalent wines are often more expensive in the old world when compared with the new. There is a large research gap between climate change impacts and the impact of *terroir*, which would benefit from being explored.

Although, there is a risk that if research remains focused on the old world, emerging trends in the new world regions could be missed. Furthermore, new world regions could possibly be more adaptable to climate change, as they do not possess the same strict regulations and appellation systems as old world regions do. Changing compositions of wine blends, as well as opportunities to irrigate, which are not allowed in some old world regions, may mean that

new world regions could mitigate some climate change challenges. Further research is needed in new world regions to understand the impacts they experience, as well as considering adaptability approaches that they could adopt.

Considerations of climate change impacts on viticulture in England and Wales

As the English and Welsh wine industry continues to expand and develop, it is essential that the industry takes note of lessons that have been learnt in other countries, and remains mindful of the stochastic nature of climate change. This will be vital in safeguarding the industry for future expansion. As the industry is relatively nascent in terms of commercial production, there is an opportunity for the sector to embrace adaptive measure to facilitate expansion that is adaptable and proactive.

The findings from the systematic map highlight that temperatures are increasing, precipitation events are ambiguous in trend, and there is much ambiguity surrounding the impact on wines from a quality perspective. Climate project scenarios produced by UKCP demonstrate that in England and Wales, temperatures (see figure 3 a and b) and precipitation levels are likely to continue to rise (see figure 3 c and d) (Met Office, 2024). It was found that whilst temperatures rising was consistent, precipitation was more varied. As England and Wales are already wet regions, producers will need to be mindful of how the risks of pests and pathogens, particularly mildews and other damp related diseases, could be of concern. Increases in temperatures are known to have an impact on phenological events, but this was not widely noted in the literature. The English and Welsh industry should be attentive to how continued temperature rises could affect phenology, to ensure there are suitable provisions, such as appropriate resourcing for earlier harvests that may clash with other crop harvest timings.

As highlighted in the systematic map, there are major knowledge gaps surrounding the social impacts of climate change on viticulture. As emphasised throughout this research, viticulture is entrenched in the social element, not only through the notion of *terroir*, but also in the impacts it has on rural economy and job generation. WineGB (2023) estimates that there are

around 2,300 full time equivalent (FTE) workers in the domestic wine industry, with a further 8,300 people employed seasonally. Given there is a further 50% growth rate forecast in FTE positions by 2025, it would be beneficial for the industry if the research gap surrounding the social impacts of climate change and viticulture was addressed. Research considering the impacts on rural economy development has been insightful, where Nesbitt et al., (2016) found that over half of growers saw climate change as a threat. More recent research by Gannon et al., (2023) has found that perceptions have now shifted, and that climate change is now seen as more of an opportunity, though not without risk.

It would be constructive for the English and Welsh wine industry to be cognisant of the links between primary impacts, such as temperatures rising and ambiguous rainfall patterns, to secondary impacts, like changes to acidity, alcohol content, and wine quality. This is perhaps one of the biggest themes to emerge from this research. Given the nascency of the English and Welsh sector, there is a real opportunity for growers and producers to take advantage of the iterative nature of their expansion, as well as their understanding of climate change impacts, as discussed in Gannon et al., (2023), to ensure that their processes and techniques are suitably adaptable.

Furthermore, it would be useful for industry such as WineGB to also be mindful of this lack of connected thinking when providing advice and guidance to growers and producers. Climate change has, and will continue to be, both a threat and an opportunity to the further expansion of the industry. Therefore, the acknowledgement and encouragement of education and research into the inter-dependencies of primary and secondary impacts will be constructive to help growers and producers to be adaptable and resilient to climate change.

It is worth bearing in mind that geographically, England and Wales fall in the same latitude as parts of Canada (Newfoundland, Labrador, and Manitoba), as well as Inner Mongolia and Russia, which have the famously cold climates. England and Wales have a much milder temperate and climate due to the Atlantic meridional overturning circulation (AMOC), which is a system of currents transporting warm water from the tropics to the poles, and the circulation has been noted to be varying in strength in recent years (Jackson et al., 2022). Latest research indicates that with the current scenario of future emissions, the AMOC could

collapse in the middle of the century (Ditlevsen and Ditlevsen, 2023). The impacts of the AMOC collapse would bring about much colder conditions to the whole of the United Kingdom, shift precipitation patterns, and make the impacts of climate change on arable farming and agriculture an order of magnitude worse than climate change without the AMOC collapse (McCarthy et al., 2023). If the collapse of the AMOC occurs, it is unlikely that English and Welsh viticulture as it is expanding today, with its intention for future expansion, would be viable. With this in mind it would be worthwhile for stakeholders across the sector to remain mindful of development in this area of research.

Fundamentally, resilience must be embedded from the offset into the emergent industry for it to be as prepared as possible, agile in response, and adaptable to the consequences of climate change it must cope with to survive and thrive.

The research in this thesis highlights the risk and inter-connectivity of climate change impacts and viticultural systems, and it would be pertinent for the English and Welsh wine industry to be cognisant of these factors in order to help build resilience and adaptability into the industry.

Limitations

This thesis has produced novel findings surrounding the observed impacts of climate change on viticulture, whilst considering implications for England and Wales, and identifying future research gaps. However, there are some key limitations to the research which should be noted.

The systematic mapping scope was challenging, due to the number of papers identified, which was over 12,000 records between the original download and the update. Ensuring that the inclusion-exclusion criteria were appropriately scoped to produce a reasonable pool of records for extraction was demanding. Widening the scope to include projected future impacts of climate change under different climate scenarios would be beneficial in helping to gain an understanding of future projections and potential impacts. This could be of use to producers to help their focus their adaptative capacity efforts. To date, there has been no

meta-analysis of the future projections of climate change and viticultural risks. A review that explored this would be beneficial to help stakeholders across the industry understand what the future may look like, and what risks they may face.

When conducting the research, only papers in English were included. Given that viticulture is truly a global agriculture found on six continents, research will be undertaken in other languages that would have useful outputs. Collaboration with other researchers fluent in languages found in major wine making regions, such as French, Spanish, German, Italian and Portuguese, would be beneficial in undertaking a truly global review. It is likely that impacts vary both internationally, and regionally, and taking this into account when conducting further research would be beneficial.

Attribution of climate change to the observed impacts was one of the biggest challenges during the systematic review, and one of the most frequent reasons for the exclusion of papers. Due to constraints, the decision was made to exclude these papers. However, if the research were to be repeated, it would be insightful to account for these papers that essentially discuss impacts of climate change, featured prominently in this thesis, such as temperature rises, changes in precipitation and ambiguous impacts on wine quality, but note that they do not say the phrase explicitly. Furthermore, the extraction coding only explored whether the factor was increasing, decreasing, or ambiguous in response to climate change. This limits the interpretations that can be drawn from these findings. It would be constructive to consider further quantification of the impacts noted, and to consider more detail around the extent of impacts.

As the English and Welsh wine industry is an emergent sector, there are limitations to the conclusions that can be drawn due to data availability. In particular, concerning aspects such as more localised climate change, specificity around aspects such as frost events, precipitation, and temperature. Development of a detailed data set would be beneficial for exploring these aspects and providing more tailored information to stakeholders.

Whilst the research here has highlighted the complexity and interconnectedness of impacts, due to constraints, this could not be explored in further detail and mapped visually. As

mentioned throughout the discussion, interconnectivity of the complex relationships between impact factors appears to be non-linear, and mapping with quantification of these interactions to see the flow between the social and ecological elements would be of great benefit. This could further support the social-ecological system foundation built by the idea of *terroir*, which could be the foundation this framework is based upon.

Section 4. Conclusions

This thesis presents the first systematic map undertaken to explore observed climate change impacts on viticulture. Key findings from this work have identified temperature and changes in phenology as the factors most noted to be increasing under observed global climate change, whilst precipitation and frost were decreasing the most globally. Considering impacts on wine, sugar and alcohol were found to be the factors most noted to be increasing, whilst acidity decreased, and there was a high level of ambiguity surrounding the quality of fruit and wine. The impacts of climate change on the social element of the social-ecological system of viticulture remains underrepresented in the literature. This research has highlighted the importance and necessity of this research gap to be filled, particularly given the negative impacts climate change can have on growers, who shoulder a large amount of risk, and have the potential future of their livelihoods in jeopardy.

The English and Welsh wine industry has been aided in its expansion due to anthropogenically induced climate change. However, with continued climate change, England and Wales are projected to continue to get warmer and wetter. This poses a greater challenge for pests and pathogens, which have already been noted in recent harvest reports. Additionally, the threat of late spring frosts remains high. Furthermore, the risk of the AMOC collapse in the mid-centaury poses a real threat to the future of the industry.

All of the impacts explored in this research are inherently complex and inter-connected. The relationships between these factors are not always necessarily linear, but are rather circular and compounding in instances. The factors explored in this research, with the exception of physiography, are embedded in the concept of *terroir*, which provides a framework for the exploration of a social-ecological system to explore viticulture. There is also an opportunity to use this system as a platform to encourage resilient and sustainable continued expansion of the industry, if it is to adapt alongside the changing environment.

Despite the limitations of this research, which includes the scope of the systematic map and lack of quantification for the complex interactions, this research still presents novel contributions to science which are of benefit. These research findings highlight the impacts

of observed climate change globally, and have pulled out key factors such as pest and pathogen changes, as well as social interactions, which can impact English and Welsh growers. The social aspect of viticultural systems is the most under-explored in the literature, and urgently requires further research in order to understand the social-ecological system in more detail, and to enhance adaptability and resilience in the system.

Climate change will continue to provide global challenges for viticulture for the foreseeable future. This research has helped to provide novel contributions to science on identifying trends in the research as well as knowledge gaps, with consideration for England and Wales. Wine making has been a part of human civilization for nearly 10,000 years, and it is hoped that this research will be a contribution to science that helps understand climate change impacts, and helps to support the viticultural system as it faces the challenges, and opportunities, of climate change head on.

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