Mapping the impact of climate change on the quality potential of UK still Chardonnay wine production: using the Chablis region as an analogous model

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Declaration of original authorship

I, Alex James Biss, hereby declare that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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Abstract

In recent decades, the UK (especially Southern and Eastern England) has developed a reputation for quality sparkling wine production. The potential for high quality still white wine from Chardonnay grapes grown in the UK was investigated using the Chablis region in Burgundy, France, as an analogy for UK viticulture. Weather data and Chablis vintage quality scores from 1963 to 2018 were analysed to model the response of vintage score to weather (key variables: mean temperature, April to September; mean minimum temperature, September; total rainfall, June to September). This weather model was applied to the UK for 1981–2000, 2010–2019 and, with climate change projections, to 2040–2059. Only 0.2% to 1.8% of UK land was found suitable in recent climatic conditions for reliable production of high-quality still Chardonnay wine, but under median and 95th percentile projections for 2040–2059 SE and E England will have the potential for high-quality still Chardonnay wine production in an average year. This analysis was extended to include the effects of topography and soils to map suitable sites for Chardonnay vineyards in the UK, evaluated against 35 wine experts' scores of current English still Chardonnay wines. Minerality, often associated with cooler regions' high-quality still white wines, was studied by analysing Chablis Premier Cru tasting notes entered into CellarTracker between 2003 and 2022. Use of the descriptor minerality was correlated with growing season temperature, sunshine hours, and vineyard aspect whereas soils and geology were not a principal source of minerality in Chablis wine. Overall, the results show that reliable production of premium quality still Chardonnay wine is likely to be possible by mid-Century in SE, S, and E England - and possibly also the Midlands and SW England under more extreme climate change.

Contributions to co-authored papers

Chapters 2, 3, and 4 are published papers co-authored with my main supervisor, Professor Richard Ellis. The papers are:

1. Biss, A.J. and Ellis, R.H., 2021. Modelling Chablis vintage quality in response to inter-annual variation in weather. *OENO One*, *55*, 209-228. https://doi.org/10.20870/oeno-one.2021.55.3.4709

2. Biss, A.J. and Ellis, R.H., 2022. Weather potential for high-quality still wine from Chardonnay viticulture in different regions of the UK with climate change. *OENO One*, *56*, 201–220. https://doi.org/10.20870/oeno-one.2022.56.4.5458

3. Biss, A.J. and Ellis, R.H., 2024. Minerality in wine: textual analysis of Chablis Premier Cru tasting notes. *Australian Journal of Grape and Wine Research*, vol. 2024, Article ID 4299446, 13 pages, 2024. https://doi.org/10.1155/2024/4299446

I conceived the ideas and analytical approaches, carried out the research and drafted the manuscript. Professor Ellis commented and advised on the research as it progressed as well as suggested edits to the manuscript. I estimate my contribution to be 85%.

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Abbreviations

AHDB	Agriculture and Horticulture Development Board
AOC	Appellation d'Origine Contrôlée
AMOC	Atlantic Meridional Overturning Circulation
C3S	Copernicus Climate Change Service
CNI	Cool Night Index
CNI2	Alternative Projection for CNI (see Chapter 3)
DEFRA	Department for Environment, Food & Rural Affairs
DEM	Digital Elevation Model
ENTAV-INRA®	Trademark for authorised French grapevine clones
FPS	Foundation Plant Services - UC Davis
GHG(s)	Greenhouse gas(es)
GIS	Geographic Information System
GWP	Global Warming Potential(s)
GST	Growing Season Temperature*
HadUK-Grid	Met Office gridded UK climate observations
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
OIV	Organisation Internationale de la Vigne et du Vin
PDO	Protected Designation of Origin
PIWI	Pilzwiderstandsfähig (fungus-resistant grape cultivars)
$P_{Jun\text{-}Sep}$	Total Precipitation from 1 June to 30 September
QGIS	The open-source GIS software used in this thesis
RCP	Representative Concentration Pathway
REP	Ratio of Economic Performance
SSP	Shared Socioeconomic Pathway
$Tmean_{Apr\text{-}Sep}$	Alternative Version of GST (1 Apr to 30 Sep)
UKCP18	Met Office UK Climate Projections

*Mean air temperature from 1 April to 31 October (Northern Hemisphere) or 1 October to 30 April (Southern Hemisphere), unless stated otherwise.

Contents

Chapter 1. General Introduction and Literature Review

1.1 Viticulture and grapevines

Viticulture is the cultivation of grapevine (genera *Vitis* and *Muscadinia* from the vine family *Vitaceae*) for the purposes of producing table grapes, dried grapes (raisins), grape juice, and fermented grape juice (wine) (Keller, 2020).

There are around 80 grapevine species in existence today; three belonging to the *Muscadinia* genus (though they are similar and arguably one species (Keller, 2020)) and the rest to the *Vitis* genus (Organisation Internationale de la Vigne et du Vin (OIV), 2017). The *Vitis* genus can be divided into three groups: Eurasian (one species - *Vitis vinifera* L.), East Asian (around 55 species, generally of limited importance to viticulture) and American (more than 20 species) (OIV, 2017). The single Eurasian species, *Vitis vinifera* L., comprises two sub-species: the cultivated form *Vitis vinifera* L. subsp. *vinifera* ("vinifera") and the wild form "*Vitis vinifera* L. subsp. *sylvestris*" ("sylvestris"). Note vinifera is the focus of the wine industry and, therefore, this thesis.

In addition, there are the naturally-occurring and intentionally bred hybrids. An example of the latter is "Kyoho", which is a hybrid of *Vitis vinifera* L. and *Vitis labrusca* L. (American group) and is now the world's most planted cultivar because of its recent and rapid rise in China (Keller, 2020). It is used to produce table grapes, which have a distinct flavour that generally appeals to an Asian market (Keller, 2020), primarily China (90% of Kyoho vineyard area), Japan, and South Korea (OIV, 2017).

Of the 74.7 million tonnes of grapes that were produced globally in 2023, around 42% (31.2 million tonnes) were pressed to produce wine and a similar amount used whole for table grapes (31.7 million tonnes) (OIV, 2024). Raisins (4.6 million tonnes), musts and juices (2.7 million tonnes) and losses (4.4 million tonnes) accounted for the rest. The four largest countries for viticulture - Spain, France, China and Italy - together account for 45% of the 7.2 million hectares of global area under vine (OIV, 2024).

The overwhelmingly dominant cultivated species for wine production is vinifera. It is grown in around 90 countries (Keller, 2020) and is the species used to make all quality wine (Venkitasamy et al., 2019). Other species from both the *Vitis* (particularly the American group) and *Muscadinia* genera, however, are regularly used for rootstocks and for hybrid breeding programmes because of certain desirable traits. These traits include fruitfulness (i.e. the percentage of buds that produce one of more flower clusters (Carroll, 2011)), resistance to or tolerance of pathogens and pests, and lime tolerance, among others. Note that, except for the rootstocks, EU legislation only allows vine varieties belonging to *Vitis vinifera* or crosses between *Vitis vinifera* and other *Vitis* species for making wine products (Šajn, 2023).

Vitis species are woody deciduous polycarpic perennials or shrubs that use forked tendrils to climb which can live to several hundred years and are further distinguished in several ways (Keller, 2020):

a) Simple leaves are hairy with five main veins, and bark shreds when mature
b) Form clusters of soft berry fruits that usually contain 1 to 4 seeds and pulp with high concentrations of sugars, organic acids and secondary metabolites
c) Long annual shoots harden into canes, nodes and internodes that can all form adventitious roots, which allows propagation by cuttings
d) Cultivated varieties (e.g. of vinifera) have mostly perfect (bisexual) flowers and are self-fertile, whereas wild species are dioecious
e) Species within the genus can interbreed to form fertile hybrids (suggesting they have a relatively recent common ancestor)
f) All species can be grafted onto each other

Muscadinia grapevines differ slightly to *Vitis*. Their tendrils are simple, leaves are hairless, and the bark does not shred (Keller, 2020). They do not root from dormant cuttings so are usually propagated by layering (though they do root from green cuttings). *Muscadinia* has 40 chromosomes compared to the 38 of *Vitis*, which means that crosses between the two genera rarely produce fertile hybrids (Keller, 2020). The exception is *Muscadinia rotundifolia* which has developed useful levels of resistance or tolerance to certain diseases (such as powdery mildew, black rot, downy mildew, Pierce's disease, phylloxera, and the dagger nematode) and can occasionally form fertile hybrids with *Vitis rupestris* (American group). It is therefore sometimes used in breeding programmes, particularly for rootstocks (Pritchard, n.d.).

Grapevine phenology is typically described using the Eichhorn-Lorenz (E-L) system, which divides the grapevine cycle into 47 stages from dormant winter bud (1) to end of leaf fall (47) (Keller, 2020). The yield of grapes in any one year is dependent on the formation of inflorescence primordia in latent buds in the previous year (essentially determining the maximum yield) and the development of the inflorescence in the current year (determining the extent to which the maximum potential is achieved) (Watt et al., 2008). Both stages are highly weather dependent (Carmo Vasconcelos et al., 2009). There is no strong evidence that grape quality is also dependent upon the weather over two years; it is primarily determined by the weather and management practices in the current viticultural year (i.e. winter dormancy to harvest – see Chapter 2).

In viticulture, grapevines usually comprise a vinifera cultivar scion grafted onto a hybrid or a non-vinifera grapevine rootstock, usually from the American group of *Vitis* species. This practice originated in the late 19th Century as a response to the phylloxera outbreak (*Daktulosphaera vitifoliae* (Fitch, 1855)) that caused the destruction of large areas of European vineyards, including 1 Mha in France alone (Ollat et al., 2024). Phylloxera is an aphid-like sap-sucking insect, barely visible to the naked eye, that feeds on grapevine leaves and most damagingly roots, creating galls and nodules that become entry points for soil-borne pathogens. The use of rootstocks from North American *Vitis* species which had evolved with and developed a tolerance or resistance to phylloxera conferred the same resistance or tolerance to the grafted scion. This practice continues today and is considered essential to the continuation of viticulture (Ollat et al., 2024).

Another consequence of the phylloxera and mildew pathogens that were unintentionally brought into Europe from North America in the second half of the nineteenth century, is that genetic diversity among cultivated grapevines has been substantially reduced. Homogenisation of consumer preference and monocultural agricultural practices have since contributed further to a reliance on only a few cultivars. The top 35 vinifera cultivars account for two-thirds of the world's wine grape area and 90% of all vinifera vines are grafted to fewer than 10 different rootstock cultivars, making the industry susceptible to disease and pesticide resistance (Keller, 2020).

As such, considerable effort has been put into breeding programmes to develop disease resistant or tolerant cultivars. Of note are the fungus resistant (“Pilzwiderstandsfähig”, known as “PIWI”) cultivars, including Cabaret Noir, Divico, Orion, Phoenix, Regent, Rondo, Solaris and Voltis (Skelton, 2025a), among many others. (In 2021, Voltis became the first grape cultivar to be added to the list of permitted cultivars in Champagne since 1927, though limited to a 10% maximum of blend). These PIWI cultivars are usually hybrids of a vinifera cultivar (known for their desirable organoleptic properties) with an American species like *Vitis aestivalis*, *Vitis labrusca*, *Vitis riparia*, or *Vitis rupestris*, or an East Asian species like *Vitis amurensis*, that confer certain resistance or tolerance of diseases and/or environmental conditions.

Despite some encouraging research (Weber et al., 2022), doubt remains as to whether wines made from PIWI cultivars can achieve the sensory profiles of wine produced from 100% vinifera cultivars, such as Chardonnay, Pinot Noir and Cabernet Sauvignon, though some argue this stance may come from consumer conservatism (Keller, 2020) and marketing reliance on varietal name (Töpfer and Trapp, 2022). Either way, PIWI grapevines seem to be gaining traction in cool climate regions (including the UK - see Section 1.4), particularly for producers looking to increase reliability of yield, reduce fungicide usage, and price their wine more competitively.

1.2 Shifting patterns of viticulture and wine production through history

Grapes are an important horticultural crop. Their global value is estimated at 67.8 bn USD, second only to tomatoes (87.9 bn USD) (Food and Agriculture Organization of the United Nations (FAO), 2025), and wine-related viticulture provides employment (in the vineyard and winery) for around one million people globally (Académie du Vin Library, 2021). In terms of international trade, wine-related viticulture is dominant and was worth 36 bn EUR in 2023, compared to 9.1 bn EUR for fresh grapes and 1.5 bn for dried grapes (OIV, 2024).

Culturally, grapes and wine have played a key role in human civilisation for several millennia (Limier et al., 2018), especially in relation to religion and religious ceremony (Birkett, 2023; Hooke, 1990), and (for premium quality wine) the nobility and ruling classes (Bouby et al., 2023), though Howland (2013) notes that since the 1970s high quality wine has become a more democratized commodity available to the middle classes. Images of grapevines, grape consumption and wine drinking have been a key part of human iconography since classical times (Bouby et al., 2023), with associations to the gods or the divine on the one hand and to human entertainment, decadence and sometimes debauchery on the other (Inglis, 2022). Of all alcoholic beverages, providing wine is the most associated with being a generous and hospitable host (Agnoli et al., 2025).

In terms of land cover, viticulture currently accounts for 7.2 million hectares (OIV, 2024), primarily distributed in the temperate zone between 30° and 50° latitude in both the northern and southern hemispheres, though these belts shift with climate and environmental change (Jones et al., 2022). A few species were (and sometimes still are) likely used for grape collection in the wild, for example in China as early as 9000 years ago (McGovern et al, 2004). Deliberate cultivation of grapevines, however, is thought to have begun in the Caucasus (Georgia, Armenia and Azerbaijan) and the Near East (Egypt, Israel Lebanon, Jordan, Syria, eastern Turkey, Iraq and western Iran), approximately 7,000 to 8,000 years ago (Keller, 2020; McGovern et al., 1996, 2017). As such, grapes were one of the earliest domesticated crops, along with olives, figs and dates (Keller, 2020).

The oldest winery known was found in Armenia and dated to around 6,000 years ago, providing evidence for the first cultivation and use of grapes for wine production (Barnard et al., 2011). Although there is evidence for Iron Age viticulture, particularly along Mediterranean shores and along the Rhone valley, it was the Roman period in concert with a warming climate (the “Roman Climatic Optimum” from 100 BCE to 200 CE (Pambianchi and Gentilucci, 2024)) that spread viticulture throughout Europe, though mostly concentrated in the south (Bouby et al., 2023). Evidence of a thriving wine industry comes from wine presses, vats, amphorae, clay jars (dolia) (sometimes including wine residue), macro remains (seeds, fruits, wood), pollen analysis (palynology), and archaeology and geophysical surveys that reveal the footprint of previous vineyards, wineries and cellars (Bouby et al., 2023). Several regions were newly cultivated with grapevines during Roman times, including areas in Germany and England (Pambianchi and Gentilucci, 2024).

Interestingly, the 1st Century CE author Pliny the Elder mentioned new high-quality varieties resistant to cooler climatic conditions at the outer periphery of the Mediterranean area, including a variety called Allobrogica (Bouby et al., 2023). Though little is known about is identity, it is likely to be a cultivar of *Vitis vinifera* rather than a separate species, and there is speculation that it is related to the cultivars Mondeuse Noire, Pinot Noir, or Syrah (Wein-Plus, 2025). Overall, palaeoclimatic data suggests that much of northern Europe (including a large part of France) was potentially favourable for viticulture in the 1st century CE. However, Bouby et al. (2023) suggest it was unlikely there existed the range of varieties to favour viticulture in more temperate zones. The varieties found in these areas show morphological similarities with varieties associated with modern Southern France, and thus were likely poorly adapted to their environment, limiting yield and quality. Tacitus, the Roman historian, remarked how difficult it was to ripen grapes in England because of the moist soil and atmosphere (Hooke, 1990).

It is difficult to form a detailed picture of what happened to viticulture at the end of the Roman period. Regions that were climatically marginal for viticulture during Roman times likely became considerably less suitable in the second half of the first millennia AD, probably because of climate change, though economic factors may also have played a part as the military, trade and societal structures associated with the Western Roman Empire were dismantled or fell into disuse (Fleming, 2021; Knowles, 2022). Certainly, there was a decrease in cultivation after 200 CE, especially in the Early Middle Ages (Bouby et al., 2023) and in areas where viticulture was newly introduced (Pambianchi and Gentilucci, 2024). In England, however, there is evidence for vineyards in the 10th and 11th Century, particularly those run by monasteries (Hooke, 1990), though whether this was a continuation from Roman times is unclear and probably unlikely (see Section 1.3).

Most evidence, however, points to a large expansion of viticulture in western Europe in the Middle Ages (900 to 1300 CE), beyond that of Roman times, driven by demand from the clergy and aristocracy, and facilitated by a warming climate and a greater range of grapevine varieties (Bouby et al., 2023). Moreover, labourers may have drunk Verjuice, an acidic juice produced from discarded grapes from early season cluster thinning and sub-optimal grapes at harvest, or used it in cooking (albeit the juice of crab-apples was a more common source of verjuice in Medieval England) (Brears, 2008).

This warming period in Europe was coincident with the establishment of European settlements in Greenland and the discovery of North America by Vikings (see Vinland Sagas). It can also be seen in the emergence of vineyards in England as far north as Ely in Cambridgeshire (52.4 °N) (Unwin, 1990 - see Section 1.3), though these vineyards were mostly curtailed by the following cold period of the Little Ice Age (c. 1300-1400 to 1700-1850 in Europe).

In 14th-century England, considerable areas of cropland, including vineyards, were converted to deer parks and pastoral farmland to maintain profitability due to a cooling climate and unsuitable weather (Gergal, 2021), though economic factors, such as the profitability of wool in international markets, likely played a significant role as well. In contrast, most traditional viticulture regions of France, Germany, Italy and Spain have retained vineyards consistently since Roman times, and possibly before, albeit there were periods of vineyard area decline.

Since the second half of the 20th century, many regions outside traditional European winegrowing areas - commonly referred to as 'New World' regions - have seen significant growth in viticulture and wine production. Important new world regions include parts of North America (particularly California), South America (especially Argentina and Chile), South Africa, Australia and New Zealand. Viticulture in these areas may have originally used in whole or part native grapevines, but over time the same European vinifera cultivars have come to dominate these production areas. Asia, on the other hand, still maintains a largely isolated and separate market to the rest of the world and has only recently begun to use European vinifera at scale, with notably mixed success in China (often due to planting in unsuitable locations (Feng and Xiang-Ling, 2025)).

Over the last few decades, global warming has accelerated and viticulture has been changing substantially as a result. Phenology is advancing (Quenol et al., 2017) and growing seasons are lengthening (Jones and Davis, 2000), all of which can impact on yield, quality, and wine characteristics (Jones, 2007a; Quenol et al., 2017). Wine producers in traditional viticulture regions in Europe are concerned with mitigating the negative impact on their crops from factors such as heat stress and drought (Jones and Schultz, 2016) and are considering how to adapt to future climate change (Neethling et al., 2017). In contrast, other regions' climates, such as England and Wales, are becoming more favourable for viticulture with opportunities to expand wine production (see Section 1.4).

1.3 History of viticulture and wine production in the UK

Two periods in UK history are notable for peaks in the number of vineyards – the Romano-British period and the medieval period. A warming in climate appears to be the main driver for these increases in viticulture, though the mechanism by which these viticultural eras end via a cooling climate is also tied to social and political events of the time.

1.3.1 Romano-British viticulture

While evidence for the import of wine and wine consumption is plentiful in Romano-Britain, there is considerably less evidence for wine production, so much so that Unwin (1990) thought it likely there were only at most tiny experimental vineyards or vines that grew singly against walls. Since then, more evidence for vineyards during the Romano-British period has emerged, suggesting a scattering of small vineyards (Brown et al., 2024). Excavations have revealed probable vineyard-like structures (typically trenches and ditches in Roman-style vineyard layout) associated with a small Villa in Surrey (Corke, 2019) and other sites in or near Roman settlements around Southern and Central England (Brown et al., 2024). Very few tools such as pruners, troughs, and wine presses to indicate wine production, however, have been found.

Vitis pollen grains and vineyard structures, however, suggest a major area of production (c. 35 hectares) may have existed in the Nene Valley in Northamptonshire (Brown et al., 2001; Turner and Brown, 2004; Brown et al., 2024) and it is possible that this part of the East Midlands was the centre of viticulture in Roman Britain. This may not have been entirely for agroclimatic reasons but may also be related to its central position to the main Roman cities, towns and legion garrisons (Brown et al., 2024).

Little can be said as to what varieties were grown and the quality of the wine. Pambianchi and Gentilucci (2024) suggested the wine was generally of poor quality, with most of the (better) wine being imported from continental Europe. Evidence suggests that what few vineyards there were in Britain were for local use only.

The arrival of viticulture with the Romans coincided with a relatively warm period in history for the UK, the "Roman Warm Period" (or "Roman Climatic Optimum"). The climate in this period was probably and approximately equivalent to the climate in Britain between 1961 and 2000 (Table 1.1). Interestingly, the 1961 to 2000 period was associated with the beginnings of the modern era of UK viticulture.

British vineyards probably fell into disuse and the land repurposed after the end of Roman rule in 410, though possibly earlier. Owning and running a vineyard was even then a marginal business, often seen as a luxury, and one that required considerable labour, especially at harvest (Purcell, 1985). A combination of a worsening climate for viticulture (Pambianchi and Gentilucci, 2024) and dwindling economic justification likely resulted in the disappearance of vineyards until the tenth century. Furthermore, viticulture was unlikely to survive the extreme cooling of the following Late Antique Little Ice Age period (Table 1.1), which is a broadly accepted spatially synchronous cooling event from 536 to 660 CE across most of the Northern Hemisphere, probably caused by extreme volcanic activity (Büntgen et al., 2016).

1.3.2 Medieval Climatic Optimum

The Medieval Climatic Optimum was another period of relative warmth for Europe and the North Atlantic region. For the UK, the period was probably also similar to the climate of 1961 to 1990 or 1971-2000 (Table 1.1). Drawing on work by Lamb (1982), Unwin (1990) thought that the similarity between the vineyard distribution in 1980s England with the vineyard distribution documented in the Domesday Book provided some evidence that the climate of 11th Century England was similar to that of the 20th Century. Chuine et al. (2004) reconstructed a temperature record from Burgundy harvest dates (from 1370) and showed that summer temperatures as high as those experienced in Dijon, Burgundy in the 1990s occurred several times earlier in medieval times (although 2003 was considerably warmer than any other year in the long-term record).

There is increasing reliable evidence for a small number of vineyards in the tenth and early 11th centuries, but firm evidence does not appear until the Domesday Book of 1086 (Unwin, 1990). This recorded 42 vineyards, generally distributed in three clusters: i) Essex and Suffolk, ii) Middlesex (now North London), and iii) Somerset and Dorset (Unwin, 1990). Vineyards were relatively small between approximately 1 and 12 acres

Table 1.1. Estimated summer temperature anomalies for Southern and Central England since Roman times (vs. 1961-1990 baseline)

Period	**Approximate Average Temperature Anomaly (°C from 1961-90 base)**	**Source**
Roman Warm Period (c. 100 BCE - 200 CE)	0.0 to +0.3	Proxy reconstructions for Mediterranean Sea surface temperat-ures (Margaritelli et al., 2020) & European summer temperatures (Luterbacher et al., 2016)
Late Antique Little Ice Age (536 - 660 CE)	-2.5	Proxy reconstructions for European Alps and Russian Altai (Büntgen et al., 2016)
Medieval Climatic Optimum (c. 900 - 1300 CE)	+0.25	Proxy reconstructions for Central England (Mann, 2002)
Little Ice Age (c. 1400 - 1700 CE)	-0.75	Proxy reconstructions for Central England (Mann, 2002)
Pre-industrial Period (1850 - 1900)	-0.3 to -0.5	Northern Hemisphere Annual Average Temperature (Morice et al., 2021)
1961–1990 baseline	0	Mean Temperature April to September for England SE and Central S (Met Office, 2025)
1971-2000	+0.3	Mean Temperature April to September for England SE and Central S (Met Office, 2025)
1981–2010	+0.7	Mean Temperature April to September for England SE and Central S (Met Office, 2025)
1991-2020	+1.0	Mean Temperature April to September for England SE and Central S (Met Office, 2025)
Latest Years (2021–2024)	+1.4	Mean Temperature April to September for England SE and Central S (Met Office, 2025)

(though there is some debate about the standardisation of measure), and, based on just one entry, yields may have been as little as 13.5 hectolitres per hectare (hl/ha) in a good year, which compares poorly to the current 10-year average of 30 hl/ha (2014-23, WineGB, 2024). Interestingly, maybe 10 of the vineyards were new or recently planted (and hence only partially cropping) and these vineyards were concentrated in Essex, which in modern time is where there is currently a rise in vineyards after the initial first growth of viticulture in South-East England. As such, despite some evidence for prior viticulture, Unwin (1990) believes the Norman invasion and Norman feudal system brought with it a considerable expansion of viticulture.

This period of relative warmth, with a peak in vineyard extent, ended with the onset of the Little Ice Age. A cooling in temperatures and increase in precipitation occurred simultaneously with social upheaval, particularly due to the Black Death (1348-49), and social unrest (notably the Peasants Revolt in 1381), which limited available labour for working in the vineyards and increased wages (Gergal, 2021). It may be that the 13th Century was already proving too difficult for profitable viticulture compared to the 11th Century; a 13th Century document relating to the Archbishop of Canterbury's vineyards notes that expenses were generally greater than receipts (Unwin, 1990) and Gergal (2021) describes how a West Sussex vineyard was converted to a deer park by 1301 overtly for profit-based reasons. Unwin (1990) concluded that, "In the 11th century, as it is today, England was at the northern limits of successful possible viticulture."

1.4 Recent impact of climate change on UK viticulture and wine production

In modern times, early pioneer Raymond Brock at the Oxted Viticultural Research Station in the 1940s demonstrated that wine grapes could be grown in the climate of England. He was followed in the 1950s by Major-General Sir Guy Salisbury-Jones at Hambledon in Hampshire, Jack Ward at Horam Manor, and the Gore-Brownes' at Beaulieu, who were the first to plant grapevines with commercial intentions (Skelton, 2020a). In total, their vineyards amounted to less than 5 ha (Skelton, 2020a).

Expansion continued throughout the 1970s, 1980s and early 1990s until it reached a peak area in 1993 of 1,065 ha (479 vineyards), amounting to a "mini-industry" (Skelton, 2020a). These vineyards were generally planted with German cultivars, such as Muller Thurgau, as well as the French-American hybrid Seyval Blanc, which are suited to the coldest possible climates under which grapes can grow (Figure 1.1).

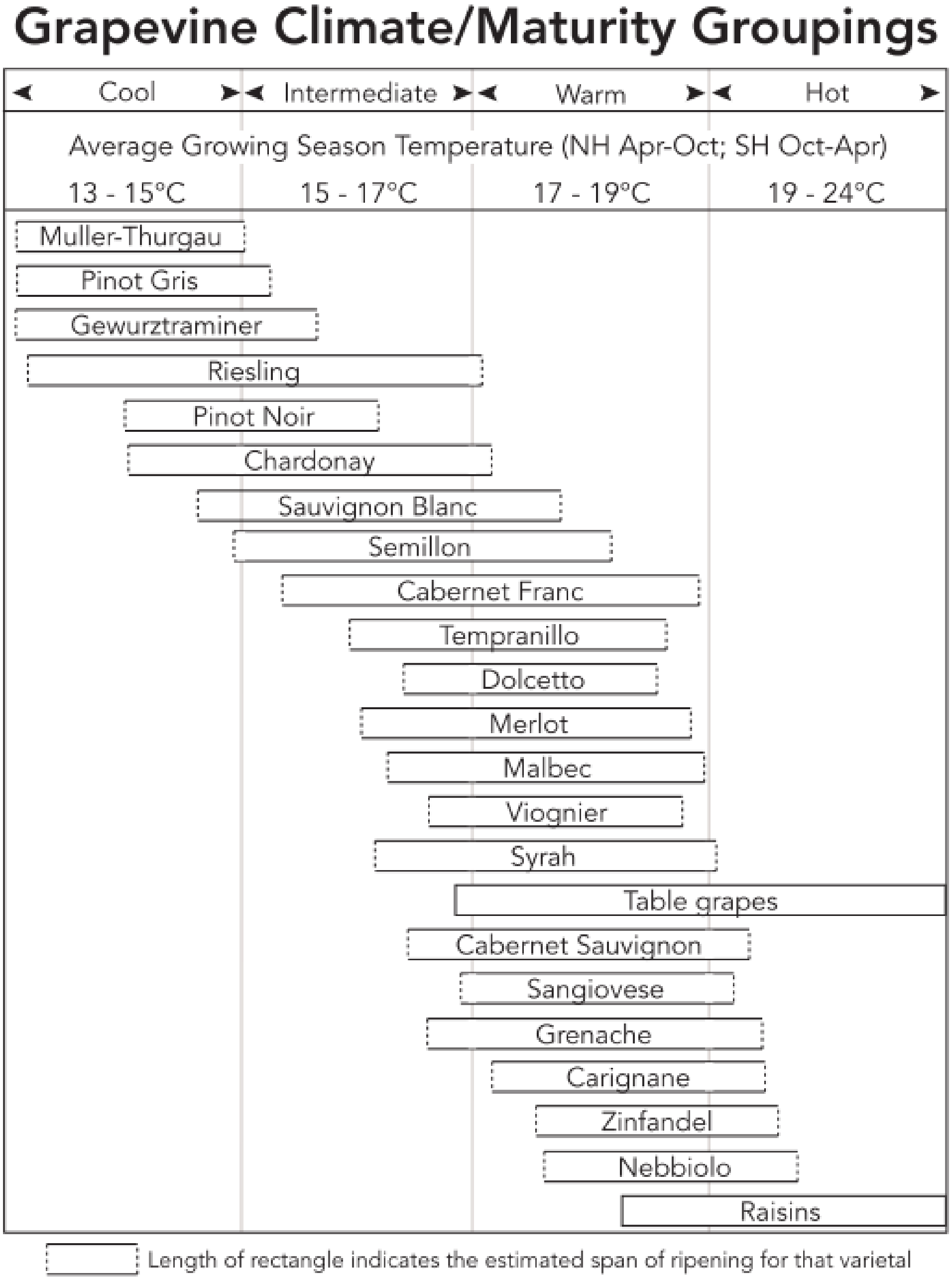

Figure 1.1. "Climate-maturity" groupings based on average growing season temperature requirements (GST) for high to premium quality wine production for the major grape cultivars. Dashed lines indicate the margins are not exact, though Jones (2006) says that boundary changes greater than +/- 0.2-0.6°C are highly unlikely. From Jones (2006).

However, from 1993 to 2004, a number of inter-related factors (adverse weather conditions and high variability, increased international competition, high duties, and inconsistent wine quality) led to 304 hectares (almost 30%) of vineyards being grubbed up (Skelton, 2020a). The award-winning success of Nyetimber's sparkling wine in the late 1990s (a producer based in West Sussex using traditional Champagne grape cultivars and wine making methods) and the hot 2003 vintage, however, contributed to a reversal of that decline.

Climate change has continued to benefit viticulture in England and Wales (Nesbitt et al., 2018), with more than a sixfold increase in vineyard hectarage from 2004 (761 ha; Food Standards Agency, n.d.) to 2024 (4841 ha; WineGB, 2025). This has been accompanied by a move away from hardy German grape cultivars towards cool climate French cultivars such as Chardonnay, Pinot Noir and Meunier that require warmer growing season temperatures (Ashenfelter and Storchmann, 2016; Nesbitt et al., 2019) (Figure 1.1 and Table 1.2). Chardonnay and Pinot Noir are two of the most popular wine grape cultivars, accounting for around 6.2% (285,455 hectares) of all vineyards worldwide (Easton, 2015). They are capable of producing popular 'everyday' wines as well as some of the greatest wines that fetch some of the highest prices at auction. Looking ahead, the market for Chardonnay wine is projected to more than double, from USD 576 million in 2025 to USD 1,186 million in 2035. This growth is driven by increasing global consumer preference for premium white wines, particularly among the expanding middle class in emerging economies (Future Market Insights, 2025). A projection from 360iResearch (2025) provides similar values (USD 637 million in 2025 to USD 904 million in 2030) (though neither of these companies provide clear details on their methodology and on what constitutes the "Chardonnay Market").

English wine producers are already using Chardonnay and Pinot Noir to produce sparkling wines, usually blended with Meunier to make a classic Champagne-style wine, which require grapes that are only just barely ripe (Clarke, 2020). Doubt remains, however, as to how consistently the UK will be able to produce high-quality still wine from these cultivars over the coming decades (Nesbitt et al., 2016). Chardonnay is rarely used to make still white wines in the UK, though the proportion of still wine has been steadily increasing since the exceptional high-quality and high-yielding vintage of 2018 (Olsen, 2021; WineGB, 2021).

Table 1.2. UK vineyard plantings by grapevine cultivar (hectares), categorized by whether cultivars expanded or contracted in area from 1999 to 2023. Data from Skelton (2025b).

	Planted Vineyard Area (ha)						***Inc/Dec on 2009 (%)***
	1999	**2002**	**2009**	**2013**	**2018**	**2023**	
WINNERS (EXPANDED AREA)							
Chardonnay, Pinot Noir & Meunier[1]	60	80	468	701	1,438	2,840	*506*
Bacchus	85	86	119	131	197	316	*166*
PIWIs[2]	14	16	98	123	166	291	*197*
Pinot Gris, Pinot Blanc & Sauv. Blanc[3]	-	-	32	45	63	150	*367*
Frühburgunder (Pinot Noir Précoce)	-	-	17	20	39	71	*311*
HOLDING UP							
Seyval Blanc	102	103	89	92	101	112	*26*
Ortega & Siegerrebe	55	28	41	49	58	62	*54*
LOSERS (CONTRACTED AREA)							
German Cultivars[4]	351	236	195	186	146	126	*-36*
Madeleine Angevine	69	56	47	46	39	34	*-27*
Müller-Thurgau	116	111	62	56	43	30	*-51*

[1]Chardonnay, Pinot Noir and Meunier account for a mean 45%, 43% and 12% of the 2009 to 2023 figures respectively. These are the three cultivars commonly used to make sparkling wine using the Champagne method. Chardonnay and Pinot Noir are also used to produce still wines.

[2]PIWIs are the cultivars bred for fungal-resistance. From greatest planting area in UK in 2023 to smallest, they comprise: Solaris (108 ha), Rondo (62 ha), Regent (30 ha), Phoenix (29 ha), Orion (13 ha), Caberet Noir (12 ha), Divico (12 ha), Sauvignac (6 ha), Muscaris (<5ha), Cabernet Cortis, Souvignier gris, Pinotin, Johanniter, Cabernet blanc, Voltis, Villaris, Bronner, and Bolero (Skelton, 2025a).

[3]Sauvignon Blanc (Sauv. Blanc) did not feature in the data until 2013: 0 ha in 1999, 2002 and 2009, 5 ha in 2013, 6 ha in 2018, and 30 ha in 2023.

[4]Excludes Bacchus, Frühburgunder, Müller-Thurgau, Ortega and Siegerrebe as these are listed separately, but includes Dornfelder, Faberrebe, Huxelrebe, Kerner, Kernling, Reichensteiner, Riesling, Schönburger, and Würzer, plus several others that have only had a minor presence in the UK (<5ha).

It is worth noting that Chardonnay is the most international grapevine cultivar (OIV, 2017); it is grown in 41 countries, the highest number of any cultivar. This is because of its versatility, being able to grow in different climates and produce different styles of wine. Moreover, producers have several options when selecting Chardonnay clone(s) (and rootstocks), depending on desired outcome of wine type and style, and local environmental conditions (e.g. weather, soil fertility, disease pressure, etc.) (see Section 6.9.5). Nonetheless, because this French cultivar is more climatically marginal for the UK, yields and quality are more sensitive to interannual variation in weather than if producers had kept to the German cultivars (Nesbitt et al., 2018).

Interestingly, several continental European wine producers have recently established new vineyards in England (e.g., Pinglestone Estate in Hampshire, owned by the Champagne house Pommery via its UK subsidiary Louis Pommery England, and Chateau Evremond in Kent, owned by the Champagne house Taittinger) (de Nicolo, 2019). Others have bought pre-existing vineyards in England (e.g., Bolney Wine Estate in West Sussex, now owned by a UK subsidiary of Henkell Freixenet [a German-based company with sparkling wine brands globally], and Hambledon Vineyard in Hampshire, now owned jointly by the port house Symington Estates and the British wine merchant Berry, Bros. & Rudd). In 2023, California-based Jackson Family Estates bought 26 hectares of land in the Crouch Valley, Essex, with the aim of planting Chardonnay and Pinot Noir for sparkling and still wine production.

These investments are a part hedge by these companies against climate change in their traditional areas of production (Watson and Beedell, 2024) and part recognition of the opportunities that climate change has brought for viticulture in Southern, South Central and Eastern England. Moreover, whilst the land purchase price paid by overseas producers is expensive in relative terms for England, it may be a fraction of the cost paid for productive viticulture land in, for example, Champagne (Watson and Beedell, 2024).

Note, however, that the UK's production of wine, or more specifically that of England and Wales, is still tiny compared to other countries. The volume of wine produced in 2023 (the highest yielding year for the UK) was 162,000 hl, placing it 46th in the world ranking (OIV, 2025a). UK production was only 0.3% and 0.4% that of the first and second ranked countries France (47,153,000 hl) and Italy (38,290,000 hl), and still well behind that of well-established but smaller nations like Georgia (ranked 18th, 1,865,000 hl) and Moldova (ranked 19th, 1,778,000 hl) (OIV, 2025a). Thus, based on the output for traditional wine producing countries, there appears to be enormous potential to increase viticulture in the UK with climate change, provided suitable locations are found for the right cultivars (Nesbitt et al., 2018) and the demand is there (see Section 1.7).

However, even in Southern and Eastern England, the climate is still marginal for viticulture, with the risk of cold, wet and/or humid conditions during the growing season. These conditions increase the risk of disease – most commonly downy mildew, powdery mildew and rot - which affect both yields and quality, and thus require expensive and potentially environmentally harmful fungicide (given the absence of proven organic methods). As such, many producers are experimenting with the fungus resistant PIWI cultivars, which are now grown on around 7% of UK vineyard land (Table 1.2), though doubts remain about the quality of the wine produced from these cultivars or how long it will take to gain the experience and expertise to create quality wines from them (see Section 1.1).

Many other UK producers, particularly those outside of the Southern and Eastern regions of England, continue to use other cultivars such as Bacchus, Seyval Blanc and Reichensteiner. While these cultivars may never achieve the perceived greatness of a Chardonnay or Pinot Noir, they are often well thought of in terms of their “Englishness”, which in the case of Bacchus is often described as a light refreshing aromatic white wine with elderflower flavours. Seyval Blanc and Reichensteiner, on the other hand, are more neutral in flavour and therefore good blending cultivars (Skelton, 2020a). Other cultivars that are well thought of currently in UK still wine quality terms are Pinot Gris (Pinot Grigio), Pinot Blanc and perhaps some red blends that comprise Rondo, Regent, and Dornfelder (Skelton, 2020a).

As well as a change in cultivars, UK viticulture has also undergone changes in agronomy over the last few decades, including planting density, trellising and training, and methods of pruning, canopy and crop management, as well as a rise in organic, biodynamic, and/or regenerative farming practices (Skelton, 2020a). There has also been an increase in professionalism and a move away from hobby-vineyards. Several viticulture and winemaking consultants now dominate the market, for example

VineWorks (established in 2006) and Vinescapes (established in 2015 as Climate Wine Consulting Ltd, and changed to Vinescapes Ltd in 2020), and they employ experts with knowledge gained from working in vineyards and wineries across the globe.

There is also now an ecosystem of professional services for UK producers. These include a trade magazine (“Vineyard”, established by Kelsey Media in 2018), an annual trade show (“Vineyard & Winery Show”, established in 2021), a representative trade body (“WineGB”, established in 2017), agronomy experts (e.g., Agrii and Agro-Pro Ltd), and UK dealers offering specialist vineyard and winery equipment, such as Bevtech Ltd, Core Equipment, Kirkland UK, NP Seymour, and Vitikit Ltd. Viticulture is now the fastest growing agriculture sector in the UK (WineGB, 2023).

1.5 Climate change projections

Cultivated grapevines are perennials that take approximately four years to reach full cropping and typically remain productive for 25 to 30 years. Given this and the substantial capital investment required for site preparation, planting and trellising – estimated at approximately £30,000 per hectare (Skelton, 2020a) – climate projections are especially important for viticultural decisions such as site location and cultivar choice. This contrasts with annual or short-lived perennial crops, which offer greater flexibility to respond to climatic variability.

Climate change projections are derived from complex Earth System Models that are continually evolving, incorporating the latest scientific understanding and improving in both spatial and temporal resolution (Bordoni et al., 2025). While accuracy has improved, risks and uncertainties remain, and projections should be understood as probability ranges rather than precise predictions. A major source of uncertainty is the extent to which humans will reduce the concentration of greenhouse gases (GHGs) in the atmosphere (see Box 1.1), either through emissions reductions or carbon capture and storage technologies, leading to a range of plausible futures. These are now represented by the Intergovernmental Panel on Climate Change’s (IPCC) Shared Socioeconomic Pathways (SSP) (IPCC, 2023) and often combined with the previous Representative Concentration Pathways (RCP – see Chapters 2 and 3).

Satellite measurements of atmospheric concentrations of GHGs, based on the 12-month average to July 2024, show that carbon dioxide (CO_2) is at 422.1 ppm, higher than at

BOX 1.1. GREENHOUSE GASES

Greenhouse gases (GHGs) are atmospheric gases that absorb and emit infrared radiation, trapping heat in the Earth's atmosphere and thereby contributing to the greenhouse effect, a process which warms the surface of the planet and is a key driver of global climate change.

Major greenhouse gases include: carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); water vapour (H_2O); ozone (O_3); and fluorinated gases (e.g., HFCs, CFCs). These gases allow incoming shortwave solar radiation to pass through the atmosphere but absorb outgoing longwave infrared radiation emitted by the Earth’s surface, thereby trapping heat (IPCC, 2021).

Greenhouse gases have different warming effects and atmospheric lifetimes. Global Warming Potential (GWP) is a measure of how much energy the emission of 1 ton of a gas will absorb over a period of time (usually 100 years) relative to the emission of 1 ton of carbon dioxide (CO_2). Taking the three main GHGs, these are:

Carbon dioxide (CO_2):

GWP:	1 (reference gas)
Atmospheric lifetime:	Long-lived (millennia)
Responsible for:	Around 64% of warming effect
From:	Extraction and burning of fossil fuels, wildfires and natural processes like volcanic activity.

Methane (CH_4):

GWP:	27 to 30 (over 100 years)
Atmospheric lifetime:	7 to 12 years (NASA, n.d.)
Responsible for:	Around 16% of warming effect (20 to 30%, NASA (n.d.)).
From:	Around 60% from anthropogenic sources (e.g. ruminant farming, rice agriculture, fossil fuel use, landfills and biomass burning) and 40% comes from natural sources (e.g. wetlands and termites). Note methane is a precursor to ozone, another GHG.

Nitrous oxide (N_2O):

GWP:	273 (over 100 years)
Atmospheric lifetime:	>100 years
Responsible for:	Around 6% of warming effect.
From:	Around 60% from natural ocean and soil sources and 40% from anthropogenic sources (including fertilizer use, biomass burning and various industrial processes).

In addition to requiring projections for GHG concentrations, modelling of climate systems also requires understanding of terrestrial and ocean sinks, and feedbacks (both positive and negative) within the climate system. These are beyond the scope of this thesis, but details and discussion are available in the latest IPCC report (2021; 2023).

Sources: NASA (n.d.); U.S. Environmental Protection Agency (EPA) (2025); World Meteorological Organization (WMO) (2024) any time in at least 2 million years (Copernicus Climate Change Service (C3S), 2025). The two other major GHGs, methane (CH_4) and nitrous oxide ((N_2O), are at 1901 ppb (C3S, 2025) and 336.9 ppb (in 2023; World Meteorological Organization (WMO), 2024) respectively, higher than at any time in at least 800,000 years (C3S, 2025; IPCC, 2023). Moreover, the CO_2 measurement is close to the CO_2 threshold described by Hansen et al. (2008) for a near ice-free planet. They pointed out that Earth was almost ice free until CO_2 fell below 450 ± 100 ppm around 50 million years ago causing a cooling trend. The atmospheric concentrations of these three gases was fairly stable in the pre-industrial period (at around 278 ppm, 730 ppb and 270 ppb for $CO_{2,}$ $CH_{4,}$ and N_2O) according to palaeoclimatic records, and has been followed by rapid increases over the past 200 years (MacFarling Meure et al., 2006).

The IPCC has defined 8 categories (C1 to C8) for GHG emission scenarios and these have been related to a modelled pathway (Representative Concentration Pathway (RCP)), associated radiative forcing by 2100 (i.e. stabilised change in energy flux to the atmosphere) in watts per square metre (W/m^2) and an SSP which describes the socioeconomic conditions required to achieve the pathway. For example, C1 is a scenario in which warming is limited to 1.5°C above pre-industrial levels by 2100 with more than 50% likelihood and with no or limited overshoot, and is related to their RCP 1.9 (W/m^2) (very low) emissions scenario, which envisions a world making significant efforts towards sustainable energy, social and economic practices (SSP1) and achieving net zero by 2050. C6 is the intermediate scenario (SSP2 / RCP 4.5) and the one most widely-accepted as our current pathway based on existing policies and trends which stabilise emissions around current levels until mid-Century before gradually declining (IPCC, 2023), whereas C8 (SSP5 / RCP 8.5) is the very highest emissions scenario (RCP8.5) where little effort has been made to mitigate climate change and CO_2 emissions double by 2050 (SSP5) (Table 1.3).

Key points from the latest IPCC report (2023), state that:

- Global surface temperature was 1.09 [5–95% range: 0.95 to 1.20]°C higher in 2011-2020 than 1850-1900.
- Key for agriculture (including viticulture), larger increases occurred over land (1.59 [1.34 to 1.83]°C) than over the ocean (0.88 [0.68 to 1.01]°C).

Table 1.3 Changes in global surface temperature for mid- and end-Century according to five illustrative IPCC emissions scenarios. Temperature differences are relative to the mean global surface temperature of the period 1850-1900. From IPCC (2023).

	2041-2060		**2081-2100**	
Scenario (Category)	**Best estimate (°C)**	**Very likely range (°C)**	**Best estimate (°C)**	**Very likely range (°C)**
SSP1-1.9 (C1)	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6 (C3)	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5 (C6)	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0 (C7)	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5 (C8)	2.4	1.9 to 3.0	4.4	3.3 to 5.7

- Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (high confidence).
- The likely range of total human-caused global surface temperature increase from 1850-1900 to 2010-19 is 0.8 to 1.3°C, with a best estimate of 1.07°C.
- Over this period, the likely contribution to global surface temperature change was as follows:
    - Well-mixed GHGs contributed a warming of +1.0 to +2.0°C
    - Other human drivers (principally aerosols) contributed a cooling of 0.0 to -0.8°C
    - Natural (solar and volcanic) drivers changed temperatures by -0.1 to +0.1°C; and
    - Internal variability changed temperatures by -0.2 to +0.2°C.
- Observed increases in well-mixed GHG concentrations since around 1750 are unequivocally caused by GHG emissions from human activities over this period.

Climatic forcing, such as volcanic activity and solar variability, was insufficient to produce globally synchronous extreme temperatures during the pre-industrial period (AD 0 to 1850) at decadal and centennial timescales (Neukom et al., 2019). Today, however, anthropogenic warming is occurring on a global scale, shifting viticulture belts north in the Northern Hemisphere and south in Southern Hemisphere. By 2010, mean decadal global temperatures were higher than any previous time during the prior

2000 years (Ljungqvist, 2010) and the warmest period of the last 2000 years occurred during the twentieth century for more than 98 percent of the globe (Neukom et al., 2019).

The UK Met Office's UKCP18 climate projections, used in Chapter 3, provide high-resolution regional climate projections specifically for the UK, in contrast to the IPCC's broader, global-scale climate change scenarios. Although developed independently, UKCP18 draws from 13 of the 28 Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model simulations used to inform the IPCC's Fifth Assessment Report, alongside simulations from their own Hadley Centre climate models (Fung et al., 2018).

1.5.1 Climate change uncertainties relevant to viticulture

There are many variables that may be relevant to viticulture that are not captured by climate and weather factors alone, including the effects of increased CO_2 concentration on photosynthesis and biomass production (Moutinho-Pereira et al., 2009; Arrizabalaga-Arriazu et al., 2020; Clemens et al., 2022; Kahn et al., 2022); changes in light spectrum (Huseby et al., 2013) - which, for example, can affect flavonol accumulation in berry skins (Blancquaert et al., 2019) - and changes in the distribution and evolution of pests and pathogens (Bois et al., 2017; Zito et al., 2018).

Interannual variability in weather will likely continue to pose a more immediate and significant concern, particularly in regions where the climate is marginal for grapevine cultivation, as is currently the case in England and Wales (Nesbitt et al., 2018).

Uncertainty also remains regarding the frequency, magnitude, and timing of extreme weather events such as hail (Brennan et al., 2025; Fraga et al., 2013), frost (Leolini et al., 2018), high intensity precipitation (Nesbitt et al., 2016), and droughts. Frost risks are particularly high in the weeks after budburst when buds are delicate, typically from April to May, and advancing phenology (i.e. earlier budburst) will have the effect of bringing budburst forward into the colder months. Questions remain over how large these effects will be, what impact they will have on the vines and the grapes, and whether growers will have the ability to cope with them whilst maintaining long-term profitability (Mozell and Thach, 2014). Certainly, recent research shows that climate change has increased the likelihood of extreme heat events (Faralli et al., 2024;

Kirchengast et al., 2025), hailstorms (Zhou and Vilar-Zanón, 2025), and raised the risk of frost damage (Faralli et al., 2024) in many viticultural areas of Europe.

Climate change, however, is unlikely to follow a linear trajectory. Natural variability will either attenuate or amplify projected changes (IPCC, 2023). For example, a large explosive volcanic eruption could temporarily mask human-caused climate change by reducing temperature for one to three years (IPCC, 2023), and a period of reduced solar activity may also lead to cooler temperatures (Franke and Donner, 2017). As such, there remains a risk of decadal-scale cold periods (Sgubin et al., 2019). Nonetheless, even if such natural variability did mask human-induced global warming, the effects of which emissions pathway we follow will be discernible from natural variability within around 20 years (IPCC, 2023).

A more serious, though low probability, risk is the potential collapse of the Atlantic Meridional Overturning Circulation (AMOC) (van Westen et al., 2024), which could lead to considerably cooler conditions in Europe and especially the UK. Such an event could have severe consequences for UK viticulture potentially rendering it unviable. There is considerable ongoing scientific debate regarding the extent to which the AMOC is slowing (Terhaar et al., 2025), whether it might reach a tipping point, and what the associated impacts could be. In their latest synthesis report, the IPCC (2023) say that although AMOC is very likely to weaken over the twenty-first Century, there is medium confidence that AMOC will not collapse abruptly before 2100. If it were to occur, however, they say it would likely cause abrupt shifts in regional weather patterns, and large impacts on ecosystems and human activities.

1.6 Wine quality and characteristics, and influence of terroir

Central to this thesis is the idea that there is an objective, stable and widespread understanding of what premium quality wine is. It seems, however, that while humans' ability to perceive visual, taste and aroma sensations is for the most part common to everyone (Jackson, 2014), differences may occur in how those sensations are processed and assessed at the individual or cultural level (Rodrigues and Parr, 2019).

At the individual level, any experience of a wine may be affected by a multitude of factors, including a taster's age (Fukunaga et al. 2005, Methven et al. 2012), what they ate before (Nygren et al. 2001), the glassware (Wan et al., 2015), social influence

(Gokcekus et al., 2014), online community influence (Gastaldello et al., 2024), their comfort and enthusiasm arising from their surroundings (de Lima et al., 2021), or even the music they are listening to (Rönnlund, 2023).

Levels of wine expertise and experience matter. Sàenz-Navejas et al. (2013) showed that experts' perceptions of intrinsic wine quality were significantly correlated, but that those of consumers and experts were not. Experts (and probably knowledgeable and enthusiastic amateurs) approach wine tasting in a different way to non-experts (Malfeito-Ferreira, 2023). There is an accepted wine-tasting technique and language to recognise and record visual, gustatory, and olfactory attributes, and an understanding of the optimal physical and psychological conditions required for "fair and honest wine assessment" (Jackson, 2014).

Shepherd et al. (2023) found that the word elegance is understood in a similar way (relating to smooth, balanced, refined and complex) and applied consistently by both wine professionals and novice wine consumers. However, intrinsic wine qualities were more important to experts for conceptualisation of elegance, compared to extrinsic qualities (branding, label, bottle, etc.) which featured more for the novice group.

Parr et al. (2020) looked at the attribute "complexity" among 22 wine professionals from New Zealand and found broad agreement that complexity was i) positively associated with quality, and ii) was about harmony, balance and the number of identifiable flavours. Visual influence was not a driver for wine professional's judgement.

Even expert judges, however, are fallible. Hodgson (2008) examined the performance of judges for a US wine competition and found that only 10% of wine judges were able to replicate their wine scores when secretly given three samples of the same wine. That said, he found more consistency in what they didn't like than what they did, and other researchers have come to similar conclusions. Sàenz-Navajas et al. (2013) found agreement on the undesirability of animal and vegetal attributes, and Parr et al. (2020) found experts all disliked strong reductive notes.

Interestingly, Malfeito-Ferreira (2023) argues that a less systematic and more holistic approach, similar to how a non-expert may approach wine, may be more appropriate for tasting. This would, he says, allow those initial aesthetic or abstract impressions (e.g., "elegant", "beautiful", "classic", "complex") to play a more critical role in recognising fine wine rather than the systematic procedure for tasting that is widely accepted (visual, aroma, taste, mouthfeel and final evaluation), and which he thinks favour wines built for commercial quality rather than fine wine.

Considerable research has looked at differences in our understanding of wine quality at the cultural level. Sàenz-Navajas et al. (2013) found that French consumers who drank both Spanish La Rioja and French Côtes du Rhône wine did not differentiate between these wines in terms of intrinsic quality, whereas Spanish consumers (who reported drinking mostly La Rioja wines) found La Rioja wines of higher quality than Côtes du Rhône wines. Similarly, Suàrez et al. (2023) found that Spanish experts who were more familiar with wines made from Verdejo and Albarino cultivars, rated these wines more highly than wines made from Bacchus, whereas British experts (who were equally familiar with all three cultivars) did not give significantly different scores across the three wine types. Rating scales may also be used differently according to culture, as demonstrated by Williamson et al. (2012) in their study of Chinese and Australian consumers (from Rodrigues and Parr, 2019).

There are also examples where no differences were found between cultures. Parr et al. (2015) and Valentin et al. (2016) found no major differences between French and New Zealand wine professionals in their assessment of wine, and Rodrigues and Parr (2019) warn that research should concentrate on familiarity rather than culture because definitions of culture are complex and go beyond ethnic origin and geographical location. Overall, they say that studies show clearly that wine expertise can override cultural differences.

Another way of approaching wine quality is to find stable associations between a wine's chemical composition and the perception of desirable sensory traits. Gambetta et al. (2016) say objective quality measures are lacking. They analysed Chardonnay wine from three different Australian regions and found that certain compounds (e.g., linalool, decanoic acid), and lower Brix and pH levels related to higher quality. Jackson (2014), while accepting the usefulness of this approach, warns that, "compounds may interact in complicated ways, not only affecting direct sensory detection, but also interpretation in the brain. Therefore, improved chemical knowledge, by itself, is unlikely to generate formulae for 'perfect' wines."

In general, the global prevalence of certain *Vitis vinifera* L. cultivars suggests a universal appeal in the wines they produce. This aligns with the findings of Parr et al. (2020), who investigated complexity in Pinot Noir wines and found that perceived quality was driven by varietal typicality, expressiveness, structure, and attractive fruit aromatics.

As such, whether parts of the UK can produce high quality still wine comparable with other regions may depend on whether its "terroir" is suitable for the most desirable vinifera cultivars. The definition of terroir according to the OIV is that it is, "a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied vitivinicultural practices develops, providing distinctive characteristics for the products originating from this area" (OIV, 2010). Terroir is discussed in Biss (2020) (Appendix 1A), as well its key environmental components in Chapters 2 and 3 (weather) and Chapter 5 (soils and topography). Additionally, a defining aspect of Chablis wine, its "minerality", is thought to come from its terroir, and this is investigated in detail in Chapter 4.

1.7 Economic arguments for viticulture in the UK

While beyond the scope of this thesis, the prima facie economic case for expanding viticulture in the UK depends on its potential for profitability compared to other agricultural sectors, both now and over the coming decades with climate change.

UK Farm business income (output less input costs) is highly variable for each agricultural sector, with the top 25% of farms earning on average twice the amount of the bottom 25% of farms in the years 2020/21 to 2022/23 (Figure 1.2 and Department for Environment, Food & Rural Affairs (DEFRA), 2024). Using yield data provided by WineGB's annual harvest reports (Skelton, n.d.-a) and input cost data from Skelton (2020a), and assuming an average grape sale of £2,500 per tonne (The Grape Exchange, n.d.), the ratio of output less input costs for viticulture is similar to the other agriculture sectors for the middle 50% of producers (1.09 for viticulture versus 1.05 for all other sectors). However, there appears to be a much greater difference between the top and bottom 25% of producers (4.0) ("Ratio of Economic Performance", REP), closer to but still much more than that of the horticulture sector in general (2.5) (Figure 1.2).

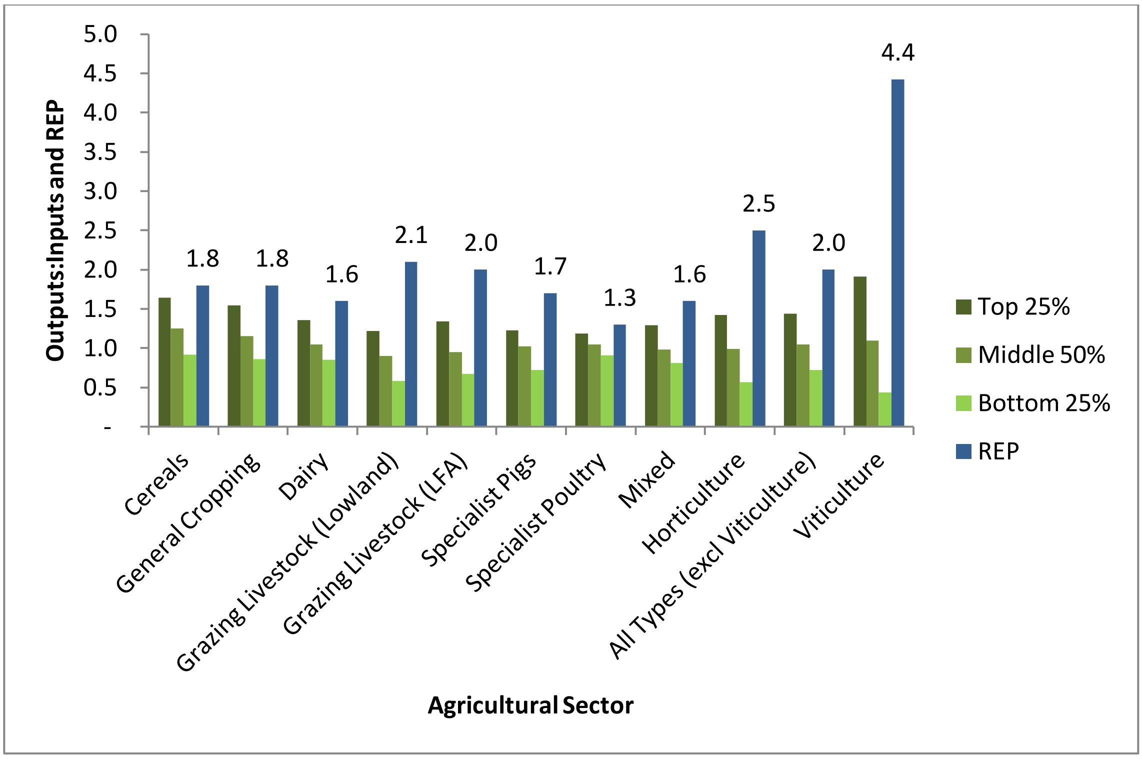

Figure 1.2. Ratio of the average output and average input costs for UK farm businesses by agricultural sector for the top 25% of farms, middle 50% (25%-75%) and bottom 25% of farms, 2020/21 to 2022/23 and the REP (Ratio of Economic Performance, i.e. average performance of top 25% of farms versus average performance of bottom 25%). All data is from DEFRA (2025), except for that relating to viticulture which was calculated based on WineGB yield information for the 2021-23 harvests, input costs from Skelton (2020a), and grape values from The Grape Exchange (n.d.). Note the capital investment required for land purchase, vineyard establishment and machinery has been accounted for by charging 6% on a total £90,000 per hectare, in line with Skelton's methodology. Assumed growing costs are £7,774 per hectare (Skelton, 2020a). See text for discussion.

Several reasons could account for the large difference in REP. First, the bottom 25% of viticulture farms likely includes newer vineyards that have not reached full cropping.

Second, many sectors received direct annual subsidies under the Basic Payment Scheme, an average 50% for all farms from 2020/21 to 2022/23; but as high as 68% of farm income for grazing livestock in less favoured areas, and only 3% of the horticulture sector (DEFRA, 2024). Viticulture rarely qualified for the Basic Payment

Scheme. The Basic Payment Scheme is now closed and being phased out by 2027. It has been replaced by Environmental Land Management schemes, which provide subsidies for environmental outcomes rather than directly related to the area being farmed. There may be more scope for viticulture to gain subsidies under this new arrangement.

Third, many farms have diversified their income streams, for example with farm shops and tourist accommodation. Such figures have not been included in the viticulture calculations presented in Figure 1.2 but are included for the other sectors. Income from diversification in the viticulture sector is important. Many UK vineyards offer, for example, vineyard tours, wine shops, venue hire, vineyard-based restaurants and accommodation, potentially increasing profitability and reducing income variability (Savills, 2024).

Finally, no account is taken here of the added-value and profitability that could come from selling wine rather than grapes, which would require certain assumptions regarding winemaking costs, sales, marketing and distribution, and the price that could be achieved for the wine. New entrants to viticulture, however, often choose to sell grapes rather than make the wine themselves, or use a contract wine-maker. As such, the figures presented here provide a more conservative estimate of the early economics of viticulture.

Looking forward, viticulture may offer a viable adaptation option to climate change. Of the 160 crops considered by Redhead et al. (2025) in their “horizon scanning” of future crops for a changing climate in the UK, they identified grapes as amongst the greatest increase in suitability, across all regions, for both a +2 and +4 °C rise above pre-industrial levels. Under the larger +4°C rise, several important crops such as onions, strawberries, oats and wheat declined in suitability for the regions where they are currently being produced.

Cereal yields are likely to reduce under heat and drought conditions (Semenov et al., 2014), though Redhead et al. (2025) note that other cultivars better adapted to warmth, such as Algerian oats and durum wheat, could be farmed as alternatives. Yields for two cereal crops (winter wheat and spring barley) and grassland in South-Eastern England were generally better in the typical climate of the 20th Century compared to the typical climate of the 21st Century (warmer temperatures, intense rainfall but a dry June), though this difference was less for pasture grassland yield, implying grassland yield is more resilient to climate change (Addy et al., 2021). Climate change may not lead to the introduction of new livestock species to the UK, but it could shift farming towards smaller ruminants, such as sheep and goats, which have greater heat tolerance than larger ruminants like cattle (Joy et al., 2020).

Increased carbon dioxide and ozone levels may also impact on the quality of many crops, including the major fruit and vegetables such as potatoes, tomatoes, apples and grapes (Moretti et al., 2010), though the increased carbon fixation and reduced stomatal conductance from higher carbon dioxide concentrations can improve water use efficiency which is important for crops grown in areas with limited water availability (van der Kooi et al., 2016).

Thus, the potential for agricultural change and diversification is large, providing greater climate resilience and potentially other environmental benefits. Legumes such as cowpea, soya bean, broad bean and chickpea, offer a good protein alternative to meat.

However, viticulture is one of the most lucrative cash crops, fifth only to cannabis, coca (cocaine), opium poppy, and tomatoes (Desjardins, 2014). Of the legal crops grown in the UK without the need of a special licence, only tomatoes are more profitable per land area, but tomatoes will tend to be grown on flatter land, especially if in greenhouses or polytunnels, whereas grapevines will be on slopes. Moreover, viticulture has the potential for considerable added value that comes with making grapes into wine.

Overall, there appears to be considerable potential to increase viticulture in the UK with climate change, provided suitable locations are found (Nesbitt et al., 2018) and demand for wine grapes is resilient. Moreover, some traditional wine-making areas currently at the warmer range of viticulture, such as Portugal and Spain, have already experienced declines in production (OIV, 2025b) that have been associated with the longer-term trends of climate change (Grazia et al., 2023). This may provide room for UK wine in the longer-term. In the short-term, there is a worry that newer UK vineyards are not yet fully cropping and when they are, there will be too much supply for current levels of demand (Skelton, 2020b).

Aside from increasing export opportunities, there may be scope to increase UK production to meet domestic UK demand (Figure 1.3). UK consumption is relatively resilient compared to a backdrop of weakening global consumption, especially in China (OIV, 2025b). The UK currently consumes (and imports) well over 100 times more wine than it produces – 13,227,000 hl versus 93,000 hl (average for 2020-24, OIV2025a). This would likely require, i) a reduction in retail price (many UK consumers think, rightly or wrongly, that UK wine is overpriced relative to imported wine (Meininger's International, 2023)), ii) an expansion of UK wine types to include more still wine, which accounts for over 80% of UK wine sales by value (GBP 5.6 bn versus total wine sales GBP 6.7 bn; Accolade Wines, 2018) but only 23% of UK production in 2023 (WineGB, 2024), and/or iii) changes in branding and marketing (Alleyne, 2025).

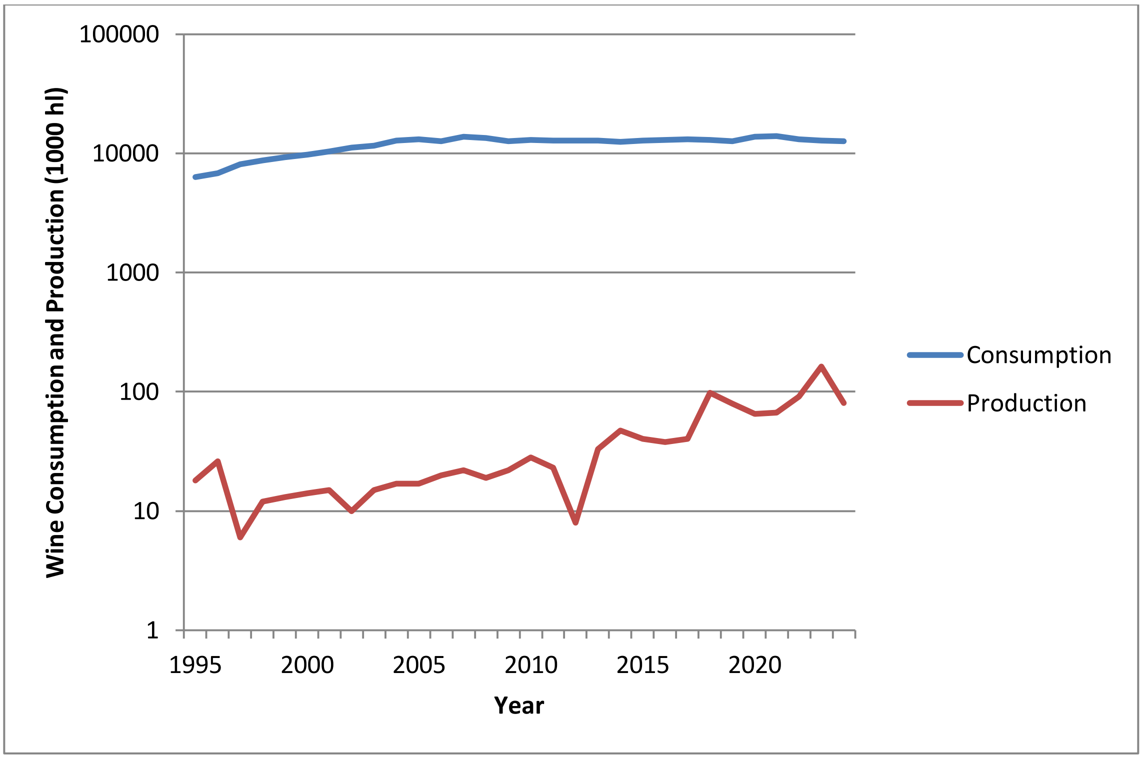

Figure 1.3. UK consumption and production of wine from 1995 to 2024. Scale is logarithmic (base 10). Data from OIV (2025a).

1.8 Thesis aims, hypotheses, and boundaries

The aim of this thesis is to use the Chablis region in Burgundy, France, as an analogy for UK viticulture; to understand what weather, topography and soils are associated with good quality still Chardonnay wine and to understand the limits to producing good to excellent wine vintages from this major cool climate French grape cultivar. This research may then be used to assist in site selection of new vineyards and choice of grapevine cultivar in the UK. Until now, no research has investigated Chablis separately to the rest of Burgundy, nor used it as an analogous template for the UK.

Specifically, this thesis tests the hypotheses that:

A. Variation in Chablis wine quality is associated with that in the weather;
B. Models based on the above can be applied to estimate future Chardonnay still wine quality across the UK both now and, with climate projections, out to mid-Century;
C. Minerality, a key high quality characteristic associated with Chablis wine, is related to weather during the growing season, not soils, geology or winemaking practices;
D. Topography and soils modulate the impact of weather and drainage at the local scale in Chablis, and thus further affect wine quality;
E. A model that combines an understanding of A and D above can be used to map suitable sites for planting Chardonnay vineyards in the UK;

For the final map results, the hypotheses for this project are:

F. The UK is able to produce grape berries for the production of still white wines that are equivalent in quality to that of Chablis, Burgundy. If so, where?
G. The UK will be able to produce grape berries by mid-Century, with projected climate change, for the production of still white wines that are equivalent in quality to that of Chablis, Burgundy. If so, where?

The thesis is focused on, and limited to, the following:

- The Chardonnay cultivar only, although findings may also be applicable to Pinot Noir and Meunier (see Section 6.8).

- Single cultivar still white wine, excluding cultivar blends, sparkling, red, or rosé. Findings may, however, be adapted to sparkling wines made from Chardonnay, Pinot Noir and/or Meunier, and red wine made from Pinot Noir (see Section 6.8).
- Grape berry and wine quality, not yield, although general yield trends may be inferred insofar as they relate to overall growing season conditions, rather than short-term extreme events (see Section 6.1).
- Chablis as an analogous region.
- The UK as the target country of interest, although the methodology may be extended with care to other emerging wine regions (see Section 6.8).
- Producers who make wine from grapes grown in their own vineyards or from grapes sourced from a clearly stated locality. In practice, producers may also contract winemakers.

The research, and series of papers, is based on the principle that the climatic, topographical and soil factors required for high quality wine production in Chablis are also applicable to the UK. The project does not take into account differing techniques used in making and/or storing the wine (such as the use of oak barrels), but is concerned only with the environmental limits to viticulture to make high quality wine.

Yield can be used as a lever to influence fruit composition and wine quality, but its effect is usually considerably smaller than that of weather. Moreover, in the context of this thesis, the UK is still generally yield-limited and any stated maximum yields (such as the English Wine PDO limit of 80 hl/ha (DEFRA, 2011)) are rarely approached under current climatic conditions. By contrast, EU regulations impose relatively strict yield caps in Chablis that act as protection against overcropping (see Section 6.9.8).

It is hoped the significance of the project will be twofold: i) it will provide an alternative methodology for assessing and mapping UK land suitability for vineyards, focused on expected wine quality, and ii) it will help with investment decision-making and vineyard planning, both for prospective and existing UK producers and also for established wine producers from outside the UK. It takes approximately 4 years for a new vineyard to achieve full cropping production and the expected productive life of a vine is around 30 years (Skelton, 2020a). Thus establishing vineyards (or changing cultivar) involves substantial risk and requires careful planning.

The PhD is data-driven and based on analysis of existing datasets. These include climate and weather data, and climate projections, from the UK and French meteorology services; digital elevation and soils data for both Chablis and the UK; Chablis vintage ratings from established and reputable wine publications/critics; tasting notes from CellarTracker (an online crowd-sourced database of tasting notes and scores) to examine the concept of "minerality"; UK land use, land designated protection status, and flood risk data to narrow down potential UK site identification; and the location of UK vineyards from Skelton's website englishwine.com for proof-of-concept purposes (Skelton, n.d.-b). The only new data comes from a survey of wine experts, which is used to evaluate the findings in Chapter 5.

QGIS (an open-source Geographic Information System) is used for geospatial analysis. Statistical and text analyses is carried out in R and R Studio.

1.9 Overview of chapters

Chapter 2 models the climate of Chablis to determine how inter-annual variation in vintage weather affects wine quality (Weather Model).

Chapter 3 applies the Weather Model from Chapter 2 to the UK for historical (1981-2000), recent (2010-19) and, using climate projections, to mid-Century (2040-59), to produce maps showing where Chardonnay vineyards can be established (climatically, though not necessarily agronomically) for the purposes of producing premium quality still white wine.

Chapter 4 uses textual analysis of tasting notes to examine the concept of "minerality", a key characteristic of Chablis wine quality, and investigates the extent to which this characteristic is linked to weather and is therefore "transferrable" with climate change.

Chapter 5 combines the findings from Chapters 2 and 3 with topography and soils data for Chablis (from Biss, 2020), and applies them to England. The result is a model (Combined Model) that classifies land in England into one of four quality levels for the current climate and for mid-Century: Unclassified, Village, Premier and Grand Cru.

Chapter 6 provides a discussion for the project as a whole, including consideration of its originality, utility, methodological concerns, and areas for further research.

Chapter 2. Preface

Chapter 2 comprises the following research paper:

Title: Modelling Chablis vintage quality in response to inter-annual variation in weather

Authors: Alex J. Biss and Richard H. Ellis

Citation: Biss, A. J. & Ellis, R. H. (2021). Modelling Chablis vintage quality in response to inter-annual variation in weather. *OENO One*, *55*(3), 209–228. https://doi.org/10.20870/oeno-one.2021.55.3.4709

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Author Contribution: This paper was co-authored with Professor Richard H. Ellis. The research design, data analysis, and manuscript drafting were carried out by Alex Biss. Professor Ellis contributed to method development and manuscript editing.

Relevance to Thesis: This chapter addresses Objective A of the thesis, concerning identification of weather factors that produce high-quality wine in Chablis, France. The model developed in this chapter is applied to the UK in Chapters 3 and 5.

Note: This paper describes the “Chablis vintage model”, which has been renamed the “Weather Model” in Chapters 5 and 6.

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Modelling Chablis vintage quality in response to inter-annual variation in weather

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ABSTRACT

The weather during grape production affects wine quality. Changes in the weather in the Chablis region of France and in the quality of Chablis wines (vintage scores) from 1963 to 2018 were analysed. Chablis wine quality improved over this period, with no Poor vintages after 1991. Summer temperature and sunshine duration both increased progressively between 1963 to 2018 with fewer frost days but no linear change detected in precipitation. Chablis vintage score was modelled as a function of mean temperature from April to September (curvilinear relation, maximum score at 16–17 °C), mean minimum temperature in September (an index of cool nights; negative relation), and total rainfall from June to September (negative relation). This simple three-factor model distinguished between *Poor* and higher-quality Chablis vintages well, but less so between *Good* and *Excellent* vintages. Application of the model to different climate change scenarios (assuming current viticultural and oenological practices) suggests that vintage scores will decline (slightly to substantially, dependent upon emissions scenario) by the 2041 to 2070 period. This reduction in quality would, however, be minimised if the warming of cool nights is less than currently forecast. The Chablis vintage score model may help identify sites with suitable climates for premium white wine from Chardonnay grapevines in emerging cool climate viticulture regions as well as aiding Chablis producers mitigate the effects of climate change.

KEYWORDS

Chablis, Burgundy, Chardonnay, viticulture, vintage, weather, climate change

Supplementary data can be downloaded through: https://oeno-one.eu/article/view/4709

INTRODUCTION

Considerable research has been carried out on the link between weather and wine quality. The general consensus from viticulture regions around the world is that weather is a major determinant of inter-annual variation in vintage quality (van Leeuwen and Darriet, 2016). A common finding is that vintage quality is related to growing season temperature and rainfall in the one to two months before harvest (Ashenfelter and Byron, 1995; Grifoni *et al.,* 2006; Ashenfelter, 2010; Lorenzo *et al.,* 2013; Outreville, 2018), though differences exist amongst regions and cultivars (Suter *et al.,* 2021). Global climate change, with considerable warming in recent decades (IPCC, 2014), requires greater understanding of crop quality-weather relations to support the future adaptation of crop production. This is more urgent for perennial, rather than annual, crops where planting decisions have consequences for decades.

Little research, to our knowledge, has focused specifically on the weather and the wines of Chablis in France. Chablis has been included implicitly, however, within more general studies of Burgundy (Outreville*,* 2018; Davis *et al.,* 2019). Chablis wines deserve particular attention.

i) Chablis wines are unique: the region's white wines, made exclusively from Chardonnay grapes, are distinct in aroma and flavour ("typicity") from Chardonnay wine produced elsewhere, including the rest of Burgundy (George, 2007).

ii) Chablis wine is a major commercial crop product: 34.3 million bottles of Chablis wine were sold in 2019 for an estimated 273 million Euros, with 417 companies (379 wine estates, 1 cooperative and 37 merchants) involved directly in viticulture and/or winemaking (Bureau Interprofessionnel des Vins de Bourgogne - BIVB, 2020).

iii) Chardonnay is a major grape variety for wine production: the world's second-most planted white wine variety (after Airen) and the wines, often of premium quality, from its berries are recognised by consumers worldwide (Organisation Internationale de la Vigne et du Vin - OIV, 2017).

iv) Chablis may be useful as an analogous model for Chardonnay production in emerging cool climate wine regions: Chablis is currently the most northerly region (latitude 47.8° N) for the production of high-quality single variety still Chardonnay wines at globally significant quantities (BIVB, 2020).

The single-variety Chardonnay wines of Chablis are protected by the European Union as a Geographical Indication (GI), a system set up to protect agricultural food and drink products where the quality or reputation of a product is attributable to its geographical origin (European Commission, 2016). Few other wine regions, if any, have been able to reproduce the flavours and aromas of a typical Chablis wine, which is: i) dry with "a firm backbone of acidity" (George, 2007), balanced with ii) the "mineral flavours of stony gunflint" (often referred to as "minerality") (George, 2007; Ballester *et al.,* 2013) and iii) the flavour and aroma of green apples, citrus fruit and/or white flowers. With bottle ageing, fine Chablis wine can become subtly oaky or nutty (even if never stored in oak barrels), honeyed, more elegant, and can develop greater intensity of minerality and fruit flavours (George, 2007; Biss, 2009; BIVB, 2021a).

Chablis typicity is said to come from its unique "terroir" – "[…] a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied vitivinicultural practices develop, providing distinctive characteristics for the products originating from this area […]." (OIV, 2010). The natural terroir features that are most often used to explain the typicity of Chablis wines are i) its weather, primarily a function of its relatively northerly latitude (for Chardonnay) and semi-continental position (George, 2007); ii) its Kimmeridgian geology and associated soils (Jackson, 2014) and iii) its topography and associated micro-climates (Droin, 2014).

This study investigates the effect of the first of the factors above within the region - weather and the quality of wines of Chablis typicity; specifically, whether or not inter-annual variation in weather over more than half a century (1963 to 2018) has had a detectable effect on Chablis wine quality. We test whether or not warming has occurred during the growing season in the region over this period, and how wine quality has fluctuated; develop a model of the historic effect of inter-annual variation in weather on Chablis wine quality, and, finally, apply that model to estimate the medium-term future for Chablis wine quality under various climate change scenarios.

MATERIALS AND METHODS

1. Study area

The Chablis wine region is located in the department of Yonne, in the northern part of Burgundy, France (Figure 1). The vineyards are within a relatively compact area (approximately 16 km (North–South) by 18 km (East–West) centred around the town of Chablis (latitude 47°48′49″ N, longitude: 3°47′54″ E, 140 metres above sea level). The topography is hilly, rising to around 320 metres and the vineyards lie on both sides of the river Serein which runs broadly North–South through the town. Chablis wines are divided into four *appellations d'origine contrôlée* (AOC). In decreasing order of quality recognition, these are Grand Cru Chablis, Premier Cru Chablis, Chablis and Petit Chablis. For the purposes of this study, all four AOCs are included in the term "Chablis wine".

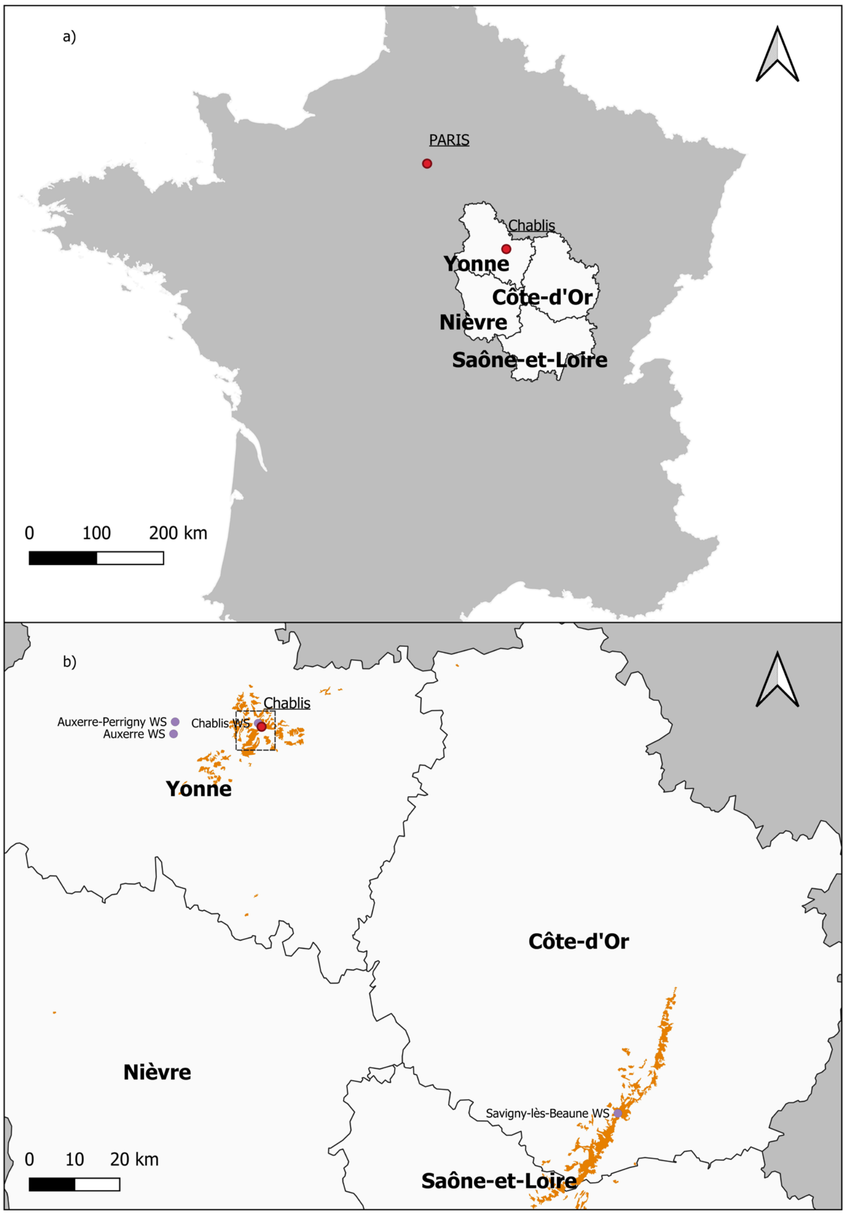

FIGURE 1. Study area: a) location of Chablis, a town in the Yonne, department of the Burgundy region, within France; b) close-up of the Yonne and Côte-d'Or departments.

Vineyard areas in orange (European Environment Agency, 2020), study area weather stations (WS, lilac circles), and grid square (dashed square) used for climate projections (Drias, 2021).

2. Model development

2.1. Chablis vintage scores

To gauge Chablis vintage quality between 1963 and 2018, vintage scores were taken from five sources: Berry Bros. & Rudd wine merchants (BBR) for the 1978 to 2018 vintages; Decanter magazine for 2005 to 2015; Wine Enthusiast (WE) for 1995 to 2018; Wine Scholar Guild (WSG) for 2000 to 2018; and The Wine Society (WS) for 1980 to 2018. These reputable and respected wine experts or institutions provide separate scores for Chablis (as opposed to incorporating Chablis into a more general score for 'White Burgundy'). Scores were standardised into a 10-point scale (as used by BBR and WS). This required doubling the Decanter and WSG scores (originally scored out of five) and deducting 50 and dividing by 5 for the WE scores (originally scored from 50 to 100). No quantitative scores were available for vintages prior to 1978, and only one source (BBR) for 1978 and 1979. Scores were inferred, therefore, for 1963–1979 from the qualitative vintage reports on the BIVB Chablis website (BIVB, 2021b) and Chablis specialist Rosemary George's book '*The Wines of Chablis and the Grand Auxerrois*' (George, 2007).

A consensus vintage score (Supplementary Information Table S1) was calculated as the mean of the several scores for each vintage (number of scores per vintage: mean 3, minimum 2, and maximum 5). This assumption that the scales correspond to each other was necessary because it was not practicable to use the ranking methodology described by Borges *et al.* (2012) due to the different vintage ranges covered by each source. The mean score was used in all statistical analyses, but for graphical presentation, the vintages were categorised into *Excellent* (>8), *Good* (6 to 8) and *Poor* (<6). This was based on the distribution of the data (mean = 7.1, interquartile range 6.5–8.3) and a general sense of what the scores mean (Cicchetti and Cicchetti, 2013).

2.2. Chablis weather data

Monthly weather data for Chablis were taken from the French meteorological service, Météo-France. The Chablis weather station (number 89068001) lies on the outskirts of the town of Chablis at latitude 47°49'19" N, longitude 3°47'26" E and elevation 141 m. It does not record sunshine duration, however. For this variable, the records from two weather stations in Auxerre, both approximately 19 km west of Chablis, were merged: Auxerre (latitude 47°48'05" N, longitude 3°32'43" E, elevation 207 m, from October 1962 to April 2013) and Auxerre-Perrigny (latitude 47°49'28" N, longitude 3°32'58" E, elevation 152 m, from April 2013 to October 2020).

This weather dataset comprised monthly readings from October 1962 (the earliest date available for key temperature measurements) to October 2020. The data were also used to generate climatic indices that are typically used for viticulture, including indices for growing season temperature and precipitation for the phenological phases important for wine quality. These included mean Growing Season Temperature (GST) (Jones *et al.,* 2005), the Cool Night Index (*CNI*) which in the Northern Hemisphere is the mean minimum temperature for September (Tonietto and Carbonneau, 2004), and precipitation during veraison and/or ripening (Ashenfelter, 2010; Baciocco *et al.,* 2014; Davis *et al.,* 2019).

To enable comparison between the climates of Chablis and the Côte de Beaune, data from the Savigny-lès-Beaune weather station (number 21590001, latitude 47°03'13" N, longitude 4°50'07" E, elevation 246 m), approximately 113 km southeast of the Chablis weather station, for the period 1961 to 2020 were also collated.

2.3. Modelling approach

Multiple linear regression was employed to develop a model of the impact of inter-annual variation in weather on the quality of Chablis wine (the "Chablis vintage model"). A range of regression approaches (manually based on exploratory Principal Component Analysis (PCA), best subset and forward stepwise) was used to create the model that explained the most variance in the vintage score (adjusted R-squared), but which also satisfied criteria for homoscedasticity (Breusch–Pagan test), the randomness of residual plots, normality of distribution (Shapiro–Wilk test) and leverage (Cook's distance). A more complex model (i.e., one with more predictor variables) was accepted only if it passed the F-test, achieved a lower Bayesian Information Criterion BIC score, and led to a 2 or more unit improvement in Akaike Information Criterion (AIC) (Bevans, 2020).

Eight meteorological measurements were considered as candidate independent variables in the Chablis vintage model: mean temperature, mean maximum temperature, mean minimum temperature, mean daily temperature range, number of days equal to or exceeding 35 °C, total precipitation, number of precipitation days >1 mm, and sunshine duration. A total of 368 candidate model variables were calculated for all months singly, for periods ranging from two to nine months between February and October, and also the period November to March to cover the vines' dormancy period in the prior winter (Baciocco *et al.,* 2014).

Despite April to October being the standard period for measuring GST for Northern Hemisphere viticulture (Baciocco *et al.,* 2014; Moral *et al.,* 2016), periods that ran through to October were subsequently eliminated as candidate model variables. This was because climate change has advanced the start of harvest in Chablis since 1980 by approximately 20 days from early October to mid-September (Biss, 2020); and so including data for October would have incorporated considerable data after grapes have been harvested. This concurs with research for other wine regions of France. Neethling *et al.* (2012) used the April to September period to represent GST for the Loire Valley, a similar latitude to Chablis (47 °N), as did Ashenfelter (2010) for Bordeaux.

2.4. Model validation

Bootstrapping (10,000 resamples) was carried out with the R 'boot' package, using both case and residual resampling methods, to find 95 % confidence intervals (basic, percentile, and bias-corrected and accelerated (BCa)) for Chablis vintage model coefficients and adjusted R^2; BCa is a methodology that corrects for bias and skewness in the bootstrap distribution.

3. Predicting the quality of Chablis wine in 2041–2070

Climate projections for Chablis were taken from the French Ministère de la Transition Écologique's *Drias les futures du climat* service (Drias, 2021) for the grid square centred at latitude 47°48'27" N and longitude 3°46'42" E, approximately 1.8 km from the Chablis weather station. Data were extracted for the RCP (Representative Concentration Pathway) 2.6, 4.5 and 8.5 scenarios at the 5th, 50th (median) and 95th percentiles, using their multi-model approach, for changes in the following variables to the period 2041 to 2070: monthly mean temperature (°C), mean minimum temperature for September (°C) (*CNI*) and monthly total precipitation (mm). The reference period for these projections is 1976 to 2005, for which data was taken from the Chablis weather station. These figures were then used in conjunction with the Chablis vintage model to predict Chablis wine quality in 2041–2070. This text presents only the median percentile projections. A more complete table, including the 5th and 95th percentile projections, is available in the Supplementary Information (Table S2).

An alternative projection for *CNI* in 2041–2070 (*CNI2*) was calculated as mean *CNI* for the base period (1976 to 2005) plus 40 % of the projected change in GST. This is because the assumption that *CNI* will rise as much as the same as GST (Drias, 2021) is not supported by the recent past. Mean minimum temperature in September has so far risen far less than GST has for Chablis and nearby regions; 38 % in Chablis (1963 to 2000), 65 % in Cote de Beaune (1961 to 2020, Savigny-lès-Beaune weather station) and 39 % in the Loire Valley (1960 to 2010, using data from Neethling *et al.,* 2012).

4. Tools

R and R Studio (version 1.3.1093, www.r-project.org / www.rstudio.com) were used for statistical analysis. Boxplots and histograms showed that the vintage score and the key climate indices for Chablis were sufficiently normal in distribution for parametric statistical analysis.

RESULTS

1. Warming and vintages of Chablis typicity

The vintage score increased significantly by around 2 points to 7.1 between 1963 and 2018 in Chablis (Table 1).

Several weather variables (sunshine and most temperature indices) but not all (indeed, none of the precipitation indices) also showed significant trends (Table 1). Mean spring/summer temperature ($Tmean_{Apr\text{-}Sep}$) increased by almost 0.5 °C per decade between 1963 and 2020 and slightly more so than mean autumn/winter temperature cumulatively ($Tmean_{Apr\text{-}Sep}$ 2.68 °C *versus* $Tmean_{Oct\text{-}Mar}$ 2.16 °C). The mean maximum rose considerably more than the mean minimum temperature (2.33 °C *versus* 1.03 °C for September). Similarly, the number of days reaching or exceeding 35 °C between 1st April and 30 September each year has risen from close to zero to almost six days; much of this occurred between 2015 and 2020 with 12, 5, 6, 7, 10 and 8 days in successive years, indicating a non-linear trend. Mirroring the above, the number of days where minimum air temperature fell below 0 °C between April and September more than halved.

Sunshine duration also increased, but this linear relationship was not as strong as for most temperature indices. No significant regression was detected for continentality, the difference in mean temperature between the warmest and coldest months (Skelton, 2007).

The regression line fitted over the study period (solid black line, Figure 2) explained over half of the variance in mean spring/summer temperature (Table 1). During this period, years have differed considerably in vintage rating for Chablis wine, but no *Poor*-quality vintages have been recorded since 1991 (Figure 2). Comparing temperature-year regressions amongst the three vintage classifications showed significant differences ($P < 0.005$): *Excellent* vintage rating years provided the shallowest slope, crossing the all-years temperature trend line in 1998. Hence overall, the post-2000 period provided a greater proportion of years with *Good* Chablis vintages than the 1963–1980 period (Figure 2).

TABLE 1. Descriptive statistics and parameters of linear regressions for vintage score (1963 to 2018) and key weather indices (1963 to 2020) for Chablis.

	Mean	SD	Gradient	SE	Total Trendline Change	Adj. R^2	P
Vintage Score	7.12	1.60	**0.037**	**0.012**	**2.05**	**0.13**	**0.004**
			Temperature Indices				
$Tmean_{Apr\text{-}Sep}$	15.9 °C	1.03 °C	**0.047 °C yr^{-1}**	**0.005 °C**	**2.68 °C**	**0.59**	**<0.001**
$Tmean_{Oct\text{-}Mar}$	6.2 °C	1.07 °C	**0.038 °C yr^{-1}**	**0.007 °C**	**2.16 °C**	**0.35**	**<0.001**
$Tmax_{Apr\text{-}Sep}$	22.3 °C	1.43 °C	**0.061 °C yr^{-1}**	**0.008 °C**	**3.46 °C**	**0.50**	**<0.001**
$Tmin_{Apr\text{-}Sep}$	9.4 °C	0.79 °C	**0.033 °C yr^{-1}**	**0.004 °C**	**1.89 °C**	**0.49**	**<0.001**
$Tmax_{Sep}$	22.0 °C	2.06 °C	**0.041 °C yr^{-1}**	**0.015 °C**	**2.33 °C**	**0.10**	**0.010**
$Tmin_{Sep}$ *(CNI)*	9.4 °C	1.44 °C	0.018 °C yr^{-1}	0.011 °C	1.03 °C	0.03	0.110
TrangeSep	12.6 °C	1.98 °C	0.023 °C yr^{-1}	0.015 °C	1.3 °C	0.02	0.145
No. Hot Days Apr–Sep (>=35 °C)	2.5 d	3.43 d	**0.105 d yr^{-1}**	**0.023 d**	**5.97 d**	**0.25**	**<0.001**
No. Frost Days Apr–Sep	6.7 d	3.58 d	**–0.064 d yr^{-1}**	**0.027 d**	**–3.66 d**	**0.08**	**0.021**
Continentality	18.0 °C	2.36 °C	0.022 °C yr^{-1}	0.018 °C	1.23 °C	0.01	0.247
			Precipitation Indices				
$P_{Apr\text{-}Sep}$	360.7 mm	83.72 mm	0.099 mm yr^{-1}	0.662 mm	5.66 mm	0.00	0.881
$P_{Jun\text{-}Sep}$	234.0 mm	62.74 mm	–0.375 mm yr^{-1}	0.494 mm	–21.36 mm	0.00	0.451
$P_{Oct\text{-}Mar}$	364.4 mm	83.27 mm	0.412 mm yr^{-1}	0.657 mm	23.5 mm	0.00	0.533
P_{Aug}	60.7 mm	35.33 mm	–0.273 mm yr^{-1}	0.277 mm	–15.53 mm	0.00	0.330
P_{Sep}	58.9 mm	34.77 mm	–0.284 mm yr^{-1}	0.273 mm	–16.19 mm	0.00	0.302
No. Rain Days Jun–Sep	34.0 d	7.38 d	–0.037 d yr^{-1}	0.058 d	–2.11 d	0.00	0.528
No. Rain Days Aug	8.4 d	3.68 d	–0.037 d yr^{-1}	0.029 d	–2.13 d	0.01	0.197
No. Rain Days Sep	8.4 d	4.07 d	–0.018 d yr^{-1}	0.032 d	–1.05 d	0.00	0.567
Monthly daily max rain Apr–Sep	107.6 mm	25.49 mm	0.214 mm yr^{-1}	0.200 mm	12.18 mm	0.00	0.289
			Sunshine (Auxerre)				
Sunshine Apr–Sep	75,038.7 min	7853.0 min	**127.6 min yr^{-1}**	**59.8 min**	**7274.9 min**	**0.06**	**0.037**

Tmean = mean temperature (°C), *Tmin* = mean minimum temperature (°C), *Tmax* = mean maximum temperature (°C), *TrangeSep* = difference between the mean minimum and mean maximum temperatures for September (°C), Continentality = difference in mean temperature between the warmest and coldest months (°C) and P = total precipitation (mm), for stated multi-month periods (in subscript). Bold: significant trend ($P < 0.05$).

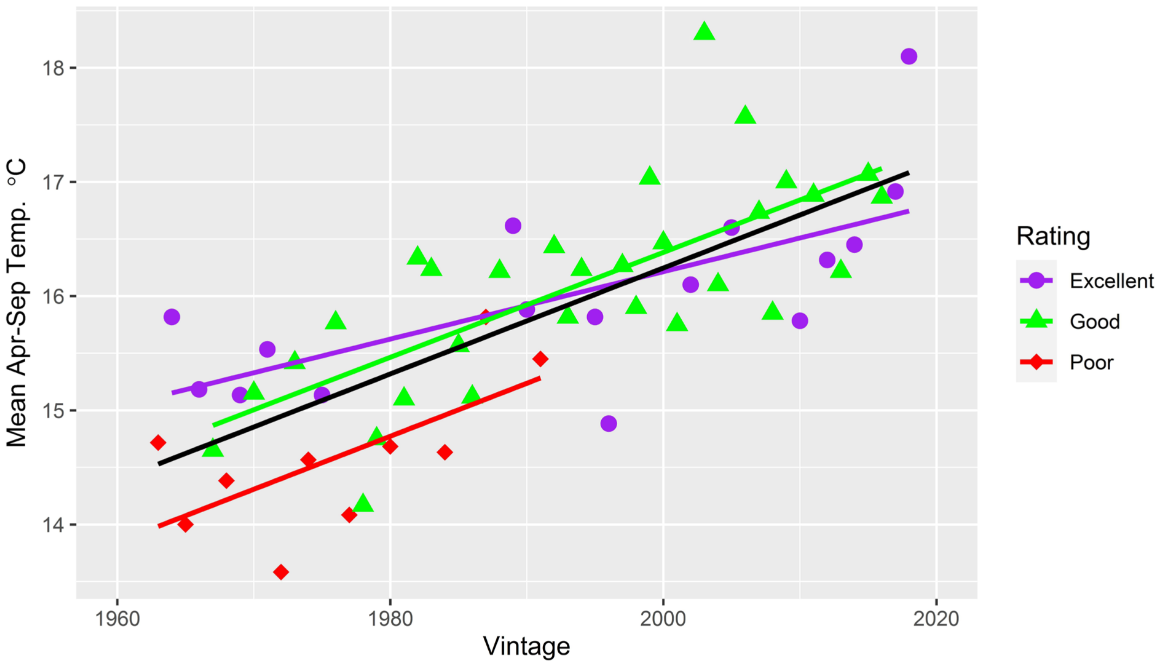

FIGURE 2. The trend of mean temperature from 1st April to 30 September (*Tmean*$_{Apr\text{-}Sep}$) in Chablis, France, from 1963 to 2018 (solid black line, Adjusted R-squared 0.56, $P < 0.001$).

Also shown are the years, and the respective regression of mean temperature against these years only, in which the Chablis wine vintage was rated as *Excellent* (purple line, Adjusted R-squared 0.44, $P = 0.003$), *Good* (green line, Adjusted R-squared 0.51, $P < 0.001$), or *Poor* (red line, Adjusted R-squared 0.37, $P = 0.04$).

2. Vintage quality in response to weather

2.1. Temperature, precipitation and period

Of the eight Chablis weather variables evaluated for this study, mean temperature accounted for the most variance amongst vintage scores. A linear regression with a second-order polynomial for the period May to July (*Tmean*$_{May\text{-}Jul}$) explained 43 % of the variance in the vintage score (Table 2). This was the highest adjusted R-squared achieved for any single-factor model and was superior to the April to September (adjusted R-squared 0.364, $P < 0.001$) and April to October (adjusted R-squared 0.321, $P < 0.001$) periods for mean temperature.

Precipitation and sunshine duration played lesser roles in the models of the vintage score; August to September was the most important period. Total August and September precipitation in a single-factor model explained around 12 to 16 % of variance (linear or plus a second-order polynomial, $P = 0.006$, 0.004, respectively), whereas sunshine duration for these months in a single-factor model explained around 12 to 20 % of the variance (linear or plus a second-order polynomial, $P = 0.004$, 0.001, respectively). Despite the above, the August to September period of sunshine duration and precipitation (nor each month alone) did not retain significance in multiple regression models including temperature as a factor.

The importance of the May to July period was clarified by comparing vintage ratings against both temperature and rainfall for different periods within spring and summer (Figure 3). In these co-plots for temperature and rainfall in March (Figure 3a) or April (Figure 3b), there is no discrimination for the vintage rating with the *Poor*, *Good* and *Excellent* vintage ratings randomly distributed. However, as the periods examined progressed from April to May (Figure 3c) through April to June (Figure 3d), April to July (Figure 3e), until May to July (Figure 3f) the *Poor* vintage ratings separated towards the bottom of the chart. The majority of *Poor* vintages occurred when the mean temperature for May to July was below 15.5 °C (Figure 3f); the only two vintages rated higher below 15.5 °C were when total precipitation for the May to July period was less than 150 mm. These co-plots, however, showed little separation between the *Good* and *Excellent* vintage ratings.

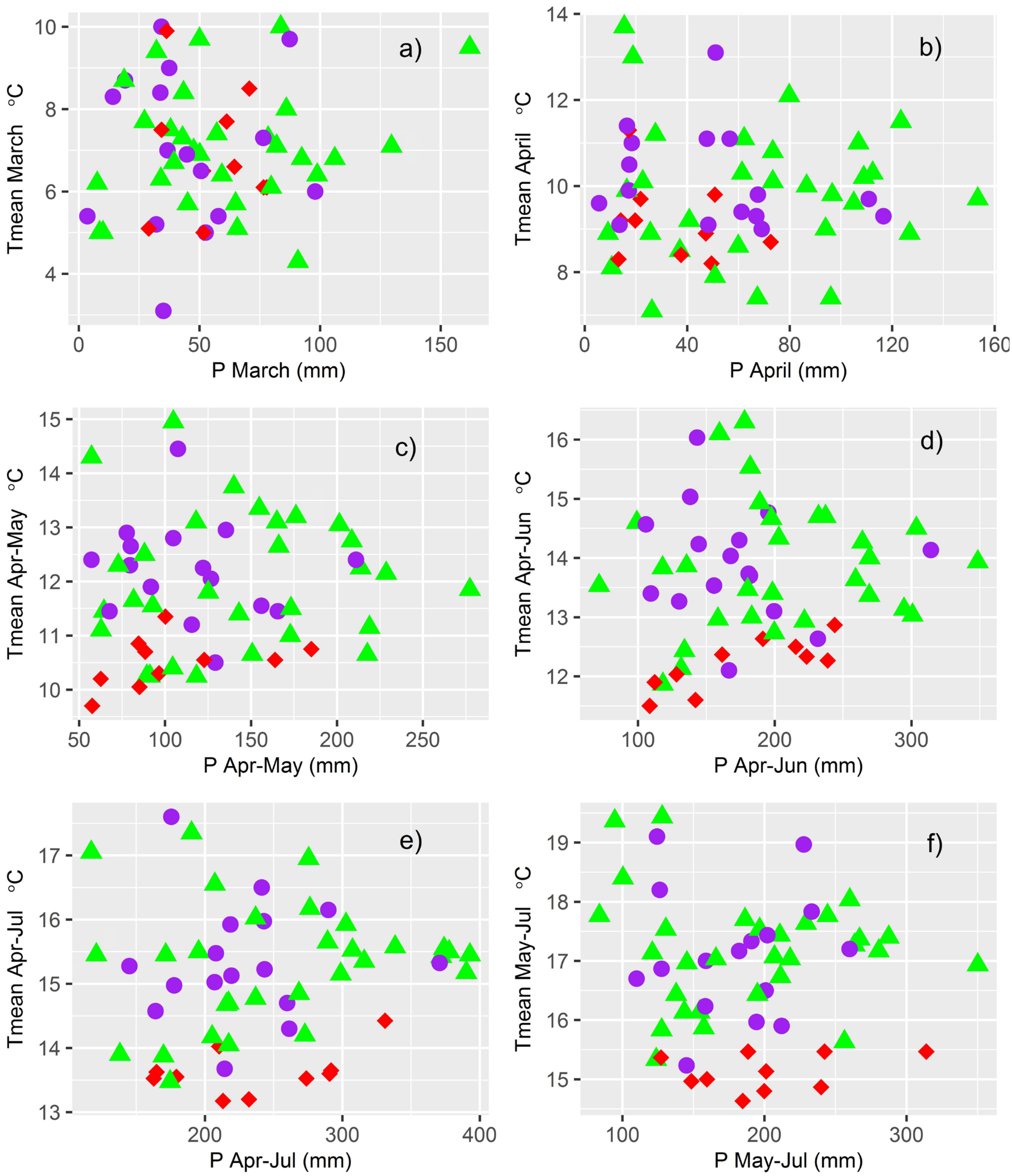

FIGURE 3. Mean temperature versus total precipitation for March (a), April (b), April–May (c), April–June (d), April–July (e) and May–July (f), and Chablis vintage rating.

The final rating classification for each vintage is marked as follows: Purple circle = *Excellent* vintage (>8 score), green triangle = *Good* vintage (6–8 score) and red diamond = *Poor* vintage (<6 score).

TABLE 2. Parameters of the multiple linear regression Chablis vintage model selected that combines linear and quadratic temperature terms (mean temperature from 1st April to 30 September ($Tmean_{Apr\text{-}Sep}$, °C), the Cool Night Index (*CNI*; mean minimum temperature for September, °C), and total precipitation from 1st June to 30 September ($P_{Jun\text{-}Sep}$, mm) to quantify the variation amongst 56 Chablis vintage scores from 1963 to 2018. For comparison, the best single-factor model to quantify variation in the same vintage scores is also provided (linear and quadratic temperature terms for mean temperature from 1st May to 31 July, $Tmean_{May\text{-}Jul}$). The factor values provide the range of weather variables across which the model was fitted. The normality and homoscedasticity tests are the Shapiro–Wilk and Breusch–Pagan tests, respectively.

	Mean of Factor Value	Range in Factor Value	Coefficient	Standard Error	Model / Factor *P*	Model / Cumulative Adj. R^2	Normality Test (*P*)	Homoscedasticity Test (*P*)
Chablis vintage model					< 0.001	0.571	0.322	0.148
Intercept			–170.90	27.05	< 0.001			
$Tmean_{Apr\text{-}Sep}$	15.81 °C	13.58–18.30 °C	22.380	3.442	< 0.001	0.172		
$Tmean_{Apr\text{-}Sep}^2$	15.81 °C	13.58–18.30 °C	–0.6790	0.1080	< 0.001	0.364		
CNI	9.42 °C	5.80–12.80 °C	–0.4089	0.1109	< 0.001	0.510		
$P_{Jun\text{-}Sep}$	236.6 mm	119.1–354.2 mm	–0.006918	0.002392	< 0.01	0.571		
Single-factor model					< 0.001	0.425	0.118	0.219
Intercept			–129.13239	27.09245	< 0.001			
$Tmean_{May\text{-}Jul}$	16.77 °C	14.63–19.43 °C	15.61145	3.21993	< 0.001	0.204		
$Tmean_{May\text{-}Jul}^2$	16.77 °C	14.63–19.43 °C	–0.44424	0.09537	< 0.001	0.425		

2.2. The Chablis vintage model

The best model identified and selected for the Chablis vintage model was:

$$\textit{(Equation 1) Vintage Score} =$$

$$22.38\ Tmean_{Apr\text{-}Sep} - 0.6790\ Tmean_{Apr\text{-}Sep}^{\ 2} - 0.4089\ CNI - 0.006918\ P_{Jun\text{-}Sep} - 170.9$$

where $Tmean_{Apr\text{-}Sep}$ is mean temperature (°C) from 1st April to 30 September, *CNI* is the Cool Night Index (°C) and $P_{Jun\text{-}Sep}$ is the total precipitation (mm) from 1 June to 30 September. The model and each term were significant and explained 57 % of the variance (Table 2) with a good fit to observations from *Poor* to *Excellent* scores (Figure 4).

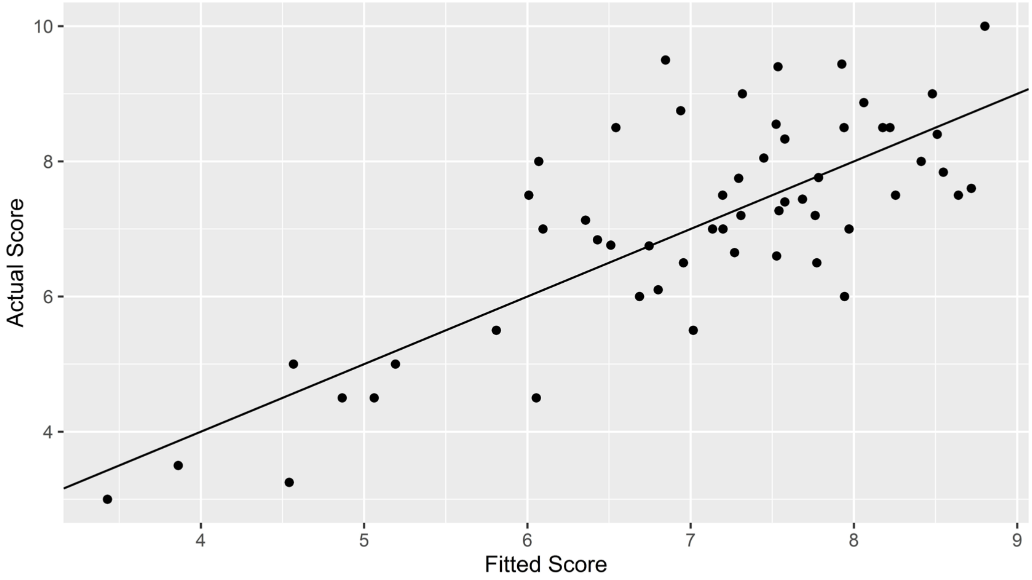

FIGURE 4. Comparison of actual Chablis vintage scores from 1963 to 2018 (●) with fitted values from the multiple regression model (Table 2). The line shown indicates perfect agreement.

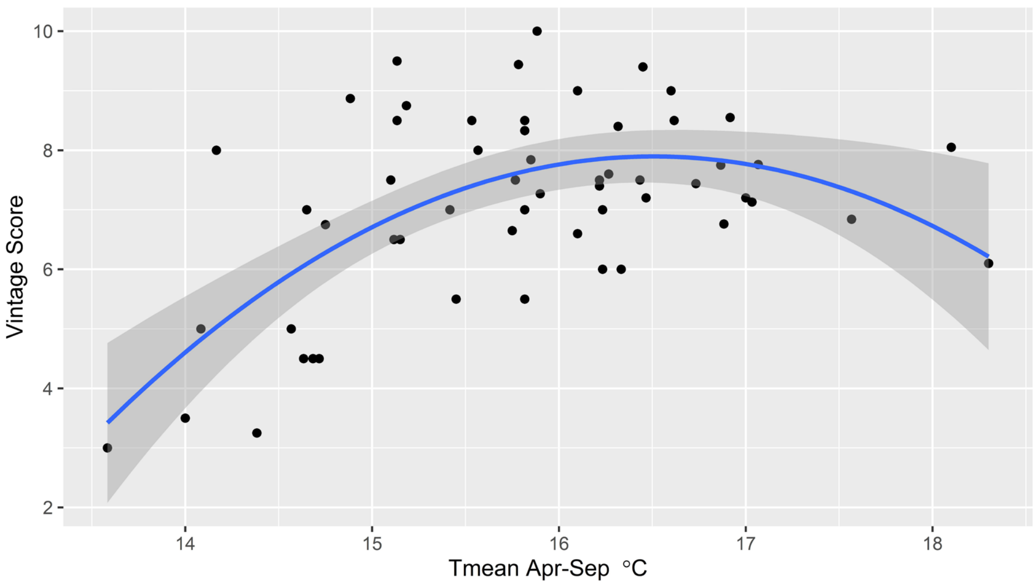

FIGURE 5. Vintage score vs. $Tmean_{Apr\text{-}Sep}$ for Chablis vintages from 1963 to 2018 (●). The grey band around the fitted regression line (in blue, Equation 1) represents the standard error.

The relationship between vintage score and mean temperature ($Tmean_{Apr\text{-}Sep}$) was curvilinear, described well by linear and quadratic terms, with an optimum for Chablis vintage score at c. 16.5 °C for Equation 1 (Figure 5).

Whereas $Tmean_{May\text{-}Jul}$ was the best period for temperature if the fitted model comprised a single weather factor alone, in the multiple regression model with other factors (*CNI* and $P_{Jun\text{-}Sep}$) included, $Tmean_{Apr\text{-}Sep}$ was superior (adjusted R-squared increased from 0.509 to 0.571).

Replacing *CNI* with mean minimum temperature for August and September ($Tmin_{Aug\text{-}Sep}$) increased the adjusted R-squared marginally (from 0.571 to 0.584), but *CNI* was retained as it is a recognised climate index for viticulture.

Replacing June to September precipitation $P_{Jun\text{-}Sep}$) with the August to September period ($P_{Aug\text{-}Sep}$) reduced model fit slightly (from 0.571 to 0.533) with the latter period not providing a significant term in the model ($P > 0.05$).

Replacing the regression equation with an early harvest version to the end of August ($Tmean_{Apr\text{-}Aug}$, $Tmin_{Aug}$ and $P_{Jun\text{-}Aug}$) and an advanced phenology version that brings all the factor periods forward by one month ($Tmean_{Mar\text{-}Aug}$, $Tmin_{Aug}$ and $P_{May\text{-}Aug}$) reduced adjusted R-squared, from 0.571 to 0.415 and 0.346, respectively.

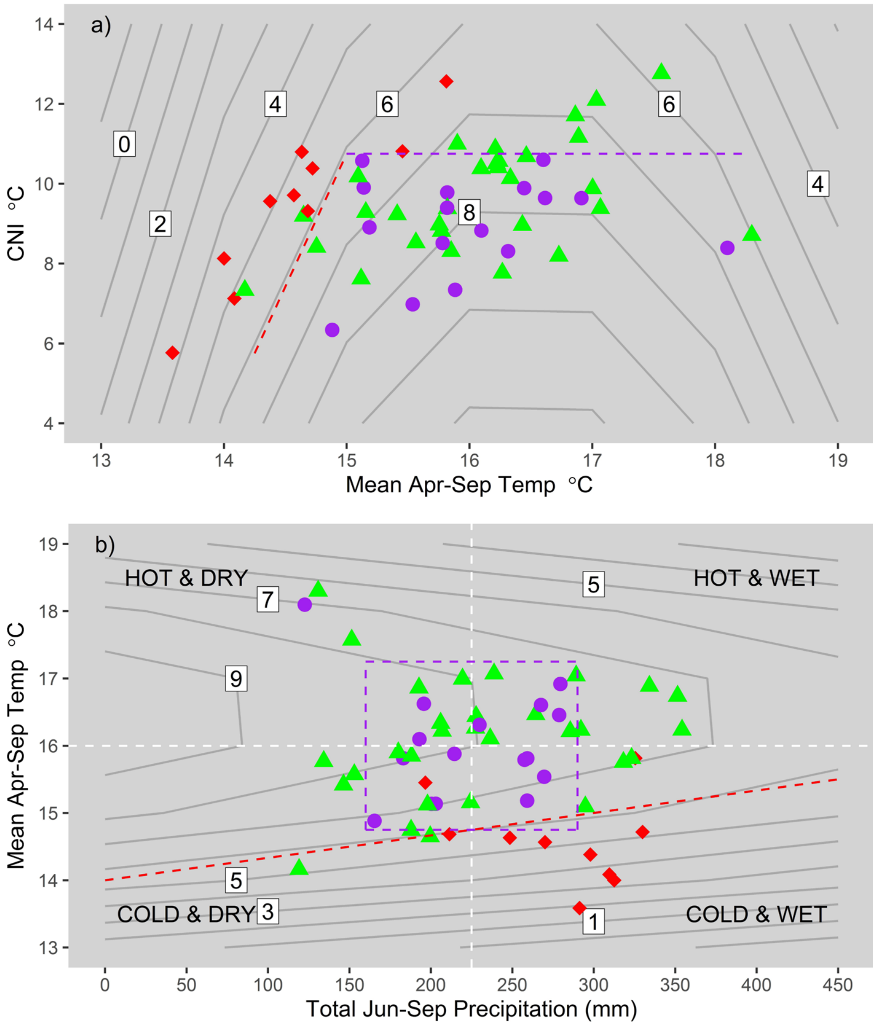

FIGURE 6. Chablis vintage ratings from 1963 to 2018.

Purple circle = *Excellent* vintage (>8 score), green triangle = *Good* vintage (6–8 score) and red diamond = *Poor* vintage (< 6 score), compared with the scores from the Chablis vintage model fitted (contour lines) in relation to weather indices: a, *CNI vs*. $Tmean_{Apr\text{-}Sep}$ where $P_{Jun\text{-}Sep}$ held constant at the long-term mean (236.6 mm); b, $Tmean_{Apr\text{-}Sep}$ *vs*. $P_{Jun\text{-}Sep}$ where *CNI* held constant at the long-term mean (9.4 °C). The broken coloured lines are described in the text.

Model performance deteriorated further for these early harvest and advanced phenology versions when applied to only the most recent 25, 20, 15 or 10 vintages with a maximum 0.290 R-squared, maximum 0.037 adjusted R-squared and $P > 0.10$.

Comparison of contour plots from the Chablis vintage model with the actual vintage ratings from 1963 to 2018 (Figure 6) identified the following boundaries of weather indices in relation to the observed vintage ratings. In Figure 6a, the red dashed line at an angle at 14–15 °C denotes the boundary between *Poor* (on left) and *Good* or *Excellent* vintages (on right), whilst the horizontal purple dashed line (at 10.75 °C) denotes the upper *CNI* limit to *Excellent* vintages. In Figure 6b, the purple square contains all *Excellent* vintages bar one (2018), whilst the red broken line denotes the threshold of acceptability below which the cool wet weather almost always provided *Poor* vintages.

2.3. Model validation

Confidence intervals for Chablis vintage model parameter coefficients, across all bootstrapping methodologies employed here, were similar in magnitude, direction and range to those calculated parametrically from the model (Table 3). Furthermore, using the BCa confidence interval,

TABLE 3. Bootstrap confidence intervals (95 %) for Chablis vintage model parameter coefficients and adjusted R-squared.

	Parameter Coefficient (2.5 %; 97.5 %)					Adj. R^2
	Intercept	$Tmean_{Apr\text{-}Sep}$	$Tmean_{Apr\text{-}Sep}^{2}$	CNI	$P_{Jun\text{-}Sep}$	(2.5 %; 97.5 %)
Chablis Vintage Model	–225.1; –116.6	15.47; 29.29	–0.896; –0.462	–0.632; –0.186	–0.0117; –0.0021	N/A
Bootstrap (residuals / percentile)	–219.9; –118.8	15.71; 28.54	–0.873; –0.470	–0.621; –0.204	–0.0115; –0.0024	N/A
Bootstrap (case / basic)	–229.2; –130.0	17.19; 29.74	–0.912; –0.518	–0.605; –0.211	–0.0120; –0.0028	0.384; 0.793
Bootstrap (case / percentile)	–211.7; –112.5	15.02; 27.57	–0.840; –0.446	–0.607; –0.213	–0.0110; –0.0018	0.348; 0.758
Bootstrap (case / BCa)	–213.3; –116.0	15.50; 27.81	–0.849; –0.462	–0.596; –0.200	–0.0116; –0.0025	0.300; 0.734

Each bootstrap comprised 10,000 resamples. Bootstrap (case /) = resampling rows of observation data. Bootstrap (residuals /) = resampling regression residuals. Bootstrap (/ basic), (/ percentile) and (/ BCa) are the basic, percentile, and bias-corrected and accelerated bootstrap confidence intervals respectively.

TABLE 4. Predicted Chablis wine vintage scores (with 95 % prediction intervals) from Equation 1, with environmental data shown, for the period 2041 to 2070 for climate projections using the RCP 2.5, 4.5 and 8.5 median scenarios (Drias, 2021) for the closest grid square to Chablis (47°48'27» N, 3°46'42» E).

	Weather Data				Chablis Vintage Model	
Year and Scenario	$Tmean_{Apr\text{-}Sep}$ (°C)	*CNI* (°C)	*CNI2* (°C)	$P_{Jun\text{-}Sep}$ (mm)	Calculated Score	Calculated Score *CNI2*
1976–2005	15.8	9.4	n/a	233.6	7.7 (5.7–9.9)	n/a
2009–2018	16.8	9.8	n/a	236.0	7.8 (5.8–10.0)	n/a
Median Projections for 2041–2070						
RCP 2.6	17.0	10.8	9.91	222.6	7.4 (5.3–9.6)	7.7 (5.7–10.0)
RCP 4.5	17.7	11.5	10.20	220.1	6.3 (4.1–8.6)	6.8 (4.6–9.1)
RCP 8.5	18.2	12.0	10.41	210.7	5.1 (2.7–7.6)	5.7 (3.4–8.2)

Two values are shown for the Cool Night Index, where *CNI2* is an alternative to *CNI* in which the increase in value from 1976–2005 to 2041–2070 was reduced to only 40 % of the projected $Tmean_{Apr\text{-}Sep}$ rise. For reference, information for the periods 1976–2005 and 2009–2018 is also presented (actual mean vintage scores were 7.1 and 8.1, respectively). A more detailed version of this table with predicted scores for the 5th, 50th and 95th percentile probabilities for each RCP scenario is provided in the Supplementary Information (Table S2).

Chablis vintage model adjusted R-squared did not fall below 0.300 in 97.5 % of bootstrap resamples (Table 3).

3. Medium-term projections for Chablis wine quality

In the intermediate RCP 4.5 emissions scenario for the period 2041–70, the Chablis vintage model (Equation 1) implies that a *Good* score would only just be achieved, markedly lower than either the 2009–2018 period or the 1976–2005 base period (Table 4). The RCP 2.6 emissions scenario provided Chablis vintage scores that are similar to the 2009–2018 period and 1976–2005 base period.

DISCUSSION

1. Chablis wine has generally benefitted from climate change to date

Chablis wine quality has improved during the study period, with no *Poor* vintages (score < 6) since 1991 (Figure 2), whilst summer temperature and sunshine duration have progressively increased with fewer frost days but no linear trend for precipitation (Table 1). This has gone hand-in-hand with a 73 % increase in vineyard area and, based on the 5-year moving average, an 86 % increase in wine production (BIVB, data by personal communication). The Chablis vintage score model (Equation 1) shows a clear historic link between recent climate change in the region, particularly warmer growing season temperature (GST; Figure 2), and better vintage scores (Figure 4). In addition to this benefit from climate change, Chablis vintage score is also likely to have risen through better vitivinicultural practices such as superior hygiene and frost protection since the 1960s (George, 2007). The effect of temperature on the vintage score quantified here (Table 2) will, in part, also have captured the improvement over time in vitivinicultural practices because of the warming over this period (Figure 2).

Providing GST is below the maximum of a cultivar's range (see below), warmer GST results in greater photosynthetic production of carbohydrates improving flowering and fruitset (Atkinson, 2011) with more reliable ripening (Jones *et al.,* 2005). In addition, phenology is advanced so that veraison and ripening occur earlier in the year when temperatures are warmer (van Leeuwen and Darriet, 2016; Leolini *et al.,* 2018). Earlier budburst does imply closer coincidence with more frost-prone months and so has the potential to reduce yield (Leolini *et al.,* 2018), as occurred throughout Europe, and specifically France, in Spring 2021.

The quadratic relationship detected between Chablis vintage score and $Tmean_{Apr\text{-}Sep}$ (Figure 5), a pattern observed for wines in other regions (Jones *et al.,* 2005), indicates that Chablis quality may not necessarily continue to improve with further warming. The peak was at 16.5 °C (Figure 5). The 2009–2018 mean value for $Tmean_{Apr\text{-}Sep}$ (16.8 °C, Table 4) is at the warm end of the optimum plateau for the vintage score evident in Figure 5, and so further warming may reduce quality. This comment is reinforced by the different regressions of temperature with the year for each rating category where the combined and *Good* quality relations are almost identical whereas that for *Excellent* quality is shallower in slope (Figure 2); extrapolation of that relationship into the future, though unwise, would suggest a lower probability of achieving an *Excellent* vintage of Chablis typicity.

2. GST is the most important factor for vintage quality

The use of monthly weather data precluded the generation of certain temperature-based indices which accumulate above daily temperature thresholds (typically 10 °C in grape) such as Growing Degree Days (GDD), Biologically Effective Degree Days (BEDD), Huglin's Heliothermal Index (HI), or the Winkler Index (WI, based on GDD). This is, however, not considered an issue; mean Growing Season Temperature (GST) as used here and advocated by Jones *et al.* (2005) and widely used is highly correlated with the other indices for measuring growing season warmth (Moral *et al.,* 2016) and is functionally no different to GDD (Anderson *et al.,* 2012).

In our multi-factor model, temperature ($Tmean_{Apr\text{-}Sep}$) was the best weather factor explaining inter-annual variation in Chablis vintage score. This is consistent with studies on Chardonnay in Burgundy (Outreville, 2018; Davis *et al.,* 2019), in other French regions such as Bordeaux (Baciocco *et al.,* 2014; Ashenfelter, 2017), Rhone (Ashenfelter, 2017) and the Loire Valley (Neethling *et al.,* 2012) with different cultivars, and regions outside of France such as Barolo in Italy and Barossa in Australia (Ashenfelter, 2017).

It is well established that sugar concentration in grape berries is positively correlated with GST (van Leeuwen and Darriet, 2016); as is the case for Chardonnay (Gambetta *et al.,* 2016).

Sugar concentration determines the potential alcohol content of the wine and whilst it is a prerequisite for high quality, excess heat can ultimately lead to over-alcoholic wines which, if accompanied by low concentration of organic acids, are "unbalanced" (Jones *et al.,* 2005; Neethling *et al.,* 2012; van Leeuwen and Destrac-Irvine, 2017). The reasons for greater sugar content at warmer temperatures may involve water loss from berries due to evaporation and greater concentration of the sugar (Pastore *et al.,* 2017) and/or physiological changes that may be genetically controlled and therefore cultivar specific (Suter *et al.,* 2021). Moreover, the composition of secondary metabolites that are responsible for the organoleptic properties of wine, and so affect quality, is changed in grapes ripened at high temperature (van Leeuwen and Destrac-Irvine, 2017).

3. Low peri-flowering period temperature is an early predictor of a *Poor* vintage

Mean temperature between May and July is particularly important for the subsequent quality of Chablis wine (Figure 3, Table 2). Flowering and fruitset typically occur in the first half of June for Burgundy as a whole (Davis *et al.,* 2019), though in Bordeaux, for example, can vary by around one month (Jones and Davis, 2000).

The polynomial relation for May to July mean temperature provided the best single-factor model for the vintage score (Table 2). A threshold of 15.5 °C for this period may provide a simple, easily-applied rule of thumb in advance of harvest to predict vintage quality; below this value vintage quality is likely to be *Poor* (83 % probability, Figure 3f). Warmth in this period is important for wine quality in other regions also (Real *et al.,* 2017). If it is too cool the flowering period is prolonged and can lead to uneven berry ripeness and wines with vegetal characteristics (Atkinson, 2011), or variable berry size within a bunch ("Millerandage") and/or berries that are incompletely fertilized ("Shot" berries) which hinder the production of a balanced wine (Gray and Coombe, 2009). Conversely, too high a temperature during flowering can cause premature veraison, inactivation of enzymes and incomplete biosynthesis of compounds associated with flavour (Jones *et al.,* 2005).

4. *CNI* is the second most important factor in the Chablis vintage model

The Cool Night Index (*CNI*) was the second most important weather variable, after GST ($Tmean_{Apr\text{-}Sep}$), in the Chablis vintage model (Table 2). This term in the model accounts for the effect of cool temperature during the ripening period in the 30 days until harvest (Tonietto and Carbonneau, 2004). Whilst warmth in the day is crucial for berry ripening, cool temperatures during the night result in the secondary metabolites associated with high-quality flavours and aromas (Tonietto and Carbonneau, 2004). Moreover, recent research by Aoki *et al.* (2021), albeit on an indigenous Japanese grapevine variety (*V. vinifera* cv. Koshu), suggests high night temperatures may promote downy mildew. This may also be relevant because Chardonnay vines are susceptible to downy mildew infection which can taint the wine (Skelton, 2020).

High night temperatures also increase respiration and the degradation of malic acid (Arrizabalaga-Arriazu *et al.,* 2020); and so cool nights preserve acidity in the berries. Acidity is an important aspect of Chablis typicity. Malic acid (usually converted to the smoother-tasting lactic acid by winemakers via malolactic fermentation) typically provides half of the total acidity of grapes and wine with tartaric acid (the other major acid) less prone to degradation during ripening (Jackson, 2014). Wines that lack malic acid (or lactic acid after conversion) may taste flat and are prone to microbial spoilage, although in excess wines can taste sour (Jackson, 2014).

It has been suggested that it is the difference in daily temperature range during ripening, rather than minimum temperature, produces important flavour and aroma compounds (Gladstones, 1992 cited by Jones *et al.,* 2005). However, in developing the model we found that *CNI* (i.e., mean minimum temperature in September) explained more variance in the vintage score and also the effect of the range between mean minimum and mean maximum temperatures for September was not significant ($P > 0.10$). Chablis vintage quality is more closely associated with acidity than secondary metabolites, and so the effect on night respiration rates may explain why mean minimum temperature, not the range, in September is an important factor for Chablis.

5. Precipitation from flowering to harvest is negatively related to vintage quality

Every 100 mm increase in $P_{Jun\text{-}Sep}$ reduced the vintage score by almost 0.7 in the model (Table 2). Moderate water stress is also associated with higher quality wine (van Leeuwen *et al.,* 2009; Fraga *et al.,* 2013; Alem *et al.,* 2019). Water stress increases the biosynthesis of secondary metabolites important to the development of aroma in wine, such as the carotenoid-derived C_{13}-norisoprenoids which are associated with floral and fruity odours (Alem *et al.,* 2019). Too much rain between flowering and ripening is also well known to reduce wine quality (Jones and Davis, 2000). This is because berries swell producing lower quality wine (Jones and Davis, 2000; Baciocco *et al.,* 2014) due to a reduction in the concentration of flavour- and aroma-related metabolites (VanderWeide *et al.,* 2021). In cooler climates, high rainfall may lead to sour rot infection, which increases the concentration of acetic acid in berries imparting an unwanted vinegar flavour to the wine (VanderWeide *et al.,* 2021). In this study, *Poor* vintages of Chablis with high $P_{Jun\text{-}Sep}$ (approximately > 275 mm) were associated with cool $Tmean_{Apr\text{-}Sep}$, suggesting sour rot may have been an issue in these vintages.

We also compared a model with August to September precipitation ($P_{Aug\text{-}Sep}$) rather than June to September ($P_{Jun\text{-}Sep}$). The shorter period was assessed because research for other wine regions emphasised the importance of rainfall in the few weeks leading to harvest (Ashenfelter and Byron, 1995; Davis *et al.,* 2019). In our assessment, however, the use of ($P_{Aug\text{-}Sep}$) resulted in a non-significant (P = 0.0642) rainfall term. This comparison suggests that the Chablis vintage score is reduced more consistently by greater rainfall over a longer period than just the last weeks before harvest.

6. *CNI* is a key differentiator between the Chablis vintage model and others for French wines

Several models of the influence of inter-annual variation in weather on wine quality in France have been devised since Ashenfelter, Ashmore and Lalonde (1993, cited by Ashenfelter and Byron, 1995) showed that much of the variability in the price of a Bordeaux vintage could be explained by its age, GST (growing season temperature, April to September), and rainfall both in August and September and also in the prior autumn and winter. Models which represent both the positive effect of temperature during the growing season and the negative effect of rainfall typically account for 35 to 60 % of the variance in the vintage score (Outreville, 2018) or can accurately categorise the top and bottom vintage scores (Baciocco *et al.,* 2014; Davis *et al.,* 2019). The Chablis vintage score model presented here (Table 2) is consistent with the above.

Focusing on Burgundy, Outreville (2018) found that temperature in July and August provided the best (positive) association and rainfall in August and September the best (negative) association with white wine quality. Davis *et al.* (2019) found that the impact of rainfall on white Burgundy wine quality varied with phenology, but the Chablis vintage model developed here, with monthly data, detected only the negative relation for June to September rainfall reported in Table 2.

TABLE 5. Comparison of the means of three climate indices, relevant to the Chablis vintage model, for Chablis and Savigny-lès-Beaune weather stations from 1963 to 2018 and 2009 to 2018.

Climate Indices	Chablis	Savigny-lès-Beaune
	1963–2018	
GST ($Tmean_{Apr\text{-}Sep}$) (°C)	15.8	16.75
CNI (°C)	9.40	11.24
$P_{Jun\text{-}Sep}$ (mm)	236.6	244.6
	2009–2018	
GST ($Tmean_{Apr\text{-}Sep}$) (°C)	16.8	17.6
CNI (°C)	9.8	11.8
$P_{Jun\text{-}Sep}$ (mm)	236.0	268.8

The main difference between our Chablis vintage model and one for white Burgundy (Davis *et al.,* 2019) is the inclusion of *CNI*, which we found to be a more important factor than rainfall.

This difference may be because acidity is more important for Chablis than other white wines from Burgundy (George, 2007). This would tally with the observation that while GST is around 1 °C lower in Chablis compared to Savigny-lès-Beaune, *CNI* is proportionally far cooler during the ripening period (Table 5) – important to the acid content of the berries. Moreover, minerality, another characteristic of Chablis wine, may be positively correlated with acidity (Ballester *et al.,* 2013). Hence, *CNI* could be a key variable in the difference in typicities between Chablis and the white wines of the Côte de Beaune, and elsewhere.

7. Model factor periods are affected by advancing phenology

The mean minimum temperature in September (*CNI*) was an inappropriate factor for the 2003 vintage because the harvest started on 25 August (George, 2007). This was also partly the case for the 2007, 2011, 2015, 2017 and 2018 vintages for which harvest began in early September (Biss, 2020). In both cases, since harvest typically takes around two weeks to complete, August or mid-August to mid-September might be a more relevant period to consider for the *CNI* in future developments of the model, as suggested by the slight improvement in model performance achieved by using August and September instead of just September. Omazić *et al.* (2020) found the same problem with *CNI* for wine regions in Croatia due to earlier harvests.

A similar issue arises for GST and precipitation from flowering to harvest, with climate change advancing the beginning and endpoints for these indices. However, no model improvement was observed by advancing these weather factor periods by one month for the most recent 25, 20, 15 or 10 vintages. Indeed, the advancement to phenology versions of the model performed poorly, but this may have been because there were no *Poor*-quality wines in these recent periods (Figure 2) and so a narrower range of vintage scores available for analysis. A larger model incorporating the effects of weather on the timing of crop development, soil water balance (such as the Dryness Index (Tonietto and Carbonneau, 2004)), or one with greater temporal resolution and more precise data for wine quality, might be an improvement. All models are simplifications of the real world, however, and our current model has the virtues of simplicity and ease of application.

8. Model limitations

We have developed, and validated, a simple model here to describe the historic effect of inter-annual variation in weather on Chablis vintage score quality. Bonada and Sadras (2015) point out that such approaches are "bound to be inconclusive" because numerous factors are either confounded or analysed insufficiently. Such factors include wind, previous years' weather and vine development, water deficit, vapour pressure deficit, viticultural and oenological practices, and extreme weather events. Neither has the increase in atmospheric CO_2 concentration since 1963 been accounted for. This may affect wine quality with, for example, faster berry development leading to reduced malic and tartaric acid concentrations (Leibar *et al.,* 2017; Arrizabalaga-Arriazu *et al.,* 2020).

There is also the subjective basis of vintage scores (Hodgson, 2008; Cicchetti and Cicchetti, 2013; Jackson, 2014). Other issues include variation in phenology from year to year and the limitation of weather data from only one station given that inter- and intra-vineyard variation in temperature and bioclimatic indices can be as great as at larger scales (Bonnefoy *et al.,* 2013). The above may help to explain why the Chablis vintage model accounted for only 57 % of the variance in the vintage score. We also acknowledge that the model was far better in distinguishing between the *Poor* and the two better vintages than between the *Good* and the *Excellent* (Figures 4 and 6). Nonetheless, the model provides a first approximation of the weather typically associated with high-quality Chablis wine production, compares well with similar models for other regions and/or cultivars, and, we argue, has utility in the comparative ease of application to different scenarios.

9. Climate change and Chablis typicity

Poor Chablis vintages appear to have been avoided in recent years due to warming (Figure 2). Looking ahead, the median probability of the intermediate RCP 4.5 scenario in combination with the Chablis vintage model suggests that Chablis producers will struggle to maintain the high quality of their wine by 2041 to 2070 (predicted score 6.3, Table 4). However, if minimum temperatures in September (*CNI*) continue to rise more slowly than maximum temperatures the decline may be reduced (*CNI2* predicted score 6.8, Table 4).

On the other hand, warming is likely to hasten ripening (van Leeuwen and Destrac-Irvine, 2017) further into August which would further increase the effective *CNI*. Representative Concentration Pathway 2.6 is the only scenario that has a chance (> 66 %) of meeting the Paris Agreement (OECD, 2017); we predict that achieving that target would provide Chablis vintage score only marginally below that of recent years (7.4–7.7 *versus* 7.8 for 2009–2018).

Vintage scores assess whether wines are of typicity. A *Good* rating, for example, indicates the wine is not an *Excellent* example of a Chablis but it may well be very pleasurable to drink (Martin, 2020). Similarly, vintages with the same score may not be identical in all regards. The 2003 and 2018 vintages were noteworthy for being unusually hot ($Tmean_{Apr-Sep}$ > 18 °C) and dry ($P_{Jun-Sep}$ < 135 mm). Their ratings were "*Good*" (score 6.1) and "*Excellent*" (score 8.1), respectively, but they were not like typical Chablis wines lacking acidity (Robinson, 2019) and minerality (Martin, 2020). This consideration is relevant to future vintages. Tables 4 and 5 show that the Chablis region's climate in 2041 to 2070, especially with the RCP 4.5 emissions scenario, may approach that of today's Côte de Beaune, a region world-renowned for its premium quality Chardonnay wines such as Corton-Charlemagne, Chassagne-Montrachet, Meursault and Puligny-Montrachet. Hence, although climate change may reduce Chablis vintage score in future (Table 4), Chardonnay grapes grown in the Chablis region are likely to continue to produce premium quality wines.

These predictions must be approached with caution. In addition to errors in the Chablis vintage model, there are uncertainties associated with emissions scenarios and climate modelling (Jacob *et al.,* 2014; OECD, 2017), including the possibility of decadal-scale cold waves (Sgubin *et al.,* 2019). It is also the case that short-term extreme weather events, such as hail and intense rain – the frequency and strength of which will increase with climate change (van Leeuwen and Darriet, 2016) – are not accounted for in the above.

Moreover, it is expected that wine producers will adapt to and/or mitigate the effects of climate change through crop management (van Leeuwen *et al.,* 2019; Santos *et al.,* 2020). The Chablis vintage model presented here may support producers in that task. A further aim is for the model to be applied to identify sites with suitable climates for premium white wine from Chardonnay grapevines in emerging cool climate viticulture regions, such as the UK, an approach to site selection advocated by Ashenfelter (2017).

CONCLUSIONS

This study has shown that both the weather in the region and Chablis vintage wine scores have changed over the period 1963 to 2018. The key findings are:

- Summer temperature has warmed progressively over this period whilst the proportions of *Poor* and *Good* vintage years have diminished and increased, respectively.
- There is a curvilinear relationship between Chablis wine quality and mean temperature during the growing season (April to September). This is the most significant factor in the Chablis vintage score model.
- *CNI* (mean minimum temperature during the period of ripening, with September used in this study) is the second most important factor in distinguishing between vintage scores.
- High rainfall from flowering (June) to harvest (September) reduces Chablis wine quality.
- Cool mean temperatures from 1st May to 31 July (peri-flowering, mean ≤ 15.5 °C) may signal a vintage of *Poor* quality.
- Whilst most climate change scenarios imply a decline in Chablis quality by 2041–2070, the decline would be small if the Paris Agreement were to be met.
- Under these scenarios, especially RCP 4.5, the climate of Chablis in 2041–2070 (and so the typicity of Chablis wine, if managed as now) may approach that of the Côte de Beaune today.

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Chapter 3. Preface

Chapter 3 comprises the following research paper:

Title: Weather potential for high-quality still wine from Chardonnay viticulture in different regions of the UK with climate change

Authors: Alex J. Biss and Richard H. Ellis

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Author Contribution: This paper was co-authored with Professor Richard H. Ellis. The research design, data analysis, and manuscript drafting were carried out by Alex Biss. Professor Ellis contributed to method development and manuscript editing.

Relevance to Thesis: This chapter addresses Objectives B, F and G of the thesis by applying the Chablis vintage model (developed in Chapter 2) to the UK to see where it will be possible, climatically, to produce premium quality still Chardonnay wine by mid-Century. Objectives F and G are only achieved in part, since this paper considers climate and weather but does not consider other environmental factors such as topography and soils. These objectives are covered in detail in Chapter 5.

Note: This paper describes the “Chablis vintage model”, which has been renamed the “Weather Model” in Chapters 5 and 6.

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ORIGINAL RESEARCH ARTICLE

Weather potential for high-quality still wine from Chardonnay viticulture in different regions of the UK with climate change

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ABSTRACT

UK viticulture is benefitting from climate change with an increase in vineyard area and a move towards French grapevine varieties, primarily Chardonnay and Pinot noir, to produce sparkling wine. Doubt remains, however, as to how good UK still wine can be from these varieties. The simple Chablis vintage model uses only three climatic indices: mean temperature from April to September, mean minimum temperature in September (cool night index) and total rainfall from June to September. It was applied to the UK for the periods 1981–2000, 2010–2019 and, with climate change projections, to 2040–2059 to locate sites in the UK with the climate potential to produce high-quality Chardonnay still wine. Weather data for 1981–2000 and 2010–2019 were taken from the Met Office's HadUK-Grid at a resolution of 5 × 5 km, and climate projections for 2040–2059 were derived from UKCP18, using intermediate emission scenario RCP 4.5 at the 5th, 50th and 95th percentile probabilities. Recent and current climatic conditions throughout most of the UK were unsuitable for sustainable production of high-quality still Chardonnay wine (only 0.2 to 1.8 % of UK land area suitable), but model scores corresponded with high-quality Chardonnay still wine production observed in some regions of England in 2018. Under the 5th percentile RCP 4.5 projection for 2040–2059, climatic conditions are similar to 2010–2019 and generally unsuitable for sustainable, high-quality still Chardonnay wine production. Under the median and 95th percentile projections for 2040–2059, however, South East England and East of England have the potential for high-quality still Chardonnay wine production in an average year, and Central England also with the 95th percentile projection. Overall, climate change is expected to benefit the production of high-quality still Chardonnay wine in the medium term, with up to 42.4 % of UK land possibly climatically (but not necessarily agronomically) suitable by mid-century. The model does not account for extreme events, however, and there is uncertainty over future inter-annual weather variability, and so the sustainability of high-quality still wine production. Planting Chardonnay clones suitable for both sparkling and still wines in the most-suitable areas of England would provide flexibility and so resilience.

KEYWORDS: UK wine, English wine, Chardonnay, Chablis, viticulture, vintage weather, climate change

INTRODUCTION

Viticulture is changing substantially as the world warms. Phenology is advancing (Quénol *et al*., 2017) and growing seasons are lengthening (Jones and Davis, 2000), all of which can impact yield, quality and wine characteristics (Jones, 2007; Quénol *et al.*, 2017). Wine producers in traditional viticulture regions in Europe are concerned with mitigating the negative impact on their crops from factors such as heat stress and drought (Jones and Schultz, 2016) and are considering how to adapt to future climate change (Neethling *et al*., 2017). In contrast, other regions' climates are becoming more favourable for viticulture as the viticulture belt shifts progressively northward in the northern hemisphere and southward in the southern hemisphere (Nesbitt, 2016).

Climate change has already benefitted viticulture in England and Wales (Nesbitt *et al.*, 2018), with a fivefold increase in vineyard hectarage from 2004 to 2021 (approximately 3800 ha; WineGB, 2021). This has been accompanied by a move away from hardy German grape varieties that are suited to the coldest possible climates under which grapes can grow, such as Muller-Thurgau, towards French varieties such as Chardonnay, Pinot noir and Pinot meunier that require warmer growing season temperatures (Ashenfelter and Storchmann, 2016; Nesbitt *et al.*, 2019). Chardonnay is one of the most popular white wine grape varieties, accounting for around 6.7 % (332,000 hectares) of all vineyards worldwide (Easton, 2015). It can produce popular 'everyday' wines as well as some of the greatest wines that fetch some of the highest prices at auction.

The potential for UK viticulture and wine production has been investigated previously. Georgeson and Maslin (2017) used a 'middle-of-the-road scenario' climate model (a further 2.2 °C warming and 5.6 % increase in rainfall) to predict the UK's suitability for new vineyards of nine grape varieties in 2100. Their map of potential Chardonnay growing areas in 2100 included large areas of the Midlands and East of England, though they warned that production of high-quality sparkling wine in Southern England might be threatened by temperatures that are too high. Another approach applied Jones' climate/maturity threshold for Chardonnay of a 14 °C Growing Season Temperature (GST; mean temperature from 1 April to 31 October) (Jones, 2006) to the UK (Nesbitt, 2016). Nesbitt (2016) found that only 10 % of vineyards (≥1 ha) in England and Wales, as of November 2015, were within areas with mean GST > 14 °C for the 30-year period from 1981 to 2010.

Nesbitt *et al.* (2018) considered UK wine production from a yield perspective and concluded that a significant number of existing UK vineyards were sub-optimally located. They also reported that the transition to French grape varieties had made UK wine production more susceptible to inter-annual variations in climate, threatening the sustainability of the industry. The sustainability of yield is thus, in large part, dependent on having a climate with an average GST that is considerably above the lower threshold of its range for the grape variety so that ripe berries are still produced in relatively cold years.

Little research, however, has considered whether the UK (or other cool regions that are warming) will have the potential to produce high-quality single-variety still wines equivalent to the Chardonnay and Pinot noir wines of Burgundy. The Burgundy region of Chablis is of particular interest. Its white wines are produced exclusively from Chardonnay grapes, and it is the most northerly major producer (47°49'19"N latitude), and the nearest area to England, of non-sparkling Chardonnay wine.

English wine producers are already using Chardonnay extensively, it and Pinot noir being the most-grown grape varieties in the UK (WineGB, 2020). This is almost entirely to produce sparkling wines, with Chardonnay usually blended with Pinot noir and Pinot meunier to make a classic Champagne-style wine, which requires grapes that are only just barely ripe (Clarke, 2020). Doubt remains, however, as to how consistently the UK will be able to produce high-quality still wine from these varieties over the coming decades (Nesbitt *et al.*, 2016). Chardonnay is rarely used to make still white wines in the UK, though the proportion of still wine has been steadily increasing since the exceptional high-quality and high-yielding vintage of 2018 (Olsen, 2021; WineGB, 2021).

The Chablis vintage model is an empirical model of inter-annual variation in Chablis vintage quality (Biss and Ellis, 2021). It estimates the vintage quality of still Chardonnay wine as a function of mean temperature from April to September (curvilinear relation, maximum score at 16–17 °C), mean minimum temperature in September (cool night index (*CNI*) during ripening; negative relation), and total rainfall from June to September (from around flowering and fruitset to harvest; negative relation). That model is applied here to identify climatically suitable sites for the production of still Chardonnay wine in the UK for the periods 1981–2000, 2010–2019, and out to 2040–2059 to understand the potential for producing high-quality still Chardonnay wine in the UK. No consideration of soils, topography, or viticultural and winemaking skill is made as part of this paper.

MATERIAL AND METHOD

1. The Chablis vintage model

To establish the climatic suitability of areas of the UK for Chardonnay viticulture with the potential to produce high-quality still wine, we used the "Chablis vintage model" (Equation 1; Biss and Ellis, 2021), henceforth the Model. This Model explained 57.1 percent of the variability in Chablis vintage quality between 1963 and 2018 and performed well in differentiating *Poor* (score < 6) from *Good* (score 6–8) and *Excellent* (score > 8) vintages.

(Equation 1)

$$Vintage\ Score = 22.38\ Tmean_{Apr\text{-}Sep} - 0.6790\ Tmean_{Apr\text{-}Sep}^{\ 2} - 0.4089\ CNI - 0.006918\ P_{Jun\text{-}Sep} - 170.9$$

where $Tmean_{Apr\text{-}Sep}$ is the mean temperature (°C) from 1 April to 30 September (a shortened version of GST), *CNI* is the Cool Night Index (mean minimum temperature for September, °C) and $P_{Jun\text{-}Sep}$ is the total precipitation (mm) from 1 June to 30 September.

Vintage Score was assessed in this Model on a scale of 0 to 10. A score below zero occurred when the model was applied to an area with climate indices measurements that lay considerably beyond the range of the Chablis region (upon which the model was built) and thus represented particularly unsuitable land. A score ≥ 6, i.e., *Good* or *Excellent*, denotes land that is capable of producing high-quality still Chardonnay wine.

2. Applying the Chablis vintage model to the UK

2.1. UK weather data

UK weather data was obtained from the UK meteorological service's (Met Office) gridded dataset of climate variables, the HadUK-Grid (Met Office *et al.*, 2018). This data is interpolated from in situ land-based meteorological station data for the whole of the UK adjusted for the Urban Heat Island effect, proximity to the coast, topography, and elevation to provide a realistic picture of climate at a location (see Met Office *et al.* (2018) and Hollis *et al.* (2019) for details of the gridding methodology and data accuracy).

The HadUK-Grid data were obtained at a resolution of 5 km × 5 km (Met Office *et al.*, 2020) for i) the 20-year period from 1981 to 2000, which is the reference period for climate change projections in the UK, and ii) annually from 2010 to 2019, and loaded into a QGIS Geographical Information System (QGIS; QGIS Association, http://www.qgis.org). It comprised monthly measurements for mean temperature (°C), mean minimum temperature (°C), mean maximum temperature (°C), and total precipitation (mm). These values were used to calculate, in QGIS, the three climate indices needed for the Model (summarised by administrative region in Table 1) and then to map UK climate suitability for 1981 to 2000 (the base period), 2010 to 2019 (recent decade), 2012 and 2018 (the worst and best vintages of the recent decade, respectively) (Robinson, 2022).

To assess the added value of the Model, climate suitability maps were also created in QGIS using a simple 14 °C Growing Season Temperature (GST) threshold (Jones, 2006) for 1981 to 2000, 2010 to 2019, 2012 and 2018, and compared to the above-mentioned maps.

2.2. UK climate projections

UK climate projections for the period 2040 to 2059, using the RCP 4.5 emissions scenario, were obtained from the Met Office UKCP18 dataset (Met Office, n.d.[a]) for each administrative region; see Fung *et al.* (2018) for a discussion

TABLE 1. Mean climate indices ($Tmean_{Apr\text{-}Sep}$, *CNI* and $P_{Jun\text{-}Sep}$) for the periods 1981 to 2000 and 2010 to 2019, derived from HadUK-Grid data and summarised by UK administrative region (Figure 1). Comparative data for the Chablis region are 15.8 °C, 9.4 °C and 233.6 mm from 1976 to 2005 and 16.8 °C, 9.8 °C and 236.0 mm from 2009 to 2018 (Biss and Ellis, 2021).

UK Region		1981 to 2000			2010 to 2019		
		$Tmean_{Apr\text{-}Sep}$ (°C)	CNI (°C)	$P_{Jun\text{-}Sep}$ (mm)	$Tmean_{Apr\text{-}Sep}$ (°C)	CNI (°C)	$P_{Jun\text{-}Sep}$ (mm)
England	East Midlands	13.0	9.2	226.9	13.8	9.5	244.4
	East of England	13.7	10.0	209.8	14.4	10.0	213.9
	London	14.7	10.8	203.9	15.3	10.9	212.6
	North East England	11.3	7.9	262.7	12.0	8.6	316.2
	North West England	12.1	8.8	360.4	12.6	9.4	439.2
	South East England	13.8	9.8	219.5	14.3	9.9	227.9
	South West England	13.3	9.8	282.6	13.8	10.2	300.7
	West Midlands	13.1	9.1	240.2	13.6	9.3	253.8
	Yorkshire and Humber	12.3	8.8	257.0	13.0	9.3	290.0
Northern Ireland		11.8	8.4	334.0	12.3	9.0	372.6
Scotland		10.4	7.3	426.6	10.9	8.0	469.4
Wales		12.2	9.0	393.6	12.7	9.4	430.2

of the data caveats and limitations. UKCP18 is the most recent set of climate projections offered by the UK Met Office, providing probabilistic projections using a perturbed parameter ensemble (PPE) of many different variants of the HadCM3 climate model. The data comprised projected absolute changes, by month, in mean air temperature (for calculation of $Tmean_{Apr\text{-}Sep}$), minimum air temperature (for calculation of *CNI*), and percentage change in precipitation (for calculation of $P_{Jun\text{-}Sep}$), from the base reference period of 1981 to 2000. For each of these variables, three thousand samples were extracted, and the 5th, 50th (median) and 95th percentile probability changes were calculated (Table 2).

These three variables are not consistent with each other (Met Office, 2018). For example, a 95th percentile increase in $Tmean_{Apr\text{-}Sep}$ does not occur during the same sample run as a 95th percentile change in *CNI* and/or $P_{Jun\text{-}Sep}$. Pearson correlation coefficients between changes in each of the three climate indices for England and Wales for the 3,000 samples were: $Tmean_{Apr\text{-}Sep}$ vs *CNI* 0.59; $Tmean_{Apr\text{-}Sep}$ vs $P_{Jun\text{-}Sep}$ –0.34; *CNI* vs $P_{Jun\text{-}Sep}$ –0.22.

In keeping with the direction of these correlations, the 5th percentile probability projection for the vintage score was made using the 5th percentile projections for each of $Tmean_{Apr\text{-}Sep}$ and *CNI* but the 95th percentile projection for P_{JunSep} and vice versa (95th, 95th, but 5th, respectively). The median projection for vintage score used the 50th percentile projections for all three variables.

The RCP 4.5 pathway was selected because it is an intermediate greenhouse gas emissions scenario and also because the range in projected values for an increase in mean summer temperature to 2040–2059 for England and Wales (+0.3 °C and +3.2 °C at the 5th and 95th percentiles, respectively) exceed those of RCP 2.6 (+0.5 °C and + 3.1 °C) and the other intermediate UK scenario RCP 6.0 (+0.3 °C and + 3.0 °C) (Table S1) (Met Office, n.d.[b]). Thus RCP 4.5 covers a greater range of possible climate scenarios. The period 2040 to 2059 was chosen to reflect the investment horizon of a new vineyard planted over the current decade, given it takes approximately 4 years for a new vineyard to achieve full cropping production and the expected productive life of a vine is around 30 years (Skelton, 2020a).

In terms of Shared Socio-economic Pathways (SSPs), RCP 4.5 is broadly equivalent to SSP2, an intermediate greenhouse gas emissions scenario with CO_2 emissions remaining around current levels until the middle of the century (IPCC, 2022; O'Neill et al., 2016). The IPCC states that reference emission scenarios from ensemble modelling typically end up in C5 to C7 categories of global warming, where the lowest category, C1, is below 1.5 °C (1.1 to 1.5 °C, 5th to 95th percentile) above pre-industrial levels by 2100 with no or limited overshoot, C5 is below 2.5 °C (1.9 to 2.5 °C), C7 is below 4 °C (2.8 to 3.9 °C), and the highest category C8 is where the median projection is above 4 °C (3.7 to 5.0°C) by 2100. The SSP2-4.5 emissions scenario, reflecting medium challenges to mitigation and adaptation, is in the C6 category, in which global warming is limited to below 3 °C (2.4 to 2.9 °C) (Hausfather, 2022; IPCC, 2022).

Absolute RCP 4.5 projections for the 2040 to 2059 period were then calculated in QGIS by applying the UKCP18 projections (Table 2) to 1981 to 2000 HadUK-Grid data (summarised in Table 1).

TABLE 2. RCP 4.5 projections (UKCP18) at the 5th, 50th and 95th percentile probability for changes in climate indices ($Tmean_{Apr\text{-}Sep}$, *CNI* and $P_{Jun\text{-}Sep}$) from 1981–2000 to 2040–2059, by administrative region. Projections for Scotland are calculated as the mean of East Scotland and West Scotland only, excluding North Scotland.

UK Region		RCP 4.5 climate projections from 1981–2000 to 2040–2059		
		$Tmean_{Apr\text{-}Sep}$ change (°C) 5th/ 50th / 95th	*CNI* change (°C) 5th/ 50th / 95th	$P_{Jun\text{-}Sep}$ change (%) 5th/ 50th / 95th
England	East Midlands	0.44 / 1.53 / 2.64	–0.21 / 1.43 / 3.21	–34.1 / –14.9 / 5.9
	East of England	0.42 / 1.53 / 2.66	–0.21 / 1.43 / 3.21	–34.1 / –14.9 / 5.9
	London	0.44 / 1.61 / 2.81	–0.24 / 1.49 / 3.39	–37.0 / –15.5 / 7.1
	North East England	0.33 / 1.30 / 2.34	–0.15 / 1.39 / 3.05	–22.9 / –7.7 / 8.4
	North West England	0.28 / 1.28 / 2.35	–0.09 / 1.42 / 3.01	–26.9 / –10.4 / 6.8
	South East England	0.47 / 1.61 / 2.81	–0.24 / 1.50 / 3.44	–36.9 / –16.5 / 5.4
	South West England	0.37 / 1.50 / 2.67	–0.48 / 1.50 / 3.53	–36.0 / –17.2 / 3.1
	West Midlands	0.32 / 1.45 / 2.59	–0.46 / 1.46 / 3.42	–30.7 / –13.6 / 5.2
	Yorkshire and Humber	0.39 / 1.44 / 2.48	–0.17 / 1.39 / 3.05	–27.1 / –11.0 / 6.7
Northern Ireland		0.27 / 1.19 / 2.18	–0.06 / 1.40 / 2.95	–26.9 / –10.2 / 7.6
Scotland		0.26 / 1.20 / 2.22	–0.07 / 1.37 / 2.87	–22.8 / –7.1 / 9.4
Wales		0.28 / 1.37 / 2.45	–0.41 / 1.44 / 3.35	–29.6 / –13.2 / 4.7

2.3 Two estimates of *CNI*

We questioned the extent to which *CNI* will rise as projected (see Results). As such, for each of the three percentile probability projections (5 %, 50 %, 95 %), two estimates of *CNI* were applied to calculate the vintage score. The first assumed *CNI* would change according to UKCP18 projections (Table 2). An alternative value (*CNI2*) was calculated in proportion to that for the change in *CNI* and the change in $Tmean_{Apr\text{-}Sep}$ that occurred between 1981–2000 and 2010–2019 (see Results 1.1). Hence *CNI2* assumed the recent historical relationship between the two indices would continue, and we used the UKCP18 projection for $Tmean_{Apr\text{-}Sep}$ for its calculation (Equation 2).

3. UK vineyards and county data

In the Results and the Discussion, reference is made to several current UK vineyards. Details of these vineyards were extracted from Skelton (2020b), which includes details of 895 vineyards (total of 3494.9 hectares). The postcode locations of 819 of these UK vineyards (totalling 3,380 hectares) were successfully geocoded into QGIS using the MMQGIS plugin (Figure 1). A number of these postcodes relate to company premises rather than exact vineyard locations (Nesbitt *et al.,* 2018), but this was not considered a material issue given the 5 × 5 km resolution of this study compared to Nesbitt *et al.* (2018) who investigated site suitability at a considerably higher spatial resolution (50 × 50 m).

The UK vineyards dataset was used to assess the suitability of existing vineyard land and, as a first approximation, to generate data at the county scale. To do this, the vineyards were grouped into counties, and then the various climate indices and potential vintage scores were sampled on the QGIS maps and weighted as a proportion of each vineyard's size to the total vineyard area in that county.

In this way, mean county data was generated based on existing vineyard locations but not overly affected by small vineyards in unusual (for example, urban) settings.

(Equation 2)

$$CNI2_{2040-59} = CNI_{1981-2000} + \left(UKCP18\ \Delta Tmean_{Apr-Sep2040-59} \times \frac{CNI_{2010-19} - CNI_{1981-2000}}{Tmean_{Apr-Sep2010-19} - Tmean_{Apr-Sep1981-2000}} \right)$$

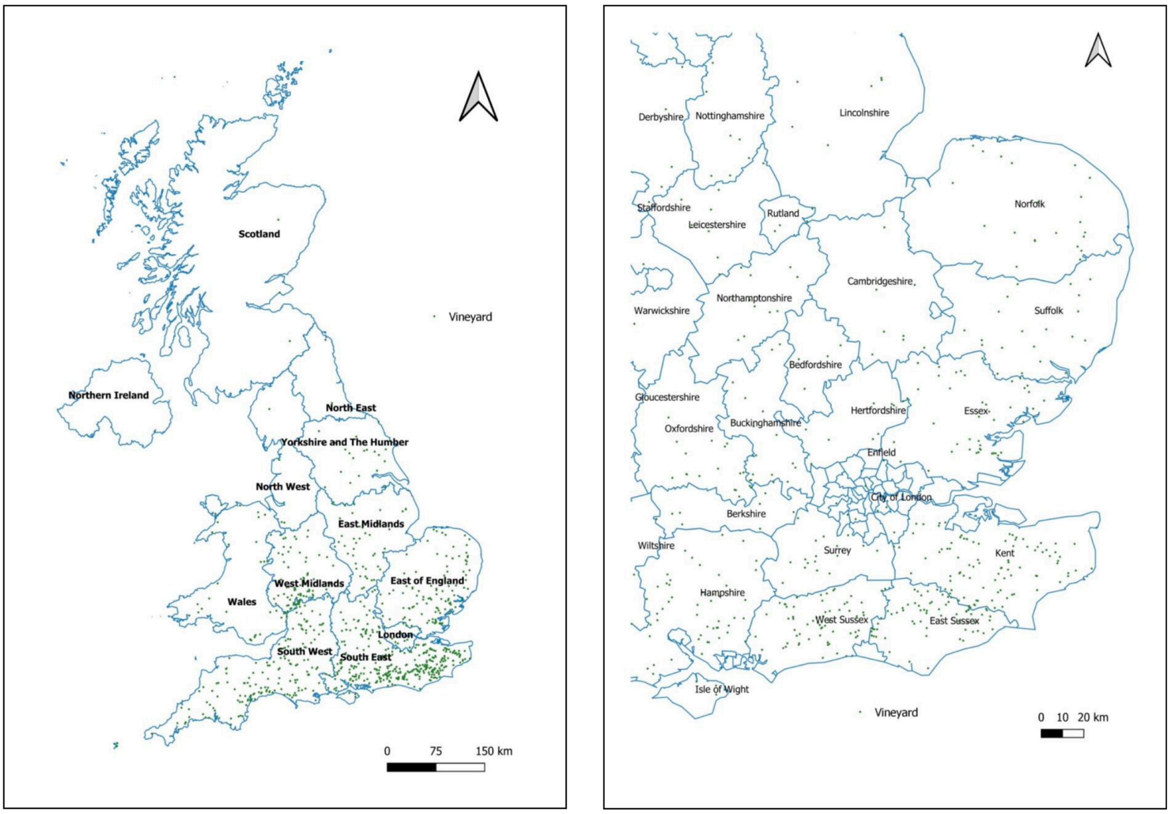

FIGURE 1. Location of vineyards in relation to administrative regions of the UK (left panel) and the counties of East of England, East Midlands and South East England (right panel, with Greater London's Enfield and City of London also marked). Location of vineyards as of 11 November 2020 from Skelton (2020b).

4. Assessing inter-annual variability for 2040–2059

UKCP18 projections for 2040–2059 were provided as mean figures for the period. The following methodology was used to derive an approximate 80 % confidence interval for the estimated inter-annual variability in vintage scores for 2040–2059. For each 5 × 5 km grid, the standard deviation (SD) for each of the three climate indices from 2010 to 2019 was calculated. These standard deviations were applied as follows to the 2040–2059 projections to estimate a 10-year lower and upper limit for vintage score:

4.1. Lower Limit

- $Tmean_{Apr\text{-}Sep\_2040\text{-}59}$ decreased by 1.282 x SD $Tmean_{Apr\text{-}Sep\_2010\text{-}19}$
- $CNI_{2040\text{-}59}$ or $CNI2_{2040\text{-}59}$ increased by 1.282 x SD $CNI_{2010\text{-}19}$
- $P_{Jun\text{-}Sep\_2040\text{-}59}$ increased by 1.282 x SD $P_{Jun\text{-}Sep\_2010\text{-}19}$

4.2 Upper Limit

- $Tmean_{Apr\text{-}Sep\_2040\text{-}59}$ increased by 1.282 x SD $Tmean_{Apr\text{-}Sep\_2010\text{-}19}$
- $CNI_{2040\text{-}59}$ or $CNI2_{2040\text{-}59}$ decreased by 1.282 x SD $CNI_{2010\text{-}19}$
- $P_{Jun\text{-}Sep\_2040\text{-}59}$ decreased by 1.282 x SD $P_{Jun\text{-}Sep\_2010\text{-}19}$

Note the major concern with the UK—an emerging cool climate wine region (Nesbitt *et al.*, 2016)—is that growing season temperatures are, or will be, too cool (rather than too hot) for still Chardonnay production. As such, the Lower Limit to vintage score is given by reducing, and the Upper Limit by increasing, $Tmean_{Apr\text{-}Sep}$.

5. Tools

R/R Studio (version 1.3.1093) was used for data analysis and visualisation, and QGIS (version 3.10.3) was used for mapping.

RESULTS

1. Change in Model climate indices from 1981–2000 to 2010–2019

1.1. *CNI* versus $Tmean_{Apr\text{-}Sep}$

From 1981–2000 to 2010–2019, *CNI* rose by 0.48 °C (SD 0.28 °C) and $Tmean_{Apr\text{-}Sep}$ by 0.55 °C (SD 0.11 °C) for the UK as a whole. The increase in *CNI*, however, was more varied geographically than for $Tmean_{Apr\text{-}Sep}$, becoming progressively greater going north and west from the South-East and East of England (Figure 2a and Table S2).

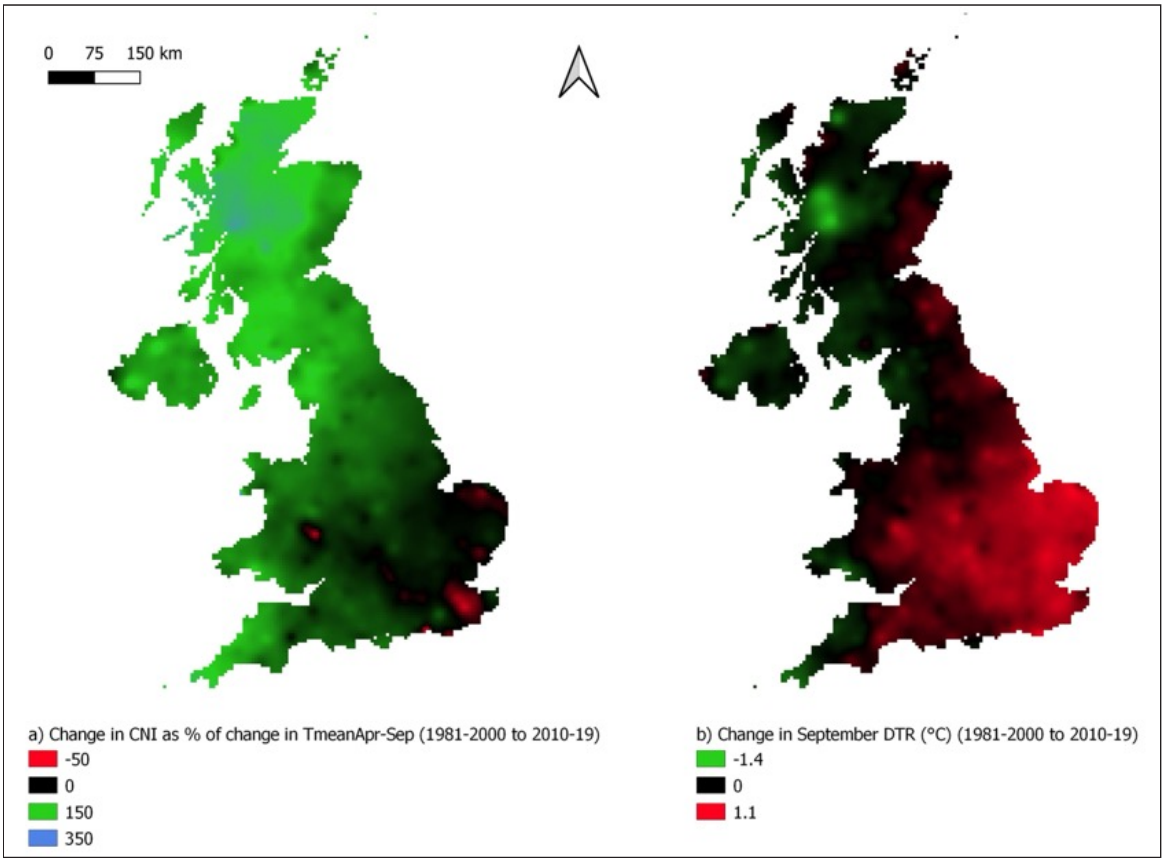

FIGURE 2. Change in climate indices from 1981–2000 to 2010–2019 in the UK.

(a) change in mean CNI as a percentage of change in mean $Tmean_{Apr\text{-}Sep}$; (b) change in mean Diurnal Temperature Range (DTR) for the month of September. Colours are graduated in the maps, from red to black to green (and to blue in (a)), to reflect the non-discrete variation in change.

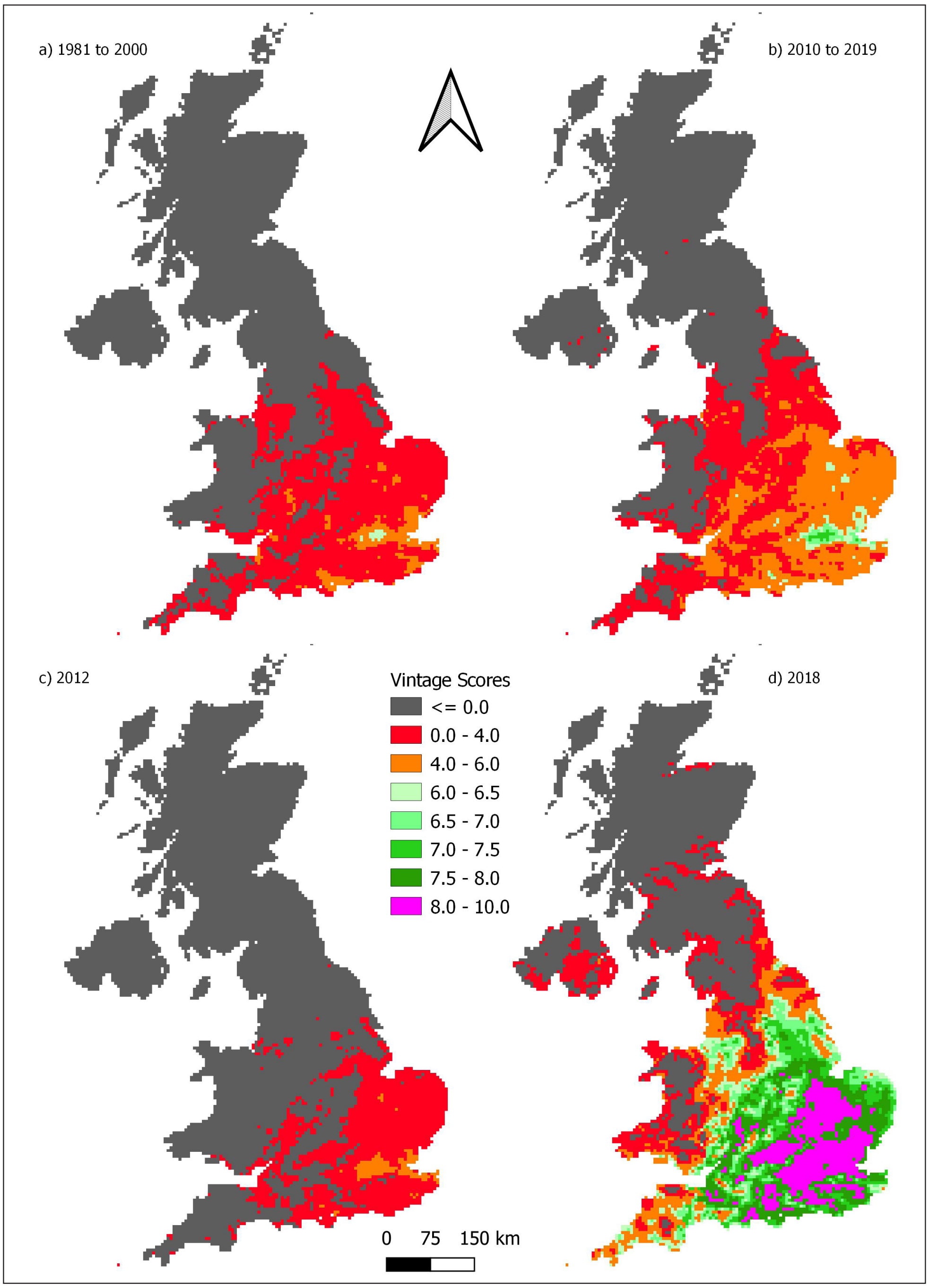

FIGURE 3. Chardonnay still wine quality score estimates across the UK provided by the Chablis vintage model.

(a) 1981 to 2000 (percentage of UK land where wine quality rated *Good* 0.2 %, *Excellent* 0.0 %); (b) 2010–2019 (*Good* 1.8 %, *Excellent* 0.0 %); (c) 2012 (*Good* 0.0 %, *Excellent* 0.0 %); (d) 2018 (*Good* 25.2 %, *Excellent* 8.8 %). Green is *Good*; purple is *Excellent*.

In certain isolated areas, *CNI* decreased in absolute terms (red and reddish areas in Figure 2a).

For example, while $Tmean_{Apr\text{-}Sep}$ rose in North West England and East of England by 0.5 and 0.7 °C, respectively, *CNI* increased by 0.5 °C in North West England but only by 0.1 °C in the East of England (Table S2).

This distribution was consistent with changes in the Diurnal Temperature Range (*DTR*) for September (Figure 2b), where mean maximum temperatures increased more than mean minimum temperatures in the East of England, South East England, and the Midlands, but vice versa for Cornwall, North West England, Northern Ireland, Western and Northern Scotland, and South Wales.

When considering inter-annual variation rather than climatic trends, it is important to note that the two variables did not always move in the same direction or with the same magnitude of change. That is, higher $Tmean_{Apr\text{-}Sep}$ did not necessarily translate into higher *CNI*. For example, the 2018 season value for $Tmean_{Apr\text{-}Sep}$ was 1.6 ° C warmer than the mean for 1981–2000, yet *CNI* was 0.3 °C cooler (mean of the top 30 counties, Table S3).

1.2. Precipitation ($P_{Jun\text{-}Sep}$)

Rainfall ($P_{Jun\text{-}Sep}$) increased from 1981–2000 to 2010–2019 by between 2.0 and 21.9 %. The increase was small (< 10 %) in southern regions and large (> 20 %) in the North East and North West of England (Table S2).

2. Applying the Model retrospectively

2.1. The UK, 1981–2000

According to the Model, only areas in inner London and around Heathrow airport in west London were capable, on average, of producing *Good* Chardonnay still wine ("Chardonnay wine") between 1981 and 2000 (Figure 3a). The maximum score achieved was 6.5, but only 0.2 % of UK land achieved a score of ≥ 6 (Table 3). Existing vineyards would have experienced, on average, $Tmean_{Apr\text{-}Sep}$ that was too cold compared to the ideal Chablis climate, though *CNI* and $P_{Jun\text{-}Sep}$ were within the ideal range (empty triangles, Figure 4).

2.2. The UK in 2010-19

The climate for the period 2010 to 2019 was, on average, incapable of producing *Good* Chardonnay wine over 98 % of the UK land area (Figure 3b and Table 3).

Places that would have been suitable for producing *Good* Chardonnay wine between 2010 and 2019 would be land in and around London (including parts of south Hertfordshire, north Surrey, and south Essex), areas that fringe the Thames Estuary (south Essex and north Kent), and some isolated areas in the East of England and Midlands, such as in Cambridgeshire, Suffolk, and Oxfordshire (Figure 3b). Existing vineyards would have experienced similar *CNI* and $P_{Jun\text{-}Sep}$ in 2010–2019, and marginally better $Tmean_{Apr\text{-}Sep}$, compared to 1981–2000, but still c. 0.5 to 1.0 °C lower than the ideal climate projected by the Model (solid circles, Figure 4).

The mean score for 2010–2019 (Table 3) hides significant vintage score variation: 2012 would likely have been *Poor* everywhere (maximum score achieved for any one 5 × 5 km grid square 5.9), 2018 *Excellent* at the best sites (maximum score 9.0), with the other eight years scoring in-between (maximum score 6.8 to 7.3). The highest-scoring existing vineyard of size (> 1 hectare) for 2010–2019 was Forty Hall Vineyard in Enfield, London (its grid square scoring a mean 6.6 for the 2010–2019 period; 4.7 for 2012, 8.4 for 2018, and 5.9 to 6.8 for the other eight vintages).

TABLE 3. Estimates of UK vintage scores for Chardonnay still wine quality and percentage of UK land scoring ≥ 6 (i.e., *Good* or *Excellent*) from the Chablis vintage model for 1981 to 2000, 2010 to 2019, and RCP 4.5 projections (UKCP18) for 2040–2059 at the 5th, 50th and 95th percentiles; CNI2 indicates estimates with a modified *CNI* (see text). The two right-hand columns show the highest-scoring existing UK vineyard (> 1 ha) and its score in each period or scenario.

Period		Mean Score[a]	Max Score[b]	UK Land (%) scoring ≥ 6[c]	Highest-Scoring Vineyard (> 1 ha)[d]	Top Vineyard Score[e]
1981 to 2000		–7.4	6.5	0.2	Forty Hall Vineyard, Enfield, London[f]	5.3
2010 to 2019		–4.8	7.2	1.8	Forty Hall Vineyard, Enfield, London[f]	6.6
2040–2059 (RCP 4.5)	5 %	–5.6	7.1	1.0	Forty Hall Vineyard, Enfield, London[f]	6.2
	5 % (*CNI2*)	–5.8	7.0	0.8	Forty Hall Vineyard, Enfield, London[f]	6.1
	50 %	–1.0	7.5	20.7	Bothy Vineyard, Oxfordshire	7.4
	50 % (*CNI2*)	–0.9	8.3	24.8	Bardsley Farms Vineyard, Kent	8.2
	95 %	2.3	7.7	39.1	Wolf Oak Vineyard, Berkshire	7.6
	95 % (*CNI2*)	2.7	9.1	42.4	Mereworth Wines, Kent	9.1

[a] Mean of mean vintage score (for the stated period) across all 5 × 5 km grid squares.

[b] Maximum mean score (for the stated period) achieved by any one 5 × 5 km grid square.

[c] Percentage of UK 5 × 5 km grid squares with a mean score equal to or greater than 6.

[d] Highest-scoring vineyard based on the mean score of its 5 × 5 km grid square for a stated period.

[e] Mean score for a stated period of highest-scoring vineyard's 5 × 5 km grid square.

[f] The administrative area designated London is the Greater London region, which includes considerable areas of farmland and woodlands at its extremities which are protected from urban development. Hence, there are suitable sites for viticulture, which benefit already from the urban heat island effect, and with a considerable number of potential customers for their wines nearby. The Forty Hill vineyard, for example, is only 20 km north of the centre of London.

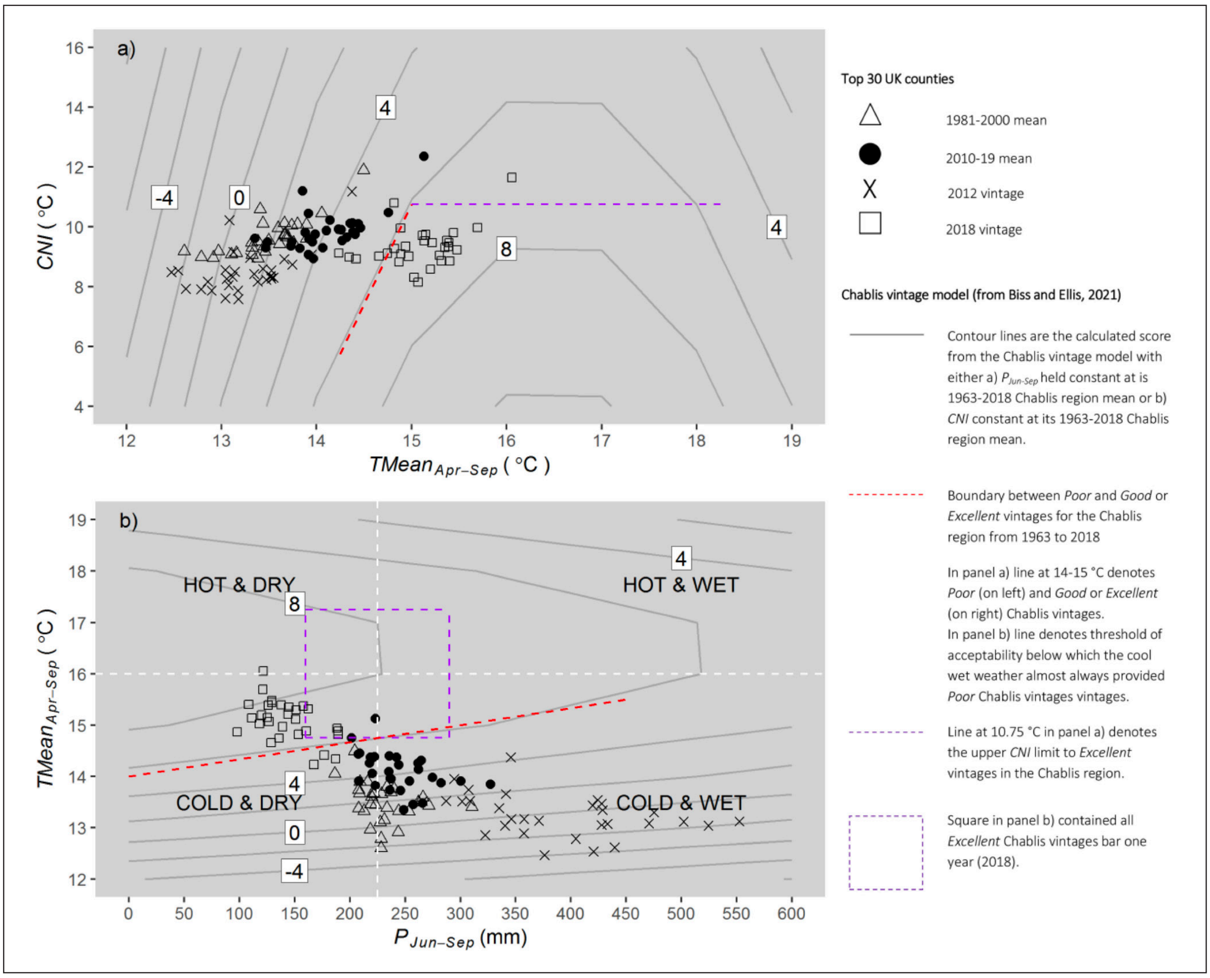

FIGURE 4. Comparison of climates for the top 30 UK counties (Table 4) in 1981–2000, 2010–2019, 2012 and 2018, and the Chablis region, France, from 1963 to 2018. Contours (vintage score) and dashed lines from Biss and Ellis (2021).

2.2.1. The 2012 vintage

No land was deemed capable of producing *Good* Chardonnay wine in 2012 (Figure 3c). Of the sizeable vineyards (> 1 hectare), Forty Hall Vineyard came closest (4.7). For all existing vineyards, 2012 would have been too cold and wet (crosses, Figure 4b).

2.2.2. The 2018 vintage

Estimates of the 2018 vintage were exceptional (Figure 3d) because the weather that year had the potential to produce high-quality Chardonnay wine throughout most of England (34.0 percent of the UK land area). In fact, the weather in 2018 had the potential to produce *Excellent* Chardonnay wine across a greater area of the UK (8.8 % of UK land area) than all but one (95th percentile projection with *CNI2*) of the mean projections for 2040–2059 considered in this study (see below). The highest-scoring existing vineyard of size (> 1 hectare) was Laithwaites' Windsor Great Park Vineyard in Berkshire (8.8).

Near-ideal high-quality Chardonnay wine production conditions were met by the majority of existing vineyards in 2018: $Tmean_{Apr\text{-}Sep}$ was sufficiently high whilst *CNI* remained below 10.75 °C (open squares, Figure 4a). Moreover, $P_{Jun\text{-}Sep}$ was some 50 to 100 mm lower than is typical for the Chablis region (open squares, Figure 4b).

3. Alternative method: applying a 14 °C GST threshold

According to the application of a 14 °C GST threshold (Jones, 2006), Chardonnay viticulture was not possible, on average, throughout most of the UK during the 1981 to 2000 period except for in and around London, parts of the Thames Estuary and a small part of southern Hampshire (Figure 5a). The 2010 to 2019 period was, on average suitable for Chardonnay viticulture in large parts of the South East and East of England and along the Severn Estuary (Figure 5b). The 2012 vintage was similar in distribution to 1981 to 2000 (Figure 5c), whereas the 2018 vintage stood out for the considerable extent of land suitability, accounting for 34.1 percent of the UK and covering most of England as far north as Lancashire and Yorkshire (Figure 5d).

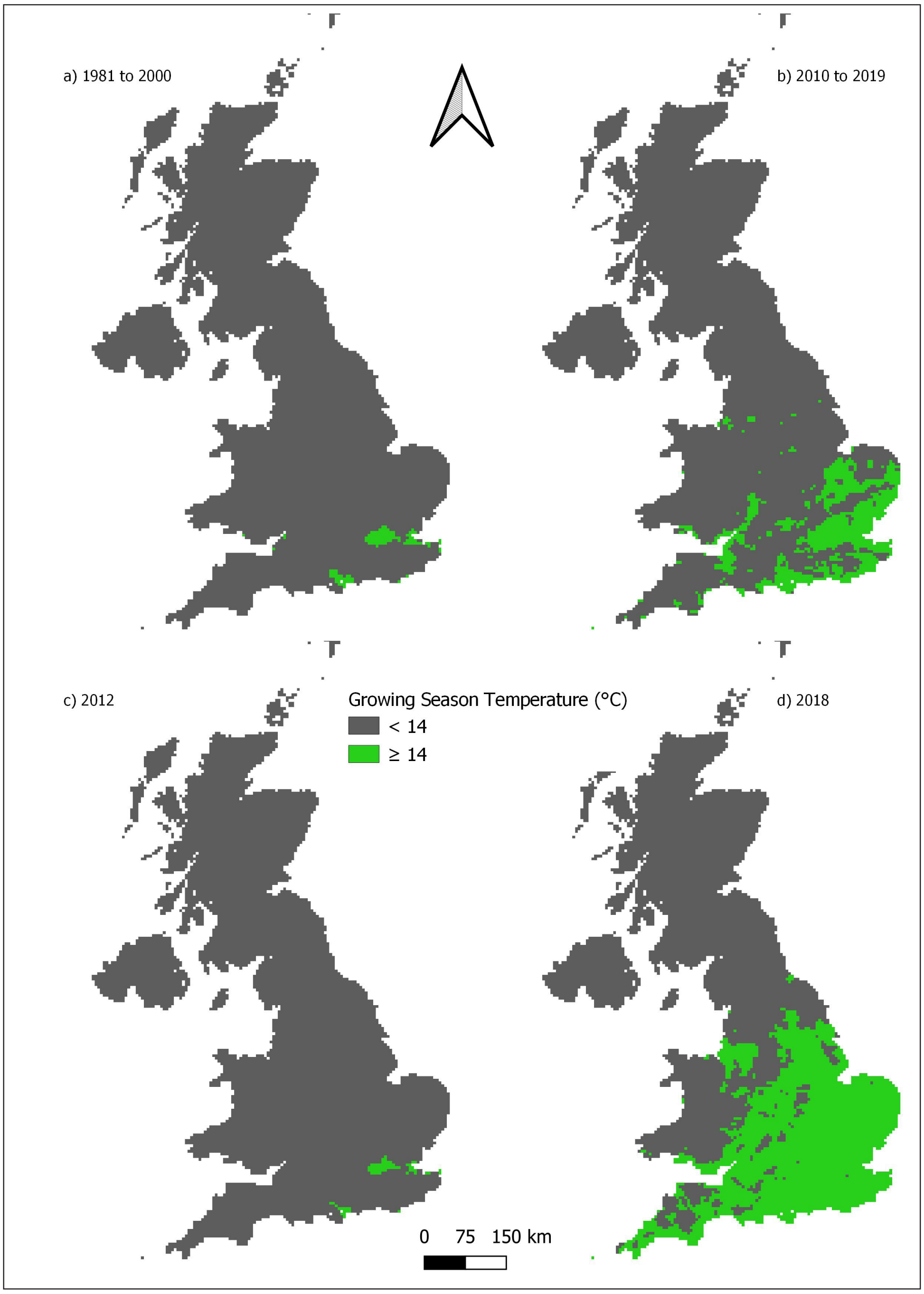

FIGURE 5. UK land suitability (in green) for Chardonnay viticulture, based on 14 °C GST threshold (Jones, 2006).
a) 1981 to 2000 (1.1 % of UK area); b) 2010 to 2019 (11.0 %); c) 2012 (0.7 %); d) 2018 (34.1 %).

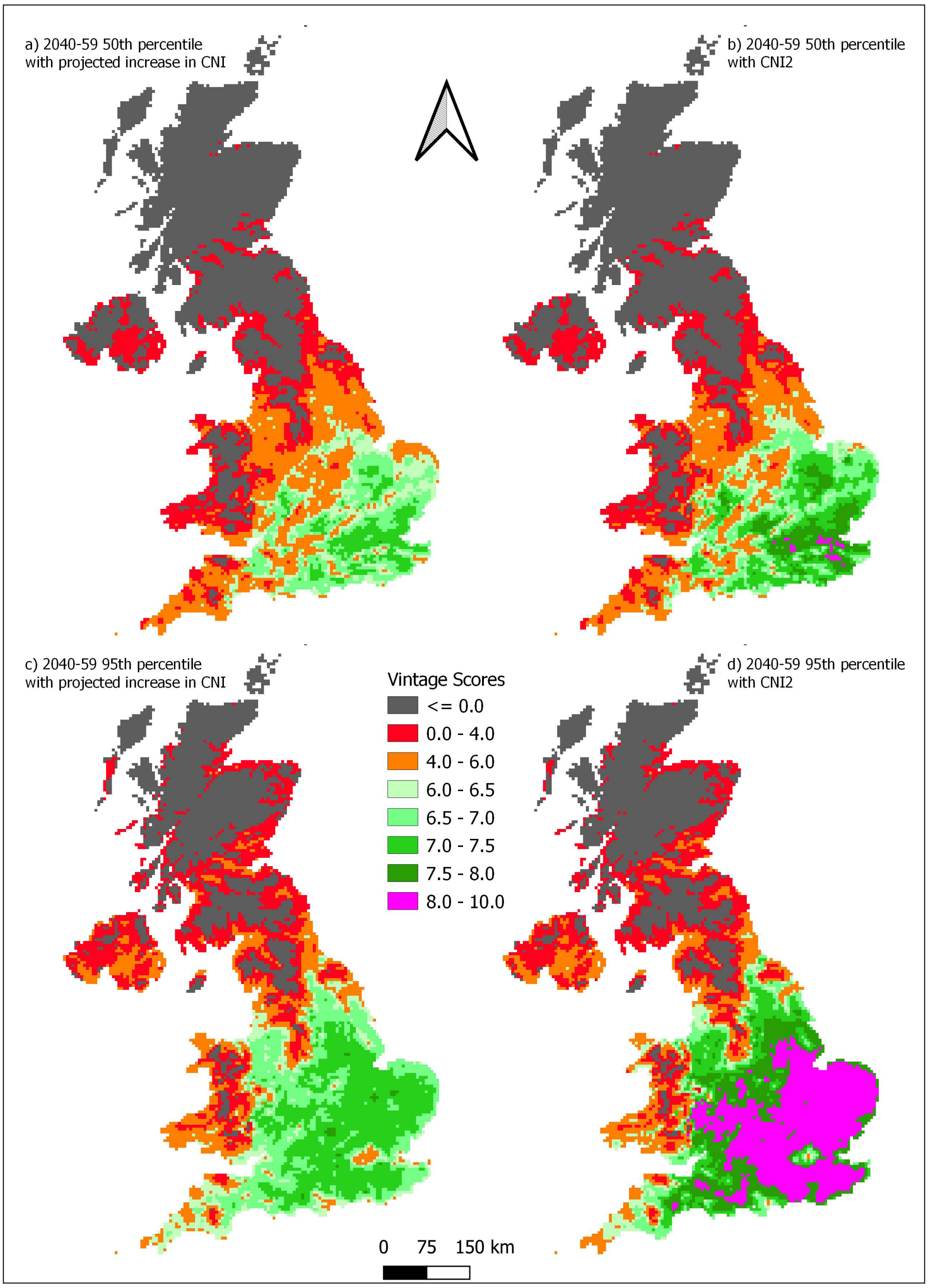

FIGURE 6. Model predictions for the vintage score of Chardonnay still wine across the UK in 2040-2059 under RCP 4.5 (median and 95th percentiles).

(a) 2040–2059 using the median RCP 4.5 projection (UK area rated *Good* 20.7 %, *Excellent* 0.0 %); (b) 2040–2059 using the median RCP 4.5 projection but with CNI2, a smaller increase than CNI projections (*Good* 24.5 %, *Excellent* 0.3 %); (c) 2040–2059 using the 95th percentile RCP 4.5 projection (*Good* 39.1 %, *Excellent* 0.0 %); (d) 2040–2059 using the 95th percentile RCP 4.5 projection but with CNI2 (*Good* 24.5 %, *Excellent* 17.9 %). Green is *Good*; purple is *Excellent*.

County	Region	Area of Planted Vines (ha)	Mean Vintage Score 1981–2000	2010–2019[b]	2040–2059 (RCP 4.5)[a] 5 % CNI	5 % CNI2	50 % CNI	50 % CNI2	95 % CNI[c]	95 % CNI2[c]
Berkshire	South East England	34.4	2.0	4.1 (0.4 – 8.0)	3.8 (0.4 – 7.7)	3.6 (0.3 – 7.6)	6.5 (3.6 – 8.7)	6.9 (4.1 – 9.1)	7.3 (5.0 – 7.7)	8.5 (6.1 – 8.9)
Buckinghamshire	South East England	19.8	2.5	4.7 (1.3 – 8.3)	4.2 (1.0 – 8.0)	4.0 (0.8 – 7.8)	6.6 (3.9 – 8.7)	7.1 (4.4 – 9.2)	7.2 (5.0 – 7.4)	8.4 (6.2 – 8.7)
Cambridgeshire	East of England	10.0	2.7	5.0 (2.0 – 8.0)	4.2 (1.0 – 7.9)	4.1 (0.9 – 7.8)	6.6 (3.8 – 8.6)	7.1 (4.3 – 9.1)	7.2 (5.0 – 7.6)	8.4 (6.2 – 8.8)
Cornwall	South West England	30.4	0.6	2.0 (−1.8 – 5.9)	2.2 (−0.8 – 6.3)	1.8 (−1.4 – 5.9)	5.1 (2.1 – 7.3)	4.8 (1.8 – 7.1)	6.2 (3.4 – 6.7)	6.2 (3.4 – 6.7)
Devon	South West England	84.4	1.2	2.6 (−1.8 – 6.3)	2.7 (−0.6 – 7.0)	2.4 (−1.0 – 6.7)	5.5 (2.4 – 8.0)	5.7 (2.6 – 8.2)	6.5 (3.7 – 7.3)	7.2 (4.4 – 8.0)
Dorset	South West England	73.2	0.8	2.7 (−1.7 – 6.6)	2.5 (−1.1 – 6.8)	2.2 (−1.1 – 6.5)	5.5 (2.5 – 8.3)	5.7 (2.7 – 8.5)	6.8 (4.0 – 7.8)	7.6 (4.8 – 8.6)
East Sussex	South East England	379.9	2.9	4.7 (2.1 – 7.7)	4.5 (1.5 – 8.1)	4.4 (1.4 – 8.0)	6.6 (4.1 – 8.5)	7.2 (4.6 – 9.1)	6.9 (4.8 – 7.0)	8.2 (6.1 – 8.3)
East Yorkshire	Yorkshire and Humber	8.6	−2.1	1.1 (−3.6 – 5.1)	−0.2 (−4.1 – 4.3)	−0.4 (−4.3 – 4.1)	3.7 (0.1 – 6.7)	3.9 (0.3 – 6.9)	5.9 (2.8 – 7.5)	6.6 (3.4 – 8.2)
Essex	East of England	249.1	3.9	5.8 (3.4 – 8.2)	5.2 (2.4 – 8.3)	5.1 (2.4 – 8.2)	7.0 (4.8 – 8.5)	7.6 (5.3 – 9.1)	7.0 (5.4 – 7.0)	8.3 (6.6 – 8.2)
Gloucestershire	South West England	84.7	2.5	4.3 (0.4 – 7.5)	4.0 (0.7 – 7.9)	3.7 (0.5 – 7.6)	6.4 (3.6 – 8.6)	6.8 (4.0 – 9.0)	7.0 (4.6 – 7.6)	8.1 (5.7 – 8.7)
Hampshire	South East England	340.3	2.6	4.3 (0.8 – 7.8)	4.3 (1.1 – 8.1)	4.1 (1.0 – 8.0)	6.6 (3.9 – 8.7)	6.9 (4.2 – 9.1)	7.1 (4.8 – 7.4)	8.0 (5.7 – 8.3)
Herefordshire	West Midlands	31.0	1.8	3.6 (−0.7 – 6.9)	3.2 (−0.3 – 7.2)	3.0 (−0.5 – 7.0)	6.0 (2.9 – 8.4)	6.4 (3.4 – 8.8)	7.0 (4.4 – 7.9)	8.1 (5.5 – 9.0)
Hertfordshire	East of England	12.2	2.7	5.0 (2.0 – 8.1)	4.2 (1.0 – 7.8)	4.0 (0.9 – 7.7)	6.6 (3.9 – 8.5)	7.0 (4.3 – 9.0)	7.2 (5.0 – 7.4)	8.3 (6.1 – 8.5)
Isle of Wight	South East England	10.2	4.5	5.7 (3.5 – 7.8)	5.7 (3.4 – 8.5)	5.5 (3.2 – 8.3)	6.8 (4.9 – 8.0)	6.9 (5.1 – 8.1)	5.9 (4.6 – 5.4)	6.4 (5.1 – 5.9)
Kent	South East England	1012.9	3.4	5.2 (2.7 – 7.8)	4.9 (2.2 – 8.2)	4.8 (2.1 – 8.2)	6.9 (4.6 – 8.6)	7.6 (5.4 – 9.3)	7.0 (5.2 – 7.0)	8.6 (6.8 – 8.6)
Lincolnshire	East Midlands[d]	16.1	−0.2	2.8 (−1.0 – 6.6)	1.7 (−1.9 – 6.0)	1.6 (−2.1 – 5.8)	5.1 (1.9 – 7.8)	5.4 (2.2 – 8.1)	6.8 (4.0 – 8.0)	7.7 (4.8 – 8.8)
Monmouthshire	Wales	19.6	1.6	3.3 (−1.2 – 6.6)	2.8 (−0.8 – 7.0)	2.6 (−1.0 – 6.8)	5.6 (2.3 – 8.2)	5.9 (2.7 – 8.5)	6.7 (3.8 – 7.7)	7.6 (4.7 – 8.6)
Norfolk	East of England	52.0	2.4	4.8 (2.1 – 7.4)	3.9 (0.9 – 7.5)	3.8 (0.8 – 7.4)	6.3 (3.8 – 8.3)	6.9 (4.3 – 8.9)	7.0 (4.9 – 7.3)	8.3 (6.2 – 8.6)
North Yorkshire	Yorkshire and Humber[e]	10.7	−1.1	1.5 (−3.6 – 5.6)	0.7 (−3.3 – 5.1)	0.5 (−3.5 – 4.9)	4.3 (0.7 – 7.2)	4.4 (0.8 – 7.4)	6.3 (3.1 – 7.8)	6.8 (3.6 – 8.3)
Northamptonshire	East Midlands	14.4	0.4	3.3 (−1.0 – 7.4)	2.3 (−1.5 – 6.6)	2.2 (−1.6 – 6.4)	5.5 (2.2 – 8.2)	5.9 (2.6 – 8.5)	7.0 (4.2 – 8.0)	8.0 (5.1 – 9.0)
Nottinghamshire	East Midlands	9.0	1.7	4.0 (−0.1 – 7.6)	3.4 (−0.3 – 7.5)	3.2 (−0.5 – 7.3)	6.1 (2.9 – 8.7)	6.4 (3.2 – 8.9)	7.2 (4.5 – 8.1)	7.9 (5.3 – 8.9)
Oxfordshire	South East England	41.8	1.5	3.8 (−0.1 – 7.8)	3.4 (−0.1 – 7.4)	3.3 (−0.2 – 7.3)	6.3 (3.3 – 8.6)	6.9 (3.9 – 9.2)	7.3 (4.8 – 7.9)	8.7 (6.2 – 9.2)
Shropshire	West Midlands	18.5	−0.6	1.6 (−3.0 – 5.3)	1.0 (−3.1– 5.6)	0.7 (−3.3 – 5.4)	4.6 (1.0 – 7.6)	4.9 (1.2 – 7.9)	6.5 (3.3 – 7.9)	7.3 (4.0 – 8.7)
Somerset	South West England	19.9	1.9	3.7 (−0.4– 7.2)	3.4 (0.2 – 7.4)	3.1 (0.0 – 7.1)	5.9 (3.1 – 8.2)	6.2 (3.4 – 8.5)	6.7 (4.2 – 7.2)	7.6 (5.1 – 8.1)
Staffordshire	West Midlands	20.1	0.7	2.8 (−1.8 – 6.8)	2.2 (−1.8 – 6.6)	1.9 (−2.1 – 6.3)	5.4 (2.0 – 8.2)	5.8 (2.3 – 8.5)	6.9 (4.0 – 8.0)	7.9 (4.9 – 8.9)
Suffolk	East of England	48.8	2.9	5.1 (2.3 – 7.9)	4.3 (1.1 – 7.9)	4.2 (1.0 – 7.8)	6.6 (3.9 – 8.5)	7.1 (4.5 – 9.0)	7.1 (5.0 – 7.3)	8.4 (6.3 – 8.5)
Surrey	South East England	126.9	1.7	3.9 (0.5 – 7.9)	3.6 (0.2 – 7.6)	3.5 (0.1 – 7.5)	6.4 (3.4 – 8.7)	7.0 (4.0 – 9.3)	7.4 (4.8 – 7.8)	8.8 (6.3 – 9.3)
West Sussex	South East England	456.6	2.9	4.5 (1.3 – 7.8)	4.5 (1.4 – 8.4)	4.3 (1.2 – 8.2)	6.8 (4.0 – 8.9)	7.2 (4.4 – 9.3)	7.2 (4.9 – 7.4)	8.2 (5.9 – 8.5)
Wiltshire	South West England	31.8	1.2	3.3 (−0.8 – 7.3)	2.9 (−0.7 – 7.1)	2.6 (−1 – 6.8)	5.8 (2.6 – 8.3)	6.1 (2.9 – 8.6)	7 (4.3 – 7.8)	7.9 (5.1 – 8.6)
Worcestershire	West Midlands	23.3	3.5	4.9 (1.0 – 7.9)	4.7 (1.4 – 8.4)	4.5 (1.2 – 8.1)	6.8 (4.1 – 8.9)	7.2 (4.5 – 9.3)	7.1 (4.9 – 7.6)	8.2 (6.0 – 8.7)

◀ **TABLE 4.** Estimated mean vintage scores (1981–2000; 2010–2019; 2040–2059) and ranges (2010–2019 only; in parentheses) with estimated 10-year inter-annual variation (2040–2059 only; in parentheses) for Chardonnay still wine for the 30 UK counties with the largest areas of planted vineyards. Scores (out of 10, where 6.0–8.0 is *Good* and >8.0 *Excellent*) provided by the Chablis vintage model (Biss and Ellis, 2021) with historical weather records (1981–2000; 2010–2019), and projected climate change (2040-2059; RCP 4.5 at the 5th, 50th and 95th percentiles). Vintage scores for each of the 819 constituent vineyards are provided in Table S4.

[a] Figures in brackets for the RCP 4.5 projections are estimated 10-year inter-annual variation at an approximate 80 % confidence level, i.e., 1 in 10 years can be expected to be worse than the lower limit and 1 in 10 years above the upper value.

[b] Figures in brackets are the 2010–2019 range, from the lowest-scoring vintage (2012) to best scoring vintage (2018).

[c] For Essex, Kent, and Isle of Wight the mean and the upper limit have the same score, or the latter is lower than the mean score. This is because the warming for the upper limit of TmeanApr-Sep is so great that it exceeds the peak of the curvilinear relation, and so the regime is supra-optimal for quality.

[d] Parts of Lincolnshire are located in Yorkshire and Humber. However, all the vineyards in the dataset used here are found in the East Midlands.

[e] Parts of North Yorkshire are located in North East England. However, all the vineyards in the dataset used here are found in Yorkshire and Humber.

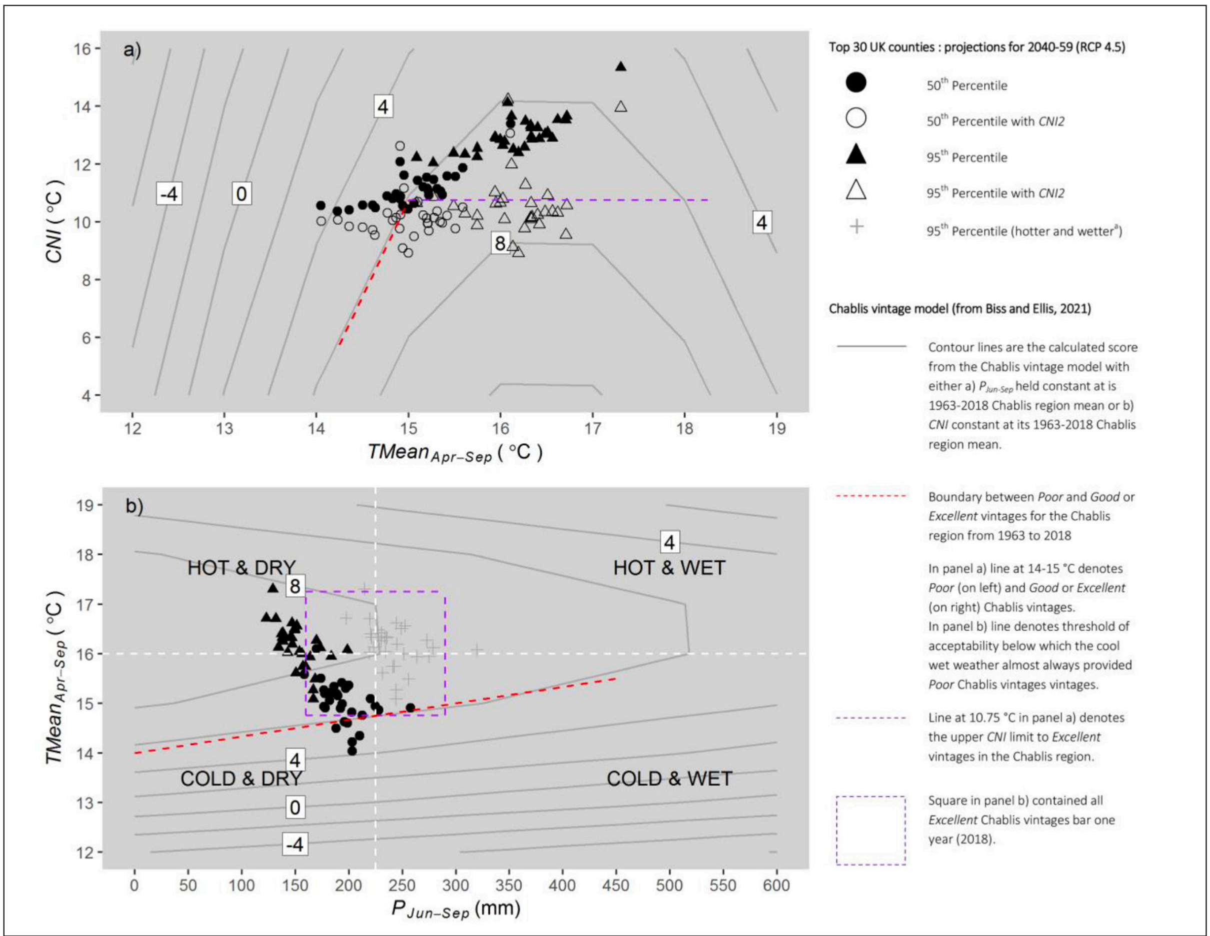

FIGURE 7. Comparison of climates between the top 30 UK counties (Table 4) in 2040–2059 and the Chablis region, France, from 1963 to 2018. Contours (vintage score) and dashed lines from Biss and Ellis (2021).

Alternative 95th percentile projection that assumes simultaneously hotter (95th percentile $Tmean_{Apr\text{-}Sep}$) and wetter (95th percentile $P_{Jun\text{-}Sep}$) summers, as opposed to the standard 95th percentile projection that assumes hotter (95th percentile $Tmean_{Apr\text{-}Sep}$) and drier summers (5th percentile $P_{Jun\text{-}Sep}$).

4. Medium-term projections for the UK in 2040–2059

4.1. 5th percentile projection

Under the RCP 4.5 5th percentile projections for 2040 to 2059, the vintage score estimates provided by the Model were similar to those presented in Figure 3b for the 2010–2019 period, with only 1.0 % of UK land area capable of producing *Good* Chardonnay wine (Table 3). Hence this projection is not described in detail.

The 5th percentile mean scores for the top 30 counties (by existing vineyard area) for 2040–2059 were all < 6, marginally lower than, or similar to, the 2010–2019 period (Table 4).

4.2. 50th percentile projection

Applying the median RCP 4.5 projections resulted in a considerable area of climatically-suitable UK land (20.7 % *Good*, 0.0 % *Excellent*) with the greatest potential vintage scores for Chardonnay still wine focused around the South East and East of England (Figure 6a).

The majority of existing vineyards from the top 30 counties provided *Good* Chardonnay wine in 2040–2059, narrowly missing or just clipping the boundary for producing *Excellent* Chardonnay wine because *CNI* was too high (solid circles, Figure 7a). Rainfall ($P_{Jun\text{-}Sep}$) was not a limiting factor to high vintage scores (solid circles, Figure 7b).

Eastern and South East England (especially Essex and Kent) had the most suitable climate for producing *Good* to *Excellent* Chardonnay wine (Table 4). However, areas of high-quality potential wine production were found throughout the South of England, Midlands and East of England, including some counties with relatively small areas of vineyard at present (as of November 2020), such as Buckinghamshire, Cambridgeshire, Hertfordshire, Suffolk, and Worcestershire.

The lower limit of the estimated 10-year inter-annual range was between 4.0 and 5.0 for most counties in South East England and East of England with currently large areas of planted vineyards (> 100 ha), namely East Sussex, Essex, Kent, and West Sussex (Table 4). All counties outside of South East England and East of England, except for Gloucestershire (3.6) and Somerset (3.1) in South West England and Worcestershire (4.1) in the West Midlands, provided a lower limit score below 3.0 (Table 4).

4.3. 95th percentile projection

The 95th percentile RCP 4.5 projections (Figure 6c,d) led to a substantial area of UK land with high-quality ratings (39.1 % *Good*, 0 % *Excellent*). There was a noticeable expansion over the median projection of areas predicted to produce high-quality wine, moving beyond the South East and East of England into the Midlands and parts of the South West (compare Figure 6c with 6a). Estimated vintage scores for the Isle of Wight (Table 4) and London (Figure 6), however, were noticeably lower than those provided by the median projection.

Existing vineyards (for the top 30 counties) were all warm and dry (solid triangles, Figure 7b), ideal for *Good* Chardonnay and, other than East Yorkshire and Isle of Wight, all the counties with large areas of vineyards currently provided scores that were at least *Good* (Table 4).

The lower limit of the 10-year range for the 95th percentile projection increased by between +0.6 and +2.7 over that for the 50th percentile (except Isle of Wight, which had a small reduction of -0.3 in the lower limit) (Table 4). Conversely, the upper limit of the range was generally reduced by between –0.2 and –1.5 for the 95th over the 50th percentile projections, except for Isle of Wight, which experienced a larger drop (–2.6) and the more northerly counties, which showed an increase in the upper limit (East Yorkshire (+0.8), Lincolnshire (+0.2), North Yorkshire (+0.6) and Shropshire (+0.3), Table 4). The overall effect is that the estimated 10-year inter-annual range for 25 of the 30 counties (98 % of the area of planted vines considered here) was narrower, with the worst vintages not being as poor and the best vintages not being as good for the 95th as the 50th percentile projection.

5. Medium-term projections for the UK in 2040–2059 with *CNI2*

If *CNI* were to continue to rise at a slower rate than $Tmean_{Apr\text{-}Sep}$, as generally occurred throughout the UK between 1981–2000 and 2010–2019 (Figure 2), then the vintage scores for the 50th percentile and 95th percentile would increase. Using the alternative projection for *CNI* (i.e., *CNI2*), which extrapolates the relationship between *TmeanApr-Sep* and *CNI* into 2040–2059 (see Method Section 2.3), the area of land deemed climatically suitable under the 50th percentile projection would be 24.8 % (up from 20.7 % with *CNI*) (Figure 6b).

The difference between applying *CNI* and *CNI2* showed great effect under the 95 % projection, with a mean difference in predicted mean scores of 1.0 compared to only 0.4 for the 50 % projection. High-quality vintage scores were provided for 42.4 % of the UK land area for 2040–2059 under *CNI2* (Figure 6d)*,* up from 39.1 % for *CNI* (Figure 6c), with *Excellent* scores when using *CNI2* (Figure 6d, 17.9 % of land area), but not *CNI* (Figure 6c, 0.0 %). Overall, the (cooler) *CNI2*-based projections showed greater potential for *Excellent* Chardonnay wine (open circles and triangles, Figure 7a). Of the top 30 counties with the largest area of vineyards (Table 4), 17 counties provided scores in the *Excellent* category when using *CNI2*-based projections, which were close to or below 10.75 °C (open triangles, Figure 7a).

The estimated 10-year inter-annual range shifted positively for both the 50th and 95th percentiles with CNI2 compared to CNI. *Excellent* scores were possible in all of the counties considered except for Cornwall, East Yorkshire, North Yorkshire and Shropshire for the 50th percentile with CNI2 and all counties except for Cornwall and the Isle of Wight for the 95th percentile with CNI2. Lower limit scores were equal to or above 4 for all counties of South East England (except Oxfordshire, 3.9) and East of England for the 50th percentile with CNI2. For the 95th percentile with CNI2, there was a general uplift in the lower limit, with many counties of South East England and East of England receiving *Good* lower limit scores between 6 and 7, including some counties that are not currently planted with large areas of vineyards (> 100 ha), namely Berkshire, Buckinghamshire, Cambridgeshire, Hertfordshire, Norfolk, Oxfordshire, and Suffolk (Table 4).

DISCUSSION

1. Assessing results and model performance against existing research

1.1. Historical periods

Though the amount of UK land area deemed capable of producing *Good* wine by the Model (Biss and Ellis, 2021) was generally lower (by 0.1 to 9.2 %) than that suggested by using the simple 14 °C GST threshold (Jones, 2006) for 1981–2000, 2010–2019, 2012 and 2018, the two methods produced similar distributions of land with suitable climates (compare Figures 3 and 4).

We maintain the Model has added value over the GST threshold approach in two regards. First, the scoring is continuous and not threshold-based, this being a more realistic assessment of viticultural suitability (Nesbitt *et al.*, 2018). Second, the Model is specific to the production of still Chardonnay wine. Moreover, a closer inspection of the distributions highlights some important differences. For example, 11.0 % of UK land (compared to only 1.8 % for the Model) is deemed capable of producing still Chardonnay wine for the 2010–2019 period on average according to the 14 °C GST threshold, with suitability concentrated in the South East and East of England, and along the Severn estuary. Even in the East of England (the region with the highest GST outside of London), GST was only just, on average, above 14 °C for the period (14.1 °C). Still Chardonnay wine requires berries grown under slightly warmer conditions than 14 °C, probably around 14.4 °C GST assuming a minimum threshold of 14.75 °C for $Tmean_{Apr\text{-}Sep}$ (approximate position of red dashed line to the right of solid circles cluster in Figure 4a). This value is based on the calculation that $Tmean_{Apr\text{-}Sep}$ is typically around 0.4 °C higher than the equivalent GST (the mean difference for 2010–2019 was 0.36 °C). Moreover, inter-annual variation would have resulted in many vintages being below the required GST threshold (see Discussion section 6). Certainly, very few major UK producers were making still Chardonnay wine until the 2018 vintage (Robinson, 2019).

The Model also produced similar results to that of Nesbitt *et al.* (2018) study for 1981-2010 with regard to the concentration of land suitability in Southern and Eastern England. Within that region, however, some differences are apparent. Their study considered the viticultural suitability of land in England and Wales from a yield perspective, combining both climate and terrestrial components (soils, land use and topography). Some key differences with the climate part of their suitability map are that their high suitability areas are i) concentrated along coastal areas and ii) stretch further south-westwards.

These differences may be accounted for by the fact that Nesbitt *et al.* (2018) were not considering still Chardonnay wine specifically, which arguably requires a greater continentality of climate to produce warm temperatures in the day but cool temperatures at night during ripening for high-quality wine. The coastal dominance of land suitability in their model, however, may arise from the component in their model that rewards i) lower inter-annual variability in GST and growing season precipitation and ii) fewer days of air frost (≤ 0 °C) in April and May since coastal areas tend to be less extreme than inland ones because of the moderating effect of coastal water and generally experience fewer frost days because of coastal breezes (Royal Meteorological Society, 2021).

The Model of Biss and Ellis (2021) used here complies with Nesbitt *et al.*'s argument that fuzzy membership is preferable to threshold values; a score between 0 and 10 is effectively a continuous way of measuring land suitability.

A potential strategy for finding land that is suitable for Chardonnay viticulture for still wine would be to overlay the maps presented here, which focus on still wine quality, with Nesbitt *et al.*'s (2018) suitability maps that focus on sustainable yields.

One implication of our findings, particularly considering inter-annual variability (Table 4), is that new vineyards planted henceforth in areas that are expected to be suitable for good-quality still Chardonnay wine in 2040–2059 could be planted with Chardonnay clones that can be used to produce sparkling wine (either as a blend or as a blanc de blanc) but will also work well for still wine in the future. For example, clones 75, 76, 95, 121, 131 and 548 are good for both types of wine (Skelton, 2020a). Moreover, it may be possible to use the May to July period to plan ahead within the year regarding whether to produce still or sparkling wine (Biss and Ellis, 2021).

1.2 Projections with climate change

Georgeson and Maslin (2017) projected forward to 2100 by applying known thresholds for GST, annual precipitation and harvest precipitation (October), using RCP 6.0 (+2.2 °C GST and +5.6 % increase in annual rainfall from 1981–2005) for several grapevine varieties, including Chardonnay. Their projection is comparable to the 95th percentile RCP 4.5 projection for 2040–2059 used in this study in terms of temperature increase (Table 2) though they assume a wetter season and harvest period. They concluded that large areas of the UK would be especially suitable for Chardonnay, but with a risk that current wine-producing areas in the South of England may become too wet or too warm for Chardonnay (and Pinot noir) and that the sparkling wine industry in the South of England may be threatened. They highlight that one limitation of their research is that the harvest may move forward into September.

Georgeson and Maslin's projections are broadly similar to ours for the 95th percentile RCP 4.5 projection in

Figure 6c,d, but in ours, the South of England provides a larger area of suitable land than Georgeson and Maslin. It is notable that the projections presented here are based on a reduction in $P_{Jun\text{-}Sep}$, but even with a 6 % increase rather than a decline, 95th percentile projections for 29 of the top 30 counties remain within the ideal range for $P_{Jun\text{-}Sep}$ and all 30 counties remain above the *Poor* threshold when compared to Chablis vintages from 1963 to 2018 (grey plusses, Figure 7b).

2. Uncertainties

Aside from the caveats associated with the Chablis vintage model (see Biss and Ellis, 2021), several well-documented sources of uncertainty exist in the projections presented in this study. These are the uncertainties associated with i) the RCP emissions scenarios and predicting which pathway will transpire (OECD, 2017), ii) the accuracy of climate models, particularly at the local and regional scale (Jacob *et al.*, 2014), and iii) the frequency and intensity of small-scale (spatial and temporal) extreme weather events (Harkness *et al.*, 2020; van Leeuwen and Darriet, 2016) that are not covered by the projections.

Note, however, that RCPs 2.6, 4.5 and 6.0 for the period of 2040 to 2059 are broadly similar in terms of their forcing effect on mean summer temperatures in England and Wales (Met Office, n.d.[b]), although RCP 4.5 has a marginally greater range between the 5th and 95th percentile probability projections (+0.3 to +3.2 °C compared to +0.5 to +3.1 °C RCP 2.6 and +0.3 to +3.0 RCP 6.0) and was thus chosen for this study to cover the largest range of possible outcomes.

The most extreme scenario, RCP 8.5, which assumes business-as-usual with regard to greenhouse gas emissions, was not studied. However, the median projection for RCP 8.5 (+2.3 °C projected rise in mean summer temperature for England and Wales) lies roughly halfway between the median (+1.7 °C) and 95th (+3.2 °C) percentile projections for RCP 4.5.

Another source of uncertainty particularly relevant to this study is how each of the three variables in the Chablis vintage model will change in relation to each other. The projections presented here for 2040–2059 assume that as $Tmean_{Apr\text{-}Sep}$ rises (from 5th to 50th to 95th percentile), precipitation will decrease. This is consistent with research that suggests Britain will have warmer and drier summers (Harkness *et al.*, 2020; Vinescapes, 2021). It is also consistent with the weak inverse relationship (r = -0.34) between $Tmean_{Apr\text{-}Sep}$ and $P_{Jun\text{-}Sep}$ *for* the 3000 model sample runs. Thus 95th percentile projections for $Tmean_{Apr\text{-}Sep}$ and *CNI* were used in conjunction with the 5th percentile projections for $P_{Jun\text{-}Sep}$, and vice versa. It is possible, however, that growing seasons will become hotter and wetter. Nonetheless, total precipitation from June to September seems unlikely to be a limiting factor, on average, to make good Chardonnay wine at the 95th percentile, even if precipitation levels were modelled the other way around (grey plusses, Figure 7b).

It is also the case that $Tmean_{Apr\text{-}Sep}$ and *CNI* may not move in the same direction or with the same magnitude from year to year. The 2018 vintage was notably hotter than the 2010–2019 average, yet its *CNI* remained below the 10.75 °C thresholds in all but two of the top 30 counties (Figure 4a). The 2018 UK vintage was exceptionally good (Olsen, 2021; WineGB, 2021), and the low *CNI* may have been an important driver of this.

Finally, whether *CNI* increases as projected by UKCP18 is also questionable. Our observation that *CNI* did not increase as uniformly (spatially) between 1981–2000 and 2010–2019 compared to $Tmean_{Apr\text{-}Sep}$ was checked against Met Office weather station data (Met Office, n.d.[c]) and substantially verified. A similar observation has also been made for Chablis, the Côte de Beaune and the Loire Valley regions in France (Biss and Ellis, 2021; Neethling *et al.*, 2012). Whether the observed relationship between $Tmean_{Apr\text{-}Sep}$ and *CNI* can be extrapolated into the future, as assumed with *CNI2*, is also uncertain, however, this may be highly relevant to future UK viticulture.

3. Is Chablis an appropriate analogy?

The Chablis region has traditionally been the most northerly producer of high-quality still Chardonnay wine at commercially significant levels, and this makes it an obvious candidate to act as an analogous roadmap for emerging English and Welsh Chardonnay viticulture as global warming shifts the viticulture suitability belt northwards. The fact that Southern England now has a similar climate to Champagne (Droulia and Charalampopoulos, 2022), and is consequently able to produce sparkling wine in the Champagne style, might suggest that continued warming will move Southern England towards a similar climate to that of Chablis, which is only around 140 and 160 km south of Épernay and Reims in Champagne, respectively.

The Chablis vintage model explained only 57.1 % of the variance (adjusted R^2) in Chablis vintage quality (Biss and Ellis, 2021), primarily because it is based on monthly data from only one weather station, so, therefore, may miss smaller-scale (temporally and spatially) but important weather events such as intense heat and hail, and because vintage scores are subjective and inexact. This level of explanatory power, however, is consistent with similar studies for other wine regions and cultivars, falling within the upper end of their explanatory range (35 to 60 %) (Biss and Ellis, 2021). The model also performed better in distinguishing *Poor* vintages from *Good* and *Excellent* vintages than between *Good* and *Excellent* vintages (Biss and Ellis, 2021).

When applied to the UK, the Model may suffer from "blind spots". For example, it may be that prior autumn and winter precipitation (not accounted for by the Model) may be more important for UK viticulture (or certain regions of the UK) than it is for the Chablis region, as is the case for the Bordeaux region (Byron and Ashenfelter, 1995). Moreover, the Model only goes to September, whereas the month of October may be crucial for UK viticulture, especially in the earlier years of the 2040–2059 period when phenology may not have yet advanced to the same extent as it has already in Chablis. The UK is an emerging wine region where temperatures are currently marginal, and harvests typically go well into October, versus the long-established Chablis region, where harvests typically occur from late August to September (Biss, 2020).

There are, of course, notable differences based on the geographic location of Chablis (differences in weather systems, continentality, length of day, etc.) and its viticultural history and terroir (most notably soil and its management, methods of wine production), and the relative experience and expertise of the two regions' wine producers. Chablis is a small region of dedicated viticulturists sharing similar geology and soils (notwithstanding the Kimmeridgian marl / Portlandian limestone distinction), climate, and history of winemaking (Biss, 2020). Vineyards in the UK, on the other hand, are dispersed widely (Figure 1) across diverse soil types. Hence, future good UK Chardonnay still wines will likely differ in typicity amongst vineyards without the common terroir and standards of, for example, Chablis. Moreover, no attempt has been made to compare the clones and rootstocks used in Chablis to those that are (or will be) used in the UK.

Despite these obvious shortcomings, the Chablis region remains the closest and most appropriate analogy for UK Chardonnay still wine production. Using model variables that are calculated only to the end of September ($Tmean_{Apr\text{-}Sep}$, *CNI* and $P_{Jun\text{-}Sep}$) also ensures the utility of the Chablis vintage model to compare both regions and provides an approach that will be valid for the UK in future as phenology advances towards grape harvests beginning before October.

4. The importance of *CNI*

A fundamental characteristic of Chablis wine is its minerality and acidity (George, 2007; Ballester *et al.*, 2013). Cool night-time temperatures during ripening (as assessed by *CNI*) are thought crucial to maintaining acidity (Arrizabalaga-Arriazu *et al.*, 2020) and possibly also minerality (Ballester *et al.*, 2013). Moreover, these characteristics are generally associated with high-quality Chardonnay still wine produced elsewhere (Tonietto and Carbonneau, 2004), albeit perhaps not at the same acidity or minerality levels as Chablis. Thus, the Chablis vintage model used here to predict UK site suitability assumes that Chardonnay produced in the UK will also need to have these high levels of acidity to produce *Excellent* wine. In this regard, we suggest that the well-recognised good and excellent Chardonnay still wine vintage produced in 2018 by many UK vineyards was not just due to the warmer than average spring/summer ($Tmean_{Apr\text{-}Sep}$ 1.6 ° C warmer than 1981–2000 mean) but also the cooler than average *CNI* (0.3 °C cooler; Results, section 1.1). However, the style of wine produced in the UK may, in fact, be different without necessarily impacting consumers' perception of its quality, perhaps with acidity levels not quite as high as Chablis. For example, *CNI* in the Côte de Beaune, also in Burgundy, is typically 1.8 to 2.0 °C higher than in Chablis (Biss and Ellis, 2021), yet the Côte de Beaune is world-famous for the quality of its white wines, such as Corton-Charlemagne, Meursault and Puligny-Montrachet. This would be positive for UK wine, perhaps pushing areas with *Good* scores into higher, possibly *Excellent* scores if evaluated against such other wines.

5. Improving projections and further research

To further hone UK site identification, topography and soils should also be considered. Continuing the Chablis analogy, it should be possible to use soil and topography data from the study of Chablis (Biss, 2020) and apply it in threshold or fuzzy membership form (as used by Nesbitt *et al.*, 2018). Ideally, the impact of increased CO_2 (Arrizabalaga-Arriazu *et al.*, 2020; Kizildeniz *et al.*, 2018; Santos *et al.*, 2020) should also be factored into the model. Although it is known that the previous season's weather can affect grape yield (Molitor and Keller, 2016; Zhu *et al.*, 2020), it is not yet known if there is any effect on quality; this might also be considered.

6. Inter-annual variation

One of the biggest issues for the viability of UK viticulture is inter-annual variability in yields (Nesbitt *et al.*, 2018). The move from German to predominantly French grapevine varieties (Chardonnay, Pinot noir and Pinot meunier) has made UK viticulture more vulnerable (Nesbitt *et al.*, 2018) because the UK climate is currently marginal for these French varieties, especially for still wine, which requires berries that are properly ripe, compared to sparkling where they are only used barely ripe (Clarke, 2020).

As such, an increase in GST (or $Tmean_{Apr\text{-}Sep}$) from now until 2040–2059 should result in improved wine quality, greater yields, *and* lower sensitivity to interannual variation, at least until GST rises above the ideal curvilinear peak value for Chardonnay (Jones *et al.*, 2005; Kurtural and Gambetta, 2021).

The estimated 10-year inter-annual variations in the vintage score are considerable (Table 4), especially for the 5th and 50th percentile projections. This problem is least in the counties of South East England and East of England that currently have the largest areas of vineyard. Moreover, these estimates of variation are not especially greater than that experienced in the Chablis region, specifically 3.0 to 8.5 for 1970 to 1979, 4.5 to 8.5 for 1980 to 1989, 5.5 to 10.0 for 1990 to 1999, and 6.1 to 9 for 2000 to 2009 (Table S1 in Biss and Ellis, 2021).

The lower limit of this range matters more. It represents the threshold to begin still Chardonnay viticulture. In contrast, upper limit scores may drop off with increased $Tmean_{Apr\text{-}Sep}$, but the wines may still be of high quality, albeit of a warmer-climate Chardonnay style of wine (as would occur in London and the Isle of Wight with the 95th percentile projections (Figure 6c,d)). In this regard, Essex, Kent and the Isle of Wight provide the greatest opportunity for still Chardonnay wine production under the median projection, extending to the rest of South East England, and parts of East of England, East Midlands, South West England and West Midlands under the 95th percentile projection (Table 4).

None of the above, however, addresses the yield concerns related to i) advancing phenology that will bring budbreak into more frost-prone periods (Leolini *et al.*, 2018; van Leeuwen and Darriet, 2016), ii) the predicted increased frequency of hail and heavy rain (van Leeuwen and Darriet, 2016; Di Carlo *et al*., 2019), iii) decadal-scale cold waves (Sgubin *et al.*, 2019), or iv) changes in patterns of viral and fungal infection (Rienth *et al.*, 2021). Frost risk has never been entirely mitigated and remains even in established wine regions such as Chablis, but siting vineyards in areas where frost is least expected and appropriate management can help (Skelton, 2020a). Research on reducing damage from frost would benefit viticulturalists across all cool climate regions.

Intense and short-lived periods of heat and sunshine may also negatively impact yields (Kennedy-Asser *et al.*, 2021; Webb *et al.*, 2009) and berry quality (van Leeuwen *et al.*, 2019), and the effect of such periods are not accounted for in the projections, even though their occurrence can be expected to increase, especially for the 95th percentile projection.

CONCLUSIONS

This study suggests:

1. The production of high-quality Chardonnay still wine was rarely possible throughout most of the UK in recent times (1981–2000 and 2010–2019). This would remain to be the case under the 5th percentile projection for climate change (RCP 4.5).

2. Considerable areas of England and Wales, particularly the South East, East of England, and Central England, should be able to produce high-quality still Chardonnay wine, on average, in 2040–2059, with the 50th and 95th percentile projections for climate change (RCP 4.5).

3. The average climate in 2040–2059 (RCP 4.5, 50th percentile projections) should be sufficiently above the threshold for Chardonnay viticulture to allow ripening even in relatively cool years in the South East and East of England, especially Essex, Kent, and the Isle of Wight, extending to Central England under the 95th percentile projection, provided inter-annual variation remains similar to, or less than, recent times.

4. If *CNI* rises less than that projected by UKCP18 and instead continues along its current path (*CNI2*), the potential quality of wine may increase further.

Aside from the uncertainties associated with emissions scenarios and climate projections, further uncertainty arises from i) generalisations and inaccuracies with the Chablis vintage model, ii) the extent to which the Model can be applied to the UK, iii) the effect of soil type on the quality of UK Chardonnay still wines and iv) how climate change will affect the incidence of frost, intense small-scale weather events and the transmission of fungal and viral disease, none of which are modelled here.

More generally, beyond its application to the UK and despite the abovementioned caveats, the Chablis vintage model provides an approximate tool for locating sites with suitable climates for Chardonnay viticulture for the purpose of producing still white wine.

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Chapter 4. Preface

Chapter 4 comprises the following research paper:

Title: Minerality in Wine: Textual Analysis of Chablis Premier Cru Tasting Notes

Authors: Alex J. Biss and Richard H. Ellis

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Author Contribution: This paper was co-authored with Professor Richard H. Ellis. The research design, data analysis, and manuscript drafting were carried out by Alex Biss. Professor Ellis contributed to method development and manuscript editing.

Relevance to Thesis: This chapter addresses Objective C of the thesis by asking whether "minerality", a key high-quality characteristic of Chablis wine, is related to weather or to other aspects of "terroir". If minerality in Chablis wine is solely, or largely, dependent on weather, this would leave open the possibility that Chardonnay still wine production in the UK could approach the quality and characteristics of wines from Chablis as climate change progresses.

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Research Article

Minerality in Wine: Textual Analysis of Chablis Premier Cru Tasting Notes

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The term minerality is often used to describe high-quality still white wines produced in cooler regions, such as Chablis. What minerality means in sensory terms and what is responsible for its presence is the subject of debate, however. This study explored the concept of minerality by analysing 16,542 Chablis Premier Cru tasting notes entered into CellarTracker between 2003 and 2022 on wines three to seven years old, together with weather, topography, and soil data for the Chablis area. The top three words used to describe Chablis Premier Cru wine were citrus, minerality, and acidity. Mentions of minerality declined between 1999 and 2019 vintages, whereas those of acidity, salinity, floral, orchard fruit, and stone fruit increased. The trends for minerality and salinity were slightly stronger with the year of tasting (2005 to 2022) than vintage. Bigram analysis indicated that consumers were more than 1.5 times as likely to refer to a stony kind of minerality as a saline one and only rarely smoky minerality. Use of the term minerality was correlated with growing season temperature and sunshine hours (negatively with each), as well as vineyard aspect (negatively with percentage vineyard area facing South or South-West), but not with Kimmeridgian soil type. The results imply that soils and geology are not a principal source of minerality in Chablis wine, but growing season warmth and sunshine are relevant to minerality. There is no simple explanation of minerality in Chablis wine; however, the recent decline in the use of this term for Chablis wine may be a consequence of three factors in combination: (i) it has become less fashionable; (ii) consumers are choosing "saline" instead of "mineral" when appropriate, but retaining it for "stony" sensations; and/or (iii) warming from climate change has reduced minerality.

1. Introduction

"Minerality" is a wine descriptor that was reportedly first mentioned in the French wine lexicon (as "minéralité") in 1988 [1] and which gained popularity among wine professionals and consumers from around 2000 [2]. It has been the centre of considerable debate by sensory researchers [3] and wine market participants who question what it is, what causes it, and whether it is a discrete wine characteristic. It is typically used as a sensory descriptor for still dry white wine from cool climate viticulture regions [4] and has been variously profiled as gunflint, wet stones, and/or seashells (amongst many descriptors), possibly with three or more subdimensions [5–7], although it remains unclear whether it is perceived as an aroma, taste, mouthfeel, or combination of these [3, 5, 7]. Wines with perceived minerality may also be said to be "mineral" or "minerally."

Producers, merchants, and critics regularly refer to minerality as a defining high-quality characteristic of wine [3, 5] and make connections between its presence and the "terroir" of the region or vineyard in which the wine is produced [8–10]. The suggestion is that the inorganic components of an area's geology and soil can be sensed in its wine by virtue of a wine's "minerality," although this literal understanding of the term has since been disputed in the academic literature [2, 3, 11]. Even so, the term still continues to be used in this way by many winemakers, merchants, and consumers [12, 13]. Some go further by describing, for example, a "gravelly" or "chalky" minerality in accordance with the geology of the wine region [6].

The counterargument to this is that minerality is used metaphorically; no one is tasting rock minerals in wine (as opposed to elemental minerals such as sodium), but there are characteristics of a wine that remind consumers of certain sensations [13]. Unlike most other descriptors, however, no compound, or combination of compounds, has been unequivocally associated with minerality, in a way that rotundone and isoamyl acetate, for example, have been associated with “peppery” [14] and “banana” [15, 16] characteristics, respectively.

Minerality in wine is often associated with acidity [5, 6, 17], although whether this is because cool climate wines tend to be both distinctly acidic and mineral, or whether minerality and acidity are different ways of describing a similar sensation, or whether the acidity is a subdimension of minerality [17], is unclear. Of the several types of acidity present in wine, succinic acid is said to be intense, salty, and bitter [6] and could potentially be responsible for minerality [3, 8]. Minor acids, such as octanoic acid, have also been associated with minerality [18]. The other major acids, however, are perhaps less likely to be confused with minerality—tartaric (“hard”), malic (“green”), citric (“fresh”), lactic (“lightly acid, tart, and sour”), and acetic (“vinegary”) [6]. Wine notes, however, rarely distinguish between different types of acidity.

Some have suggested that minerality is perceived in wine when there is a lack of fruit and floral aromas and flavours [5, 6, 19], though this possibly excludes citrus fruit characteristics which are often associated with minerality [3]. Anecdotally this makes some sense, as Chardonnay wines from warmer climates tend towards the stone and tropical fruit aromas and flavours, and less mineral [3].

Rodrigues et al. [17] found that some producers think minerality can be masked by winemaking practices. These include oak barrel fermentation and ageing (particularly with new oak), contact with sediment (lees; primarily dead yeast cells) through ageing on lees or batonnage (stirring lees into wine), and/or malolactic fermentation (a process that converts the harsh malic acid to the softer lactic acid). In other words, the strong aromas, flavours, and/or textures associated with these vinification practices could mask the expression of minerality in wine (though some respondents in Rodrigues et al.’s study thought that lees contact kept the wine in a moderately reduced state and thus was good for minerality).

One hypothesis gaining more traction is that minerality comes from reductive wine-making and storage processes that produce or maintain sulphurous compounds, but not enough to spoil the wine with off flavours [4, 20, 21]. For example, insufficient yeast assimilable nitrogen (YAN) in wine must can lead to the production of more permanent sulphur compounds (such as methionol) as opposed to the highly volatile forms (such as hydrogen sulphide, ethanethiol, and methanethiol) that have low boiling points and volatilise when a bottle of wine is aerated [20]. Insufficient YAN can also result in the production of hydrogen sulphide at a later stage of fermentation when it is less likely to be purged [22]. The increased use of stainless steel vats for fermentation and increased use of synthetic cork and screw cap bottle closure systems in cool climate wine regions, which reduce oxygen permeability into the wine compared to the use of oak barrels and traditional cork closure systems respectively, are also consistent with the simultaneous rise of minerality since around 2000 [3].

Certain sulphurous compounds may produce reductive off-aromas or more desirable minerality-related traits depending on their concentration levels and what other compounds they are present with. It may be that hydrogen disulfane, for example, a polysulfane which generally produces eggy and sewage-like aromas, produces instead a flint-like aroma when smelt in isolation [4]. Similarly, other sulphur compounds can contribute to aromas that have been associated with minerality, such as methaniol for shellfish-related aromas [19] and benzyl mercaptan [23] and benzenemethanethiol [24] for “empyreumatic” (smoky) characteristics.

A major difficulty is that agreement has not been reached on what minerality is in terms of its sensory profile [25] or, equally problematic, that the sensations referenced are too numerous. Minerality remains an ill-defined concept [5, 21]. Nonetheless, most wine professionals and consumers maintain it is a real and distinct sensation, for example, Szymanski [13].

Chablis is a wine known for its mineral flavours [5, 13, 26] and is thus an excellent test case for the concept of minerality [17, 19, 27]. Chablis typicity is said to come from its unique terroir. The natural terroir features that are most often used to explain the typicity of Chablis wines are (i) its weather, primarily a function of its relatively northerly latitude (for Chardonnay) and semicontinental position [26]; (ii) its Kimmeridgian geology and associated soils [28]; and (iii) its topography and associated microclimate [29].

This paper uses text analyses to explore Chablis Premier Cru tasting notes in CellarTracker, a crowd-sourced database of wine-tasting notes. It looks at how “minerality” has been used as a wine descriptor since CellarTracker was created in 2003 and whether there are any trends in its usage since that time. The paper goes on to explore associations between minerality and other wine characteristics, such as acidity. Finally, an attempt is made to relate minerality to vintage weather, topography, and soil type. The overall aim is to understand whether any existing theories for the source of minerality are borne out by wine notes in the CellarTracker database. This includes testing the following hypotheses:

(1) Minerality is associated with the following flavours, aromas, and/or textures: acidity (positive) [5]; shellfish (positive) [19]; reduction (positive) [4–6, 21]; fruit and floral (negative) [19]; oak (negative) [17]

(2) Minerality is not associated with geology and soils [2]

(3) Minerality is positively associated with cooler vintage weather [4]

(4) Minerality is more positively associated with South-East and Eastern facing slopes than South and South-West slopes [19]

(5) Chablis wines from the left side of the river Serein exhibit higher levels of minerality than those from the right side [19]

We also consider whether textual analysis of CellarTracker notes can be used to increase understanding of minerality. Substantial research combining sensory panels with chemical analyses of wines has investigated the concept of minerality, which led to some of the hypotheses for minerality discussed above (including Ballester et al. [5]; Baroň and Fiala [8]; Heymann et al. [6]; Zaldívar Santamaría et al. [25]). Malfeito-Ferreira [3], however, states that consumers' perception of minerality has been relatively little studied. The examination here of a large body of wine-tasting notes from consumers aims to redress that balance and confirm, or not, if some of the explanations provided previously are consistent with Chablis Premier Cru wine, probably the most famous mineral wine.

2. Materials and Methods

2.1. Study Area. The Chablis wine region is located in the department of Yonne, in the northern part of Burgundy, France (Figure 1). The vineyards are within a relatively compact area (approximately 16 km (North-South) by 18 km (East-West) centred around the town of Chablis (latitude 47°48′49″N, longitude 3°47′54″E, 140 metres above sea level). The topography is hilly, rising to around 320 metres, and the vineyards lie on both sides of the river Serein which runs broadly North-South through the area. Chablis wines are produced from Chardonnay grapes only and are divided into four appellation d'origine contrôlée (AOC). In decreasing order of quality recognition, these are Chablis Grand Cru, Chablis Premier Cru, Chablis, and Petit Chablis. The Grand Cru and Premier Cru appellations are divided into 7 and 40 vineyard areas, respectively, called "Climats" (Figure 1). The 40 Premier Cru Climats are grouped into 17 larger principal Climats (Supplementary Table S1).

For the purposes of this study, only Chablis Premier Cru wine was analysed. Chablis Premier Cru is widely regarded as the AOC that produces the most typical Chablis wine [32]. Moreover, Chablis Premier Cru vineyards are planted on both sides of the river Serein and provide the opportunity to test the effect of topography on minerality [19, 30]. By contrast, Grand Cru Chablis vineyards are located in a much smaller area concentrated on the eastern side of the river ("right bank"), close to the town, with a predominantly South-West aspect (Figure 1). They produce less than one-eighth the amount of wine as the Chablis Premier Cru AOC [32], resulting in considerably fewer tasting notes. Chablis and Petit Chablis AOC wines rarely state which vineyards their grapes come from and were therefore unsuitable for this study.

2.2. Tasting Notes. Wine tasting notes for Chablis Premier Cru wines were extracted from CellarTracker (https://www.cellartracker.com), an online crowd-sourced database of tasting reviews that was created in 2003 and publicly launched in 2004 [33]. Of the 29,999 Chablis Premier Cru tasting notes entered into CellarTracker on 31 August 2022, 27,672 notes were written in English and selected for analysis.

The mean age of Chablis Premier Cru wine tasted by its contributors increased from 4.3 yrs in 2003 to 7.3 yrs in 2022 (Supplementary Figure S1, red line). This trend was controlled for by limiting the wine notes analysed to wines between 3 and 7 years in age (Supplementary Figure S1, black line). This is also the peak drinking window for Chablis Premier Cru wine [32]. A larger drinking window of between 3 and 10 years, which some commentators may argue is more appropriate [34], would still have left an upward trend in the data (Supplementary Figure S1, blue line). There were a total of 16,542 English-language tasting notes within the 3- to 7-year age range.

The 16,542 tasting notes were then grouped and analysed by (i) vintage year (1999–2019), (ii) tasting year (2005–2022, i.e. excluding earlier years with insufficient tasting notes), and (iii) principal Climat (14 Climats, i.e., 17 minus three with insufficient tasting notes—Berdiot, Chaume de Talvat and Côte de Vaubarousse) (Supplementary Figure S2).

Though the tasting notes related to vintages as far back as 1995, over 99.7% of them were for vintages from 1999 to 2019. Supplementary Table S2 and Figure S3 provide further details on the database, including the numbers of distinct tasters, distinct wines, tasting notes per vintage, tasting notes per age of wine when tasted, and tasting notes per principal Climat.

Most contributors to CellarTracker are amateurs, from different backgrounds, with different levels of tasting experience. They are also mostly from North America and northern Europe [30]. These factors may have a cultural influence on how the wines are reviewed [35, 36] and how minerality is perceived [7, 9]. Nonetheless, CellarTracker is the largest consumer-submitted database of wine ratings in the world [37] and the closest thing available to a market judgement for wines, especially for wines that do not have a traded secondary market. It offers a large sample size of tasting notes from enthusiastic wine consumers who wrote their notes unprompted by academic study. The data are, therefore, free from response biases [38] and can be usefully employed for identifying associations and testing hypotheses about the sensory profile of minerality in wine and its causes.

2.3. Text Analyses, Indices, and Statistics

2.3.1. Organising Tasting Note Words into Wine Descriptor Groups. Tasting notes were tokenized into separate words according to the method described by Silge and Robinson [39]. The words were then organised into groups that were appropriate for describing white wine (Supplementary Figure S4), based on a survey of online and academic sources (e.g., Ballester et al. [5]; BIVB [40, 41]; Iobbi et al. [42]; Miquel [43]; Espinase Nandorfy et al. [21]; Seal [44]; Wine Folly [45]). Derivatives and common misspellings of each

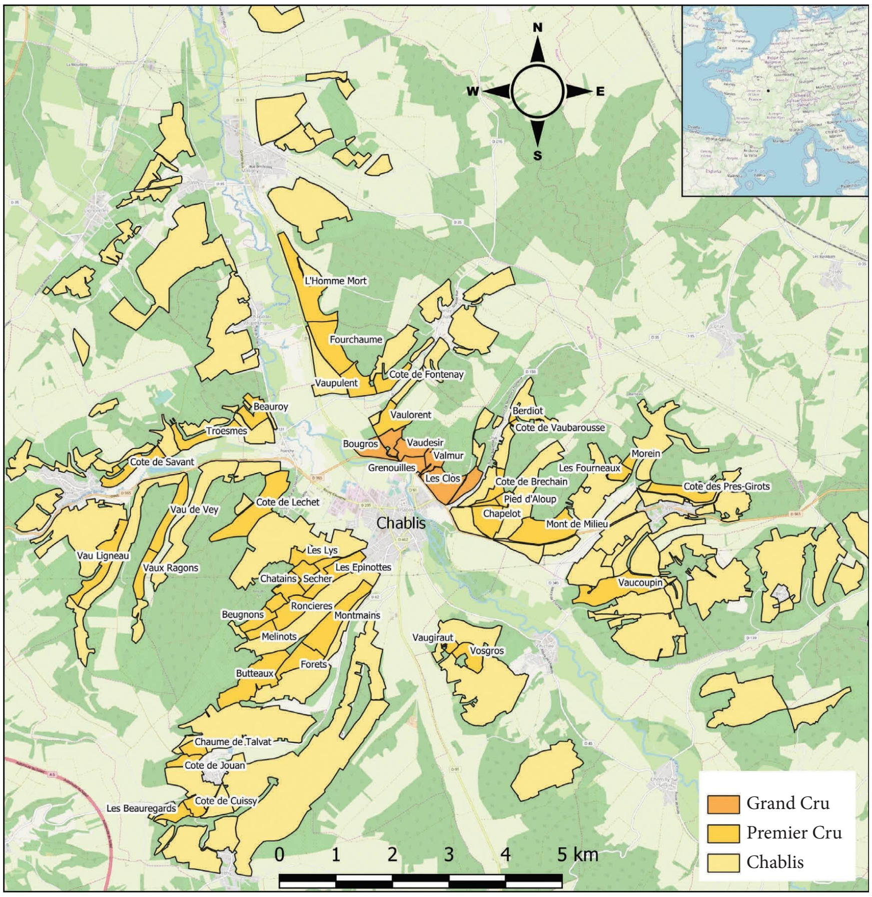


Figure 1: Map of study area showing the location of vineyards for the three main appellation d'origine contrôlée (AOC) of Chablis: Chablis Grand Cru (dark orange), Chablis Premier Cru (orange), and Chablis (yellow) (also referred to as "Village Chablis") from Biss [30] and Bureau Interprofessionnel des Vins de Bourgogne (BIVB) [31].

component word were included; for example, "lemon", "lemony", and "lemoney" were all allocated to the citrus word group (see Supplementary Table S3 for a detailed breakdown of each group).

Some words required clarification using a bigram (two consecutive words) before they could be allocated to the correct group. For example, the word "stone" may refer to a large pebble or if followed directly by the word "fruit" would instead refer to aromas and flavours of apricot, nectarine, or peach.

In a similar vein to Ballester et al. [5] three sub-dimensions, the official website for marketing Chablis wine says there are three categories to describe minerality: "ocean," "land," and "smoke" [40]. Their ocean category includes salty aromas and flavours such as iodine, "ocean spray," "fresh oyster," and "inside of a shell"; their smoke category includes terms such as sulphur and "freshly struck match"; and their land category includes chalk, limestone, flint, wet stone, and "rain on warm ground" (perhaps alluding to the aromas of petrichor). These categories were used for bigram analysis of the word "minerality" in order to investigate if a word before a mineral word specified what kind of minerality the taster was referring to, such as chalky minerality. Interestingly, BIVB's land category includes gunpowder and gunflint, which we instead included in the smoke category based on an understanding of its sensory perception in the literature [4, 21, 24]. This reclassification, however, had a negligible impact on the results (Supplementary Figure S5).

No distinction was made between aroma (nose), flavour (palate), and texture (mouthfeel) given the inconsistency with which CellarTracker users noted these distinctions. Some issues were difficult to automate and require manual oversight. For example, the word "oysters" could be referring to the oyster shell flavours of a wine or a food pairing.

2.3.2. Negations. Each word belonging to a descriptive group was checked for a negation word up to four words before and four words after it. For example, "none of the Chablis minerality I expect" would be identified because of the words "none" and "minerality" in positions 1 and 5, respectively. These lists were produced in R but checked manually, and a score of 0, −0.5, or −1 was ascribed dependent on whether the negation was invalid (e.g., "no lemon but minerality is there"), partial (e.g., "not quite the minerality of 2002"), or total (e.g., "none of that classic minerality"), respectively.

2.3.3. Creating the Indices. An index value was calculated for each descriptive group (for each vintage, tasting year and Climat) by applying the following rules:

(i) An occurrence comprised at least one mention of the characteristic. Repeated mentions within the same wine note of any words within the descriptive group were only counted once. For example, "Excellent wine. Lemon and lime aromas, good salinity and minerality." would register +1 for each of the citrus, saline, and minerality word groups.

(ii) An occurrence was deducted or halved depending on whether the characteristic was said to be negated/missing/very low (deducted in full) or low/less than it should be/less than expected (halved) (see above).

(iii) For the dataset sorted by tasting year, there were no deductions, however. This dataset was used to discover whether some descriptive terms had become more or less fashionable, in which case it did not matter whether a contributor was using the term to indicate the presence or not of an aroma, flavour, or texture.

(iv) The number of occurrences for each descriptive group (less negation) was summed by (i) vintage, (ii) tasting year, and (iii) Climat and expressed as a proportion of the total number of tasting notes in that vintage, tasting year, or Climat. This gave an index number from 0 to 1, where 0.5 was equivalent to 50% of tasting notes.

2.4. Soils. Soil data were taken from Biss [30]. The Chablis vineyards are distributed over eight cartographic soil units [Unités Cartographique de Sol (UCS)]. Each comprises between three and ten different soil types (Unites Typologique de Sols). The unit of most importance to this study is UCS n_30 (UCS30). It is associated with the Kimmeridgian slopes which are considered a key characteristic of the Chablis terroir and so relevant to these wines' mineral character [32, 41]. The proportion of UCS30 soil in the principal Premier Cru Climats varied from 0 to 100 [30].

2.5. Topography. Topographic data for the principal Chablis Premier Cru Climats were taken from Biss [30]. This comprised the following variables: aspect, slope gradient, elevation, and relative elevation. Relative elevation, the magnitude of one cell's elevation in relation to the cells around it, was calculated according to Goings [46].

2.6. Chablis Vintage Weather. Weather data for the Chablis region were obtained from the French meteorological service, Météo-France, using the procedures outlined by Biss and Ellis [47]. Climate indices typically used for viticulture were then derived. These included mean growing season temperature (GST) [48]; the cool night index (CNI), which in the Northern Hemisphere is the mean minimum temperature for September [49]; and precipitation during veraison and/or ripening [50–52]. Most weather data were from the Chablis weather station (number 89068001, latitude 47°49′19″N, longitude 3°47′26″E, elevation 141 m just outside the town of Chablis). The exception was sunshine data, which was merged from two weather stations in Auxerre, about 19 km west of Chablis: Auxerre (latitude 47°48′05″N, longitude 3°32′43″E, elevation 207 m, and Auxerre–Perrigny (latitude 47°49′28″N, longitude 3°32′58″E, elevation 152 m).

2.7. Statistics and Tools. We used R/R Studio (version 1.3.1093) for textual analyses (using the tidytext package), statistical analyses and data visualisation, and ArcGIS 10.4.1 (ArcGIS) (Esri, Woodlands, CA, USA) for mapping and spatial analysis. The Bonferroni correction was applied for multiple correlations where stated. This correction method is conservative [53]; i.e., it is good for screening out false positives and controlling the family-wise error rate [54] but can result in a high rate of false negatives. Spearman's rank was preferred to Pearson correlation throughout the study as some variables under investigation failed normality tests.

3. Results

3.1. Trends in Minerality and Other Wine Characteristics

3.1.1. By Vintage. The top three word groups used to describe the flavours and aromas of Chablis Premier Cru wine were citrus, minerality, and acidity (Table 1). While these word groups dominated wine-tasting notes for vintages from 1999 to 2019 (Table 1), orchard fruit aromas and flavours more than doubled in mentions over this period of vintages are from 0.12 to 0.31 (Figure 2, Table 1). Acidity, stone fruit, and floral notes also trended upward significantly (Figure 2, Table 1).

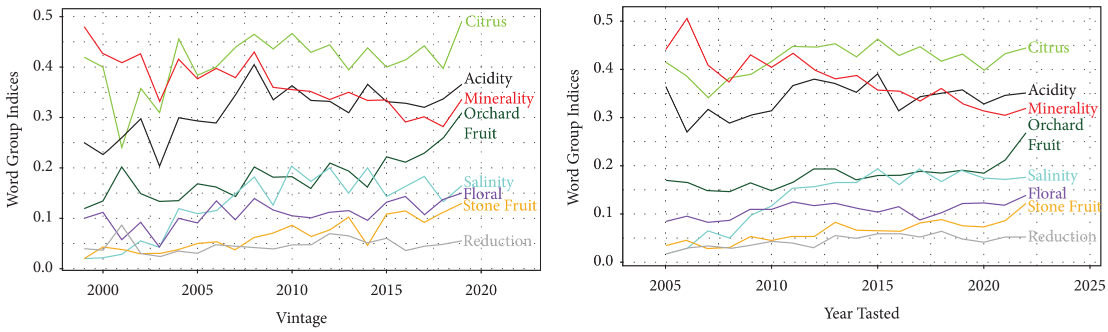
The minerality word group decreased by an average of 0.007 per year between the 1999 and 2019 vintages, equivalent to a total fall of 0.14 in the index (Figure 2, Table 1). None of the other word groups, including the potential minerality-related word groups (reduction, salinity, shellfish, and stony), experienced a similar statistically significant decline with vintage (Figure 2, Table 1); in fact, the saline word group increased over the same vintage period by 0.15 (Figure 2, Table 1).

3.1.2. By Year Tasted. Similar (though smoother) trends were found when these word groups were plotted against tasting year instead of vintage (Figure 2, Table 1). The trends

Table 1: Median, interquartile range (IQR), and linear trend in word groups used to describe Chablis Premier Cru wine in CellarTracker tasting notes against vintage (1999 to 2019) and tasting year (2005 to 2022). Word groups in bold exhibited linear trends that were significant at the p < 0.05 level with Bonferroni correction, i.e., (0.05/14). The word group indices range in value from 0 (zero presence) to 1 (found in 100% of all tasting notes); thus, a slope of 0.01 is effectively a 1% increase per year of the word group in absolute terms. All wines were between 3 and 7 years of age when tasted.

	Vintage (1999 to 2019)						Tasting year (2005 to 2022)					
	Median	IQR	Slope	SE	R^2	p	Median	IQR	Slope	SE	R^2	p
Acidity	**0.33**	**0.04**	**0.0053**	**0.0013**	**0.45**	**<0.001**	0.35	0.05	0.0023	0.0014	0.14	0.129
Citrus	0.42	0.05	0.0043	0.0018	0.22	0.030	0.43	0.04	0.0030	0.0013	0.26	0.031
Floral	**0.11**	**0.04**	**0.0026**	**0.0008**	**0.37**	**0.003**	0.11	0.02	0.0019	0.0006	0.40	0.005
Lees	0.04	0.01	−0.0005	0.0005	0.04	0.364	0.04	0.01	−0.0005	0.0005	0.05	0.394
Minerality	**0.36**	**0.07**	**−0.0070**	**0.0010**	**0.70**	**<0.001**	**0.38**	**0.07**	**−0.0087**	**0.0011**	**0.79**	**<0.001**
MLF	0.14	0.04	−0.0011	0.0013	0.04	0.404	0.13	0.02	−0.0002	0.0009	0.00	0.800
Oak	0.11	0.03	−0.0026	0.0011	0.23	0.028	0.12	0.02	−0.0014	0.0006	0.29	0.021
Orchard fruit	**0.18**	**0.06**	**0.0060**	**0.0010**	**0.63**	**<0.001**	**0.18**	**0.02**	**0.0039**	**0.0009**	**0.55**	**<0.001**
Reduction[a]	0.04	0.01	0.0006	0.0005	0.07	0.260	**0.05**	**0.02**	**0.0018**	**0.0004**	**0.57**	**< 0.001**
Salinity	**0.14**	**0.06**	**0.0077**	**0.0014**	**0.62**	**<0.001**	**0.16**	**0.07**	**0.0095**	**0.0014**	**0.75**	**< 0.001**
Shellfish	0.08	0.03	−0.0006	0.0007	0.04	0.360	0.09	0.02	0.0000	0.0007	0.00	0.957
Stone fruit	**0.06**	**0.05**	**0.0047**	**0.0006**	**0.79**	**<0.001**	**0.06**	**0.03**	**0.0040**	**0.0005**	**0.78**	**< 0.001**
Stony[a]	0.21	0.03	−0.0001	0.0016	0.00	0.940	0.20	0.02	0.0001	0.0007	0.00	0.851
Tropical fruit	0.09	0.03	−0.0003	0.0010	0.00	0.795	0.08	0.02	0.0005	0.0007	0.04	0.453

[a]In this study, "gunflint" words were included in the reduction word group and "flint" words in the stony word group. Flint, however, may be used in tasting notes as shorthand for gunflint and could thus be considered a reductive or smoky characteristic rather than stony. Simulation of this alternative categorisation for flint showed that it had little material effect on the results (Supplementary Figure S6, Tables S4 and S5).



(a) (b)

Figure 2: Trends in word groups used to describe Chablis Premier Cru wine in CellarTracker tasting notes against vintage (a) and year tasted (b). Secondary and tertiary word groups (lees, MLF, and oak) or word groups that did not exhibit a linear trend (lees, MLF, shellfish, stony, and tropical fruit $p > 0.05$) have been omitted from the Figure. All wines were between 3 and 7 years of age when tasted.

for minerality, salinity, and reduction were slightly stronger for tasting year than vintage (compare slopes for each in left and right of Table 1).

3.2. *Associations between Minerality and Other Wine Characteristics*

3.2.1. Bigram. Bigram analysis on the CellarTracker database showed that users occasionally qualified what they meant by "minerality" by adding a word before it in their tasting notes, broadly falling into "stony minerality" (593 occurrences, mostly "chalk" and "stone"), "saline minerality" (255), "seashell minerality" (105), and "smoky minerality" (44) groups (Table 2). These bigrams occurred in approximately 6% of tasting notes.

3.2.2. By Vintage. A significant negative correlation was found between the minerality index and each of the orchard fruit, salinity, and stone fruit indices (r_s (19) = −0.57, −0.48, −0.66 and p = 0.0071, 0.0294, 0.0012, respectively) but not with any of the other ten word groups. Only the correlation with stone fruit was significant after Bonferroni correction, however ($p < 0.00385$, i.e., $p < 0.05$ with Bonferroni correction for 13 pairwise correlations).

Table 2: Bigram analysis of Chablis Premier Cru tasting notes in CellarTracker, where a "mineral," "minerals," "minerally," or "minerality" word is the second word in the bigram.

Bigram group	First word[ab] (number of occurrences)[c]	Total occurrences
Stony minerality (Land)	chalk (220), **ferrous (1)**, earth (8), **flint (75)**, graphite (0), gravel (5), granite (1), gypsum (0), **iron (1)**, kimmeridgian (3), lead (0), limestone (40), marl (0), pebble (1), rock (23), soil (1), slate (18), stone (196)	593
Saline minerality (Ocean)	brine (9), **iodine (4)**, marine (5), ocean (11), oceanspray (0), saline (128), salt (76), saltwater (0), sea (13), seabreeze (0), seasalt (0), seashore (3), seaside (3), seaweed (3), seawater (0)	255
Seashell minerality (Ocean)	oyster (4), oystershell (2), seashell (27), shell (72), shellfish (0)	105
Smoky minerality (Smoke)	cabbage (0), cardboard (0), corn (0), egg (0), funk (0), fusil (0), gunflint (1), gunmetal (0), gunpowder (1), gunsmoke (1), lapsang (0), matchstick (0), reduction (5), rotten (0), rubber (0), smoke (34), skunk (0), struckmatch (0), sulphide (0), sulfide (0), sulfur (1), sulphur (1)	44

[a]Includes derivatives and common misspellings of the word type, for example, "chalky" and "chalkey". [b]Categorisation of first-word types has been made in accordance with BIVB descriptions for minerality [40] with adjustment for "gun-" words (gunflint and gunpowder) which were moved to the smoke group. Seashell was separated from saline in order to test the work of Rodrigues et al. [19], though BIVB groups the two together into an "ocean" category. BIVB refers to the stony category described here as "land." [c]Word types marked in bold highlight potential miscategorisations. Flint may be shorthand for gunflint and possibly considered smoky instead of stony; iron and ferrous could be confused with iodine and therefore considered saline rather than "land." Given the number of occurrences involved, only the categorisation of "flint" is materially an issue (see Discussion). The overall order and magnitude of importance between the bigram groups would remain, however, even with these alternative categorisations. All wines were between 3 and 7 years of age when tasted.

For associations among all word groups (not just minerality), only the correlation between acidity and salinity ($r_s(19) = 0.75$, $p = 0.0001$) was significant (Figure 3). The other pairs did not pass the significance test of $p < 0.00055$ (i.e., $p < 0.05$ with Bonferroni correction for 91 pairwise correlations) and/or were overly dependent on an outlier (assessed using a Grubbs' test followed by a new correlation without the outlier).

3.2.3. Minerality Differences between Left- and Right-Bank Premier Cru Wines. A paired-samples t-test revealed a small but statistically significant difference in mean minerality between left- and right-bank wines when averaged by vintage (t (19) = 2.30, $p = 0.033$). Left-bank wines were 0.022 higher in mean minerality than right-bank wines (Figure 4).

3.3. Associations with Weather. Moderate Spearman's rank correlations were found between certain wine characteristics and weather, though some at a lower significance ($p < 0.10$) and without Bonferroni correction (Table 3).

In general, minerality was negatively and tropical fruit was positively associated with temperature and sunshine hours, while fruit and floral characteristics, excluding citrus, were negatively associated with precipitation during the growing season (Table 3 and Supplementary Figure S7). Minerality was not correlated with precipitation variables. Stone fruit was positively associated with the sunshine indices only ($p < 0.10$).

Acidity was significantly ($p < 0.05$) correlated (negatively) with mean minimum temperature in both the August and September ($Tmin_{Aug\text{-}Sep}$) and September (CNI) periods (Table 3 and Supplementary Figure S7).

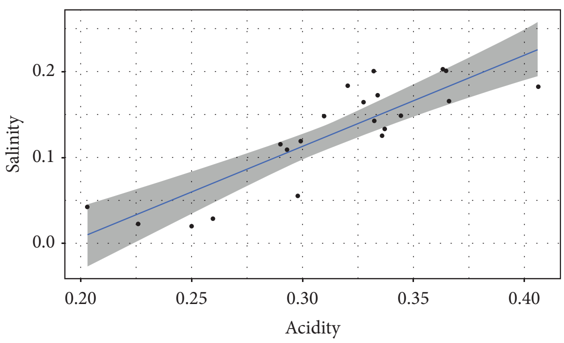


Figure 3: Mean salinity versus mean acidity for Chablis Premier Cru wine (1999 to 2019 vintages) from CellarTracker tasting notes. All wines were between 3 and 7 years of age when tasted.

3.4. Associations with Soil Type. No significant Spearman's rank correlations were found between the percentage of vineyard area with Kimmeridgian UCS30 soil type and wine characteristics ($p > 0.05$ with Bonferroni correction for 11 pairwise comparisons (excluding lees, MLF and oak)), except for the association with the reduction word group (r_s (12) = 0.87, $p < 0.001$). The effect was small, however (range in reduction index <0.04).

3.5. Associations with Topography

3.5.1. Aspect. Minerality was the only word group found to have a significant association ($p < 0.05$) with aspect. It was negatively associated with the percentage of Climat vineyard area facing South or South-West (r_s (12) = −0.65, $p = 0.012$) and positively facing East or South-East (r_s (12) = +0.56, $p = 0.037$) (Figure 5).

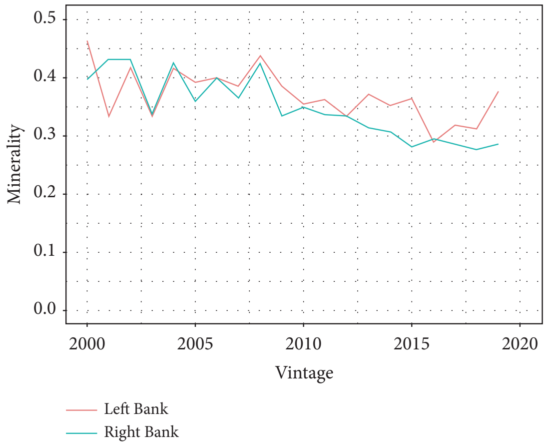


Figure 4: Mean minerality versus vintage for left- (red) and right-bank (blue) Chablis Premier Cru wine from CellarTracker tasting notes. The 1999 vintage was omitted from the analysis due to insufficient sample numbers (<30 tasting notes) after splitting into left- and right-bank wines. All wines were between 3 and 7 years of age when tasted.

Table 3: Significant Spearman's rank correlation coefficients ($p < 0.10$) between vintage weather indices and word groups used to describe Chablis Premier Cru wine (1999 to 2019) in CellarTracker tasting notes. Nonprimary aroma and flavour word groups (lees, MLF, and oak) were excluded from the analysis. All wines were between 3 and 7 years of age when tasted.

		Coefficient (r_s)	Significance (p)
Temperature			
$T\text{mean}_{\text{Apr-Sep}}$	vs. minerality	−0.43	0.052
	vs. tropical fruit	0.59	0.005
$T\text{mean}_{\text{Apr-Oct}}$ (GST)	vs. minerality	−0.48	0.029
	vs. tropical fruit	0.54	0.011
$T\text{mean}_{\text{May-Jul}}$	vs. tropical fruit	0.50	0.022
$T\text{min}_{\text{Sep}}$ (cool night index)	vs. acidity	−0.45	0.043
$T\text{min}_{\text{Aug-Sep}}$	vs. acidity	−0.57	0.007
	vs. orchard fruit	−0.37	0.099
	vs. salinity	−0.41	0.064
	vs. tropical fruit	0.40	0.069
Sunshine			
$\text{Sunhours}_{\text{Apr-Sep}}$	vs. minerality	−0.57	0.007
	vs. stone fruit	0.40	0.072
	vs. tropical fruit	0.38	0.086
$\text{Sunhours}_{\text{Aug-Sep}}$	vs. minerality	−0.51	0.019
	vs. stone fruit	0.41	0.063
	vs. tropical fruit	0.38	0.093
Precipitation			
$\text{P}_{\text{Jun-Sep}}$	vs. floral	−0.55	0.010
	vs. stone fruit	−0.38	0.086
$\text{P}_{\text{Jun-Oct}}$	vs. floral	−0.54	0.013
	vs. orchard fruit	−0.42	0.059
	vs. stone fruit	−0.42	0.062
	vs. tropical fruit	−0.46	0.035

3.5.2. Gradient. The mean slope of vineyards in each Climat was not associated with the minerality index (r_s (12) = 0.25, p = 0.383) but was negatively associated with shellfish (r_s (12) = −0.82, $p < 0.001$), saline (r_s (12) = −0.69, p = 0.008), and stony (r_s (12) = −0.56, p = 0.038) characteristics (Figure 6). Only that with shellfish was significant with Bonferroni correction ($p < 0.0045$) however.

3.5.3. Elevation. The mean elevation of the Climat vineyard area was not associated with the minerality index (r_s (12) = 0.09, p = 0.773), nor any other wine characteristic.

3.5.4. Relative Elevation. The mean relative elevation of Climat vineyard was not associated with reports of minerality (r_s (12) = −0.38, p = 0.186), but it was positively

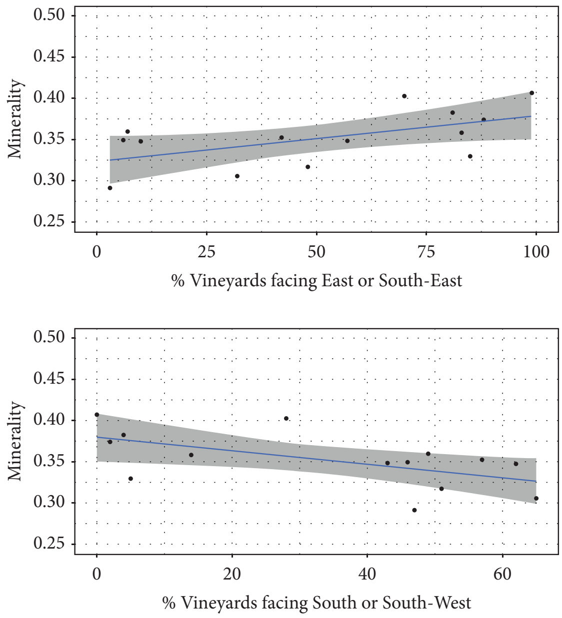


Figure 5: Mean minerality of principal Chablis Premier Cru Climats (from CellarTracker tasting notes) in relation to aspect, i.e., the percentage of Chablis Premier Cru Climat area facing East or South-East (upper pane; regression slope = +0.0006, SE = 0.0002, $R^2 = 0.32$) or South or South-West (lower pane; regression slope = −0.0008, SE = 0.0003, $R^2 = 0.34$). The Premier Cru wines ranked from highest to lowest for minerality (with side of river) were Vau de Vey (Left, 0.41), Côtes de Jouan (Left, 0.40), Vaillons (Left, 0.38), Côte de Léchet (Left, 0.37), Montée de Tonnerre (Right, 0.36), Montmains (Left, 0.36), Les Fourneaux (Right, 0.35), Fourchaume (Right, 0.35), Beauregard (Left, 0.35), Vaucoupin (Right, 0.35), Vauligneau (Left, 0.33), Beauroy (Left, 0.32), Mont de Milieu (Right, 0.31), and Vosgros (Left, 0.29). All wines were between 3 and 7 years of age when tasted.

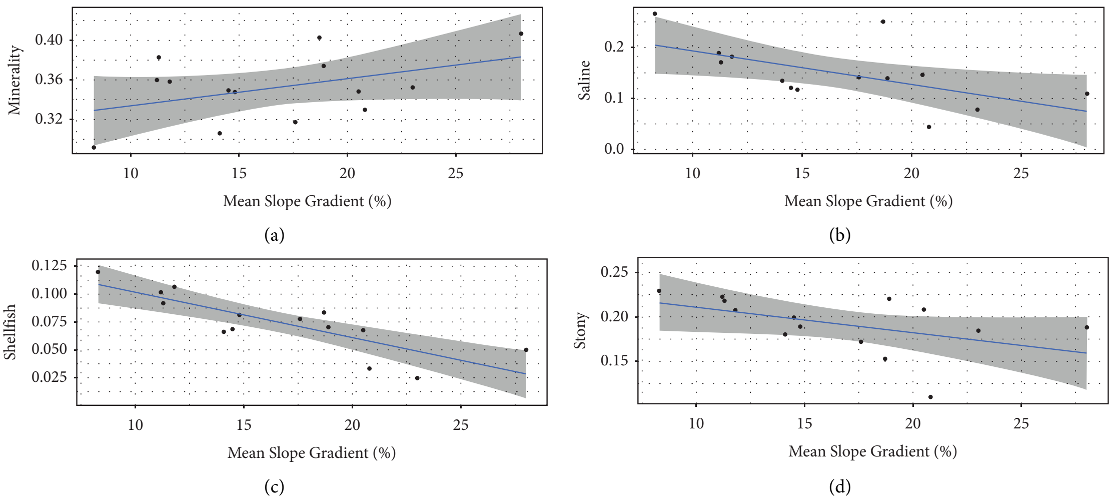


Figure 6: Mean indices for the word groups (a) minerality, (b) saline, (c) shellfish, and (d) stony (from CellarTracker tasting notes) in relation to the mean slope gradient of 14 principal Chablis Premier Cru Climats. Spearman's rank correlation between slope gradient and minerality was not significant ($p > 0.05$), but that for slope gradient versus saline, shellfish, and stony characteristics was. All wines were between 3 and 7 years of age when tasted.

associated with the shellfish (r_s (12) = +0.64, p = 0.017) and stony (r_s (12) = +0.59, p = 0.029) word groups. The total range in these word group indices was small (around 0.05), however, and neither was significant with the Bonferroni correction. No other word groupings were correlated ($p < 0.05$) with relative elevation, except for the floral word group (r_s (12) = +0.59, p = 0.030), but this was overly dependent on an outlier (assessed using a Grubbs' test followed by a new correlation without the outlier; (r_s (11) = +0.50, p = 0.072)).

4. Discussion

Textual analysis of Chablis Premier Cru tasting notes in CellarTracker has provided an understanding of what consumers mean in sensory terms when they refer to minerality, what may be driving the presence of minerality in wine, and how the use of the term minerality has changed over the study period.

Bigram analysis on the CellarTracker database showed that users occasionally specified what they meant by "minerality" by using a qualifying word before it in their tasting notes (Table 2). If this is representative of the whole, it suggests nonspecific minerality references in Chablis Premier Cru tasting notes are over 1.5 times as likely to be referring to stony sensations such as chalk, stones, and pebbles than they are saline, salty, and seashell sensations [40].

The decline in the use of the term "minerality" over the last 20 years or so can be interpreted in several ways (i) that it has become less fashionable as a descriptive term, especially since the idea that it is directly connected to the soils and geology has been widely discredited [2, 10]; (ii) that users have been more careful in its usage—perhaps choosing the term "saline" (and to a lesser extent "reduction") instead of "mineral" when appropriate, but perhaps retaining the term for "stony" sensations; and/or (iii) that there has been a real decrease in "minerality" in Chablis wine over the study period.

Our analyses suggest that all three explanations may have played a part. The rate of decline in the use of the term minerality and the rate of increase in the use of the term salinity are greater when looked at by year of tasting than by vintage (Table 1), which is not the case for most other wine descriptor groups (the one exception is reduction). This suggests that a change in fashion may have played a part and that users may have instead chosen to substitute minerality with a more precise saline descriptive term or less frequently a reductive or acidic term. Malfeito-Ferreira [3] points out that experts generally prefer using words other than minerality. This preference may be spreading to the wider consumer market.

Nonetheless, the negative correlations between minerality and each of sunshine and warmth (Table 3) suggest that it is a real phenomenon affected by the vintage year's weather. This ties in with the widely accepted idea that minerality is associated with cool-climate wines [3, 17]. An alternative explanation, however, could be that CellarTracker users were aware of which vintages were "hot," "classic," or "cold" and adjusted their expectations and perceptions accordingly.

Our observation that Climats on the left side of the river Serein provided slightly more mineral wines than those on the right side (Figure 4) confirms the findings of Rodrigues et al. [19]. Once again, however, this might be explained by preconceptions about the "minerality" of Climats on the part of CellarTracker users. The findings are more convincing, however, when minerality is plotted against the vineyard aspect, with East and South-East facing Climats (typically left bank) more mineral than the South and South-West facing Climats (typically right bank) (Figure 5). This is consistent with research suggesting minerality may be inversely related to berry maturity [17], with the South and South-West facing slopes receiving greater warmth from the accumulation of heat into the afternoon, promoting greater berry maturity and consequently less mineral wines [19].

The increase, by vintage, in floral, orchard fruit, and stone fruit wine notes (Table 1 and Figure 2), typical of warmer climate Chardonnay styles, suggests the simultaneous decline in minerality may be real and correspond to the long-term warming trend in Chablis [47]. Arguably, the perception of floral, orchard fruit, or stone fruit descriptors would be less affected by preconceptions about wine from warmer vintages because it is a more subtle observation than detecting tropical aromas and flavours in a wine from a hot year. It also ties in with research that suggests minerality may be perceived when there is an absence of fruit and floral notes [7, 19, 25].

However, fruit and floral aromas and flavours were related (negatively) to precipitation, whereas minerality, acidity, reduction, and salinity (the minerality and minerality-related terms) were not (Table 3). In other words, a wet period from fruit set to harvest may result in a lack of fruit and floral aromas and flavours, but this does not necessarily translate into an increase in minerality.

Interestingly, there was little evidence for the widely accepted observation that minerality and acidity are closely and positively associated [5]. While it is true that minerality, acidity, and citrus descriptive word groups characterised Chablis Premier Cru wines over the study period (Figure 2), evidence from this study suggests that acidity and minerality (albeit there may be a changing definition of minerality throughout the study period) may be determined by different environmental conditions. While minerality was related to warmth and sunshine, acidity was associated (negatively) with mean minimum temperatures during the ripening period ($Tmin_{Aug\text{-}Sep}$ and CNI) (Table 3) when high night temperatures increase respiration and the degradation of malic acid in grape berries [55].

Instead, acidity was most strongly associated with salinity (Figure 3), suggesting these word groups are either being used to describe similar sensations or that many tasters had difficulty differentiating between them. Salinity was also associated with mean minimum temperature in August and September ($Tmin_{Aug\text{-}Sep}$), albeit at a lower significance ($p < 0.10$) than acidity (Table 3), providing further evidence for the association between acidity and salinity. One of the acids naturally present in wine, succinic acid, is in fact salty in taste [3, 6, 8].

The negative association found between vineyard gradient and shellfish notes (Figure 6) is also interesting. Rodrigues et al. [19] found that methanethiol, a sulphur-containing volatile compound responsible for shellfish aromas, was higher in left-side Chablis wines compared to right-side wines, and they postulated it could play a role in the sensation of minerality by masking fruit and floral aromas. Indeed, left bank Climats are steeper (17.3%) on average than right bank Climats (14.7%) (excluding the smallest Climats of Berdiot, Chaume de Talvat, and Côte de

Vaubarousse which had too few wine-tasting notes for separate analysis). Thus, the gradient may be positively correlated to the presence of methanethiol, and this may lead to the masking of fruit and floral aromas, though the process by which this might happen is unclear. No direct association, however, was found in this study between vineyard gradient and minerality.

Reductive terms were (with lees) the least mentioned of all descriptive word groups for vintages from 1999 to 2019 (Table 1). Only 4% of tasting notes (i.e., a median index score of 0.04) referred to any kind of reduction in the wine. This compares to minerality with a median index score of 0.36.

This result implies that "overt" signs of reductive processes, i.e., ones that produce sulphur compounds responsible for empyreumatic and/or off-odours, are not a key feature of Chablis Premier Cru wine. This does not necessarily mean, however, that reduction is not involved in other minerality-related characteristics, such as flinty [4] and shellfish [19] aromas.

Our choice of how to allocate descriptive words to particular word groups obviously had an impact on the results, though we believe not in a material way. We chose to put flint words into the stony word group given a literal understanding of the term and the possibility that CellarTracker users are referring to some kind of edgy stony character [56], rather than using the term as shorthand for gunflint. When we tested moving over these words to the reduction word group instead, the change to the results was small and immaterial to our overall findings (Supplementary Figure S6 and Tables S4 and S5).

Our study found no evidence for any association (positive or negative) between minerality and (i) percentage of Kimmeridgian soil type [11, 17, 30] or (ii) flavours and aromas associated with lees contact, oak ageing/fermentation, and/or malolactic fermentation. Thus, no support can be given to the idea that minerality is related to soils and geology or that minerality can be masked by winemaking processes [17, 25]. That said, there may be other soil characteristics—such as stoniness, soil depth, and clay content—that affect soil temperature and water availability and thus affect ripening [17], which were not investigated here.

Minerality is an ill-defined and enigmatic concept [5, 10] that needs clarity for producers, merchants, and consumers alike and needs standardising into a group of aroma and/or taste compounds [6]. In this regard, the findings of this study help in understanding what minerality means for consumers of Chablis wine and—given Chablis is widely accepted as an archetypal mineral wine [13]—this would likely translate to other cool climate white wines.

How minerality is perceived, however, may vary with grapevine variety [3]. This may be due to differences in biochemistry. Tominaga et al. [24], for example, found that Chardonnay wines from Burgundy, France, contained two to three times as much benzenemethanethiol as the other grape varieties in their study (Sauvignon blanc, Semillon, Cabernet Sauvignon, and Merlot). As such, despite the need for a universal understanding of minerality [4, 36], some caution is required in applying the findings of this study to cultivars other than Chardonnay.

These findings may also be of value to cool-climate wine producers who want to make mineral wines, including those from emerging wine regions such as the UK. This is because the best explanation for the presence of minerality in our data was one where minerality is driven by vintage weather rather than any direct connection to soils and geology, winemaking practices, or wine storage. As such, although the CellarTracker data were unable to throw light on the mechanism and compounds that cause minerality, we hypothesise high minerality wines could be produced anywhere with a suitable climate and with generally good conditions for growing cool climate grapevines.

5. Conclusions

The use of the descriptive term "minerality" has declined over the last 20 or so years in Chablis Premier Cru tasting notes in CellarTracker. This was probably due to three factors: (i) the warming of growing season temperature (GST) due to climate change, (ii) a decline in the popularity of the term, and (iii) the increasing use of alternative descriptive terms, such as "saline" (where appropriate) with retention of the minerality word for "stony" perceptions.

For CellarTracker users, the term "minerality" was primarily associated with "stony" perceptions (including "chalky," "flinty," and "stony") and secondarily with "saline" and "seashell" perceptions (including "saline," "salty," and "shelly"). Empyreumatic and off-odour words associated with reductive processes and sulphurous compounds, however, such as "egg," "smoky," and "sulphur," were not a major feature of Chablis Premier Cru wine.

The hypothesis that minerality in Chardonnay wine is driven by vintage weather (i.e., negatively correlated with GST and sunshine hours) was supported by the study. No evidence was found to support the suggested association of minerality with soils and geology (specifically the presence of Kimmeredigan soils), nor that malolactic fermentation and/or contact with oak barrels and lees have any masking effect on minerality. Some evidence was detected, however, to support the idea that minerality is inversely correlated with stone and tropical fruit, though only by virtue of them being oppositely associated with GST and/or sunshine hours, rather than any direct relationship between them.

Though minerality and acidity are both a typical feature of Chablis Premier Cru wine, the presence of each is likely driven by different vintage weather factors: acidity is driven by night-time temperatures during ripening, whereas minerality is driven by temperatures and sunshine throughout the growing season.

Textual analysis of the large database of tasting notes in CellarTracker has provided interesting insights about the perception of wine characteristics and the sources of these characteristics. The specific findings of this study in relation to the minerality of Chablis wine (arguably the most famous wine for minerality) may be useful to wine industry professionals and consumers who want clarity on the meaning and causes of minerality in wine and perhaps also to winemakers in both traditional and emerging wine regions who seek to produce mineral wines.

Data Availability

The data used to support the findings of this study are available from the following sources: tasting notes https://www.cellartracker.com/; weather https://meteofrance.com/; topography and soils https://onlinelibrary.wiley.com/doi/full/10.1111/ajgw.12433.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Supplementary Materials

Supplementary Table S1 lists the 17 principal Chablis Premier Cru Climats and their land area. Supplementary Figure S1 shows the mean age of Chablis Premier Cru wine tasted in CellarTracker notes against Year Tasted. Supplementary Figure S2 provides a schematic representation of how the CellarTracker Chablis Premier Cru tasting notes were organised into separate subdatabases for analyses. Supplementary Table S2 and Supplementary Figure S3 provide descriptive statistics for the CellarTracker Chablis Premier Cru tasting notes. Supplementary Figure S4 shows the descriptive word groups selected by the authors for text analysis, and Supplementary Table S3 lists the component words and bigrams for these word groups. Supplementary Figure S5 shows how the assignment of gunflint, gunpowder, and gunmetal words to the "reduction" word group instead of the "stony" word group made a negligible difference in the results. Supplementary Figure S6 shows how the assignment of flint words to the "reduction" word group instead of the "stony" word group would have made some small difference to the results. Supplementary Table S4 and Table S5 show the relationship differences that would have resulted from the reassignment of flint words from the "stony" to the "reduction" word group. Supplementary Figure S7 provides selected significant Spearman's rank correlation scatterplots between word groups used to describe Chablis Premier Cru wine and certain vintage weather variables. (*Supplementary Materials*)

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Chapter 5. Identification of suitable sites for high-quality still wine from Chardonnay viticulture in England: an assessment of topography and soils

5.1 Introduction

England has become a respected producer of sparkling wine (Nesbitt et al., 2019). A warming climate over the last few decades has allowed a move away from hardy German grapevine cultivars towards more commercially popular French cultivars (Chardonnay, Pinot Noir and Pinot Meunier), primarily to make sparkling wine using the traditional method of the Champagne region (WineGB, 2023).

However, though there have been a few exceptional vintages (e.g., 2018), most producers in England have yet to reliably produce premium quality still wine from these cultivars and doubt remains about the potential for English still wine (Nesbitt et al., 2016). In response to a survey from this study (see Section 5.2.8.2), Malcolm Gluck, a renowned wine writer and columnist, said, "…the idea of a complete chardonnay from anywhere in the UK is as fanciful and possibly as ridiculous a notion as growing tea in the Arctic. Great English wine is largely a fantasy, compared with the wines from elsewhere in Europe (not to speak of the rest of the world)," (personal communication, 2 December 2024).

Other market participants are, however, more open to the idea of premium quality English still Chardonnay wine. A commercial buyer for a major UK wine merchant said, "it's a fascinating topic and there is so much progress to be made, I'm glad that there is serious research into it," (Appendix 5A).

5.1.1 Impact of weather on wine quality

The consensus from viticulture regions around the world is that weather is a major determinant of wine quality (Berghe and Bouton, 2024; van Leeuwen and Darriet, 2016). A common finding is that vintage quality is primarily related to growing season warmth (Ashenfelter, 2017; Baciocco et al., 2014; Davis et al., 2019; Neethling et al., 2012). Additional climatic factors, such as precipitation (Outreville, 2018) and mean minimum temperature during the ripening period (Cool Night Index (CNI)) (Biss and Ellis, 2021; Tonietto and Carbonneau, 2004) are also important, though their weighting depends on cultivar and region (Suter *et al.*, 2021). Overall, weather plays a major role in determining berry sugar concentration (and thus potential alcohol of the final wine after fermentation), as well as concentration levels of organic acids and secondary metabolites.

Chablis is an area in the very north of Burgundy, France, which produces only white wine from Chardonnay grapes. Its average growing season temperature is around 1°C cooler than the other main white wine producing area of Burgundy, the Côte de Beaune (Biss and Ellis, 2021). Biss and Ellis (2022) argue that climatically Chablis provides a model for future reliable production of high quality still Chardonnay wine in the UK, given it is (and has been for centuries) the most northerly producer of premium quality still Chardonnay wine at commercially significant levels.

Chardonnay is a grapevine cultivar that can thrive under a wide range of growing season temperatures, from around 14°C to over 17°C (mean temperature April to October, northern hemisphere) (Jones, 2007b). The upper limit is less exact (Jones, 2007b) and may be extended through certain agronomic practices (van Leeuwen et al., 2019). At this upper end it can still be a successful grapevine choice, albeit the flavour profile may change to that of a warm climate Chardonnay, typically high in alcohol and tropical fruit flavours, and low in acidity. At the lower end of the temperature range, cool climate Chardonnays are typically high in acidity with citrus and/or orchard fruit flavours, though with age better wines can become softer, honeyed and more intense (Biss, 2020). Thus, although the style of wine may change, once (or if) parts of England reach the climate of the Chablis region there are some two to three degrees of further warming in which it would likely be able to produce high quality wines from Chardonnay grapes.

5.1.2 Impact of topography

While climate is widely accepted as a key determinant of wine quality at the regional scale (van Leeuwen et al. 2004; Prata-Sena et al. 2018), there have been many papers that suggest topography — specifically elevation, slope and aspect — play a key role in determining wine characteristics at the local level (Anesi et al., 2015; Bavaresco et al., 2007; Bramley et al., 2011; Fraga et al., 2017; Roullier-Gall et al., 2014; Rupnik et al., 2016; Scarlett et al., 2014).

Anesi et al. (2015) found that the metabolites within the berries were related to certain environmental factors, such as strong light/shading, low/high temperature, elevation and water deficit, indicating that topography can influence the biochemical make-up of the grapes. Similar studies by Scarlett et al. (2014) and Rupnik et al., (2016) also demonstrated the effect of topography on berry rotundone concentration (a compound associated with a 'peppery' character) and berry acidity respectively.

The processes by which topography impacts wine characteristics are complex. Topographic features interact with weather and climate – modifying solar irradiation, air circulation, drainage, and soil conditions – all of which affect vine physiology and grape quality (Jones, 2015).

Aspect is particularly important in vineyard siting. In cool northern hemisphere climates, south, south-west, and southeast-facing slopes optimize heat accumulation, aiding grape ripening (Stafne, 2015). This is especially true of southern and south-western exposures, which benefit from the accumulation of heat into the afternoon and early evening, though this can lead to overheating and diminished acidity during hot years. In contrast, eastern and south-eastern-facing slopes offer early morning sun, reducing the risk of rot and mildew by drying morning dew rapidly.

Elevation and relative elevation are also crucial for vineyard location. Goldammer (2015) notes that vineyards situated along hillsides rather than on hill tops or bottoms are less prone to high winds, frost and flooding. Additionally, a 100-metre rise in elevation typically reduces temperature by about 0.65°C (Royal Meteorological Society, 2024), shortening the growing season and affecting grape ripening.

Slope gradient affects soil water status, with steeper slopes increasing runoff and soil drainage leading to water deficits (Brillante et al., 2018). While moderate water stress can enhance wine quality (Brillante et al., 2018; van Leeuwen, Sgubin, et al., 2024), for some white wine grape cultivars such as Chardonnay, excessive stress, particularly in hot years, can harm the wine by reducing aromatic compounds and acidity (Brillante et al., 2018).

Slope gradient also affects the amount of solar radiation received at the ground (Erley and Jaffe 1979); a steep south-facing slope will receive more energy per unit area than a flatter south-facing slope because the sun's rays are concentrated into a smaller area. This affects both berry ripening and drying of berries after rainfall. There is an interaction between slope gradient and aspect, however; as slope gradient increases, the range of beneficial aspects for solar radiation narrows (Figure 5.1).

The uplift in solar radiation irradiation, however, does not necessarily lead to an equivalent rise in temperature. A 10% slope facing due South in Uckfield, East Sussex, England, may receive the same irradiation as a 2% slope facing due South in Chablis (Figure 5.1), but the two areas are unlikely to experience similar temperatures. Many factors intervene to prevent this happening, including regional climate and weather patterns, atmospheric conditions, humidity and cloud cover, proximity to large water bodies, vegetation and soil characteristics, and obscuration of the sky (Huang et al., 2008). These factors determine levels of solar radiation received on the ground and rates of heat exchange.

Calculating the amount of temperature uplift from slope gradient and aspect has generally been based on empirical observation. Manley (1944) observed a 1.5 to 3.5 °C difference in Spring, Summer and Autumn mean minimum temperatures between a “favourable hill slope” and “normal low-lying” land in the Midlands in England. More recently, Behr (2022) found that there was between a 0 to 0.15 °C change in temperature for every 1 W/m^2 of irradiance (across all four seasons and three climatic regions in Germany), with the ratio highest in Spring and Autumn. Based on the figures presented for Uckfield in East Sussex (Figure 5.1), this would equate to between a 0 and 2.25 °C uplift in temperature for a 15% slope facing due South compared to a 2% slope, or up to 5.25 °C uplift compared to a 15% slope facing due North. This is consistent with the research of Seyfried et al. (2021), who showed that for a watershed in Idaho, USA, soil temperatures on south facing slopes were on average 4.7 °C warmer than adjacent north facing slopes.

Such topographically-induced differences in temperature are significant for viticulture. This is particularly the case for cool climate wine regions such as England and northern France, given that seasonal and topographic effects on solar irradiation generally increase with latitudinal distance from the equator (Gunton et al, 2015; Jakhrani et al., 2010; Seyfried et al., 2021).

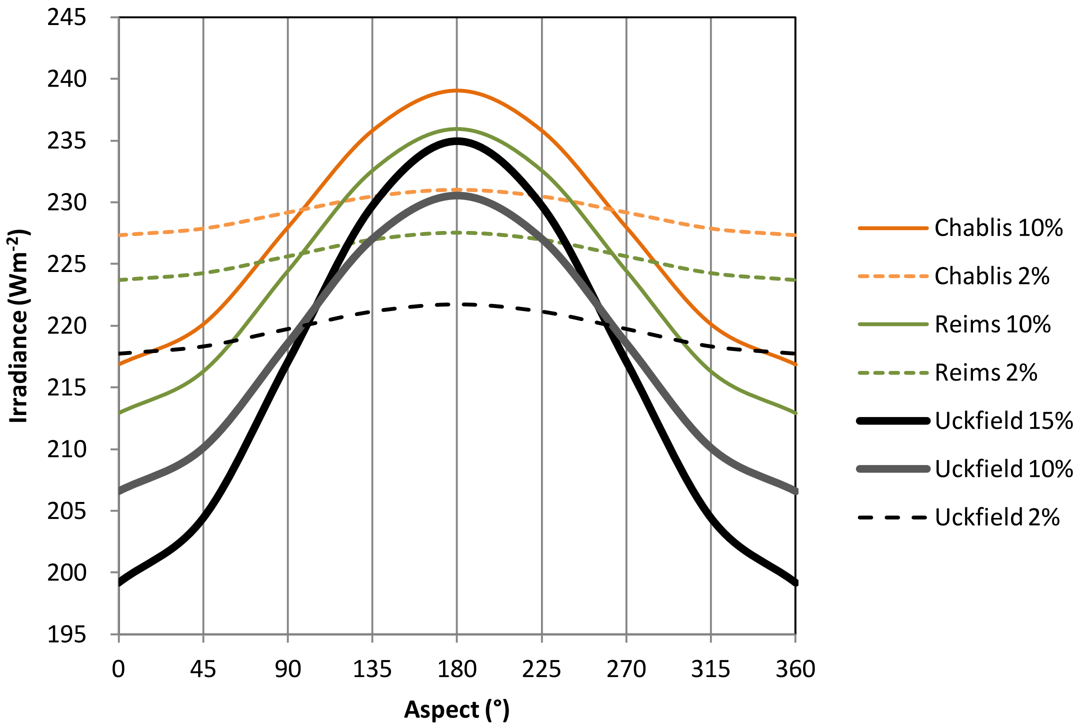

Figure 5.1. Mean irradiance for different steepness slopes vs aspect (mean of 15 May, 15 July and 15 September) for i) Uckfield, East Sussex, UK (grey/black), ii) Reims, Champagne, France (green), and iii) Chablis, Burgundy, France (orange). Note how a 15% slope in Uckfield receives more irradiance than a 2% slope in Uckfield provided aspect is in the range of c. 100° to 260°. Note also how a 15% slope in Uckfield can experience similar levels of irradiance to a 2% slope in Chablis and a 10% slope in Reims, provided aspect remains in the range 135° to 225°. Calculated from meteoexploration (n.d.) using the following assumptions: i) Elevation – Uckfield 50m, Reims 200m, Chablis 200m; ii) Relative Humidity 50%; iii) Ozone Thickness 300 DU; iv) Ground Albedo 0.2; v) Visibility 30.0km.

5.1.3 Impact of soils

An extensive body of research indicates that the effect of soil on grape berry quality is considerably less than differences in quality due to inter-annual variation in weather (Rankine et al., 1971; van Leeuwen et al., 2018; Anastasiou et al., 2023; Bambina et al., 2024). Nonetheless, soils are an integral part of the grapevine environment – playing a crucial role in determining water availability, nutrient and micronutrient availability, aeration and warmth (Koundouras, 2022; van Leeuwen, Schmutz, et al. 2024) – and the importance of certain soil properties will depend on how they interact with temperature and precipitation during key phenological stages (Anastasiou et al., 2023; Table 5.1). As such, the influence of soils on grape composition may be greater in years with more extreme weather conditions (Wheeler et al., 2021).

The idea that soil characteristics, particularly mineral content, can be tasted directly in the wine has been widely discredited (Maltman, 2013; and see Chapter 4) though producers, merchants and consumers regularly allude to such direct processes. There are more indirect pathways to influencing quality, however. Soil physical properties such as texture (the proportion of sand, silt and clay), structure and depth, are generally considered more important for wine quality than soil chemistry because they impact on soil temperature, water storage, drainage, and root development (Koundouras, 2022).

In cool climates like England, low temperatures and excess water are often a limiting factor to quality (Table 5.1), though extended periods of heat and drought are still possible. Thus, the greater concern is placed on drainage of water and increasing soil temperatures, particularly in the rooting zone (van Leeuwen et al., 2018), but with an eye to maintaining sufficient available water to the grapevines during hot and dry conditions such that water deficits do not become severe. Moderate water deficits are generally considered beneficial for grape quality (Alem et al., 2019).

The water balance of vineyards and its consequent effect on vine water status is key to both yield and berry quality – specifically concentration of sugars, and aromatic and phenolic compounds (Zito et al., 2024), and acids (Ramos et al., 2020). For example, water availability around flowering and fruitset, and from veraison to the end of ripening has been shown to affect berry weight, acidity, anthocyanins and other phenolic compounds in Tempranillo grape composition in Rioja, Spain (Ramos et al., 2020; Martínez-Vidaurre et al., 2024), albeit this is not necessarily comparable to the production of Chardonnay grapes in the much cooler climate of England.

Table 5.1. Interaction of physical soil properties and extremes of temperature and precipitation on grapevine phenology and grape quality, biased towards consideration of cool climate conditions such as in England.

	Soil Water Holding Capacity, Available Water & Drainage	Soil Warmth & Depth
Budburst (early Spring)		
Wet or Cold	• Waterlogged soils reduce oxygen availability, impair root function and delay budburst, which may impact negatively on eventual grape quality through a knock-on delay to berry development and maturation (Persico et al., 2023). • Wet soils warm more slowly than dry soils (Tesic et al., 2002), delaying budburst.	• Cool soils delay budburst, which impacts negatively on eventual grape quality through a knock-on delay to berry development and maturation (Persico et al., 2023). • Deep soils warm more slowly than shallow soils in the rooting zone (van Leeuwen et al., 2018), delaying budburst.
Dry or Hot	• Pre-veraison water stress negatively affects aroma quality and acidity (Bellvert et al., 2016).	• Soils with high heat-retention capacity (e.g. coarse, gravel or rocky soils) and low albedo warm the root zone and encourage earlier budburst (van Leeuwen et al., 2018), though with consequent increased risk of exposing buds to frost.
Flowering & Fruitset (late Spring & early Summer)		
Wet or Cold	• Waterlogged soils may lead to reduced oxygen for roots, accumulation of toxins through anaerobic respiration, decreased photosynthetic efficiency (Wang et al., 2021), and poor flowering. • Wet soils increase risk of fungal infection with consequent negative impact on berry quality.	• Soils with low-heat retention capacity may experience a decline in soil temperature from warm to cool through the flowering period, which is associated with reduced fruit set (Field et al., 2020). This can lead to uneven berry ripeness (Atkinson, 2011), "Millerandage" and/or "Shot" berries which hinder the production of a balanced wine (Gray and Coombe, 2009).
Dry or Hot	• Loamy and silty soils that retain moderate moisture and allow upward movement of moisture in soil by capillary action (Jackson, 2014) buffer against lack of precipitation, supporting flower viability. • Pre-veraison water stress negatively affects aroma quality and acidity (Bellvert et al., 2016).	• Deep soils (with associated deep vine rooting) buffer against lack of precipitation, supporting flower viability (Bellvert et al., 2016).

Veraison (mid Summer)		
Wet or Cold	• Wet soils with high available water may result in moisture-related problems (fungal and rot risks) and/or dilution of berry solutes (Jones and Davis, 2020).	• Deep soils may provide too much available water increasing vine vigour at the expense of quality (van Leeuwen et al., 2018)
Dry or Hot	• Soils with better water retention help prevent severe water deficit through increased available water.	• Deep soils (with associated deep vine rooting) help prevent severe water deficit through increased available water. • Soils with high albedo help prevent severe water deficit through reduced evaporation.
Ripening (late Summer & early Autumn)		
Wet or Cold	• Soils with high available water content may result in berry swelling and dilution of solutes (Zhang et al., 2016; Meggio, 2022). • Wet soils may reduce grape quality by increasing fungal risks.	• Deep soils may provide too much available water increasing vine vigour at the expense of quality (van Leeuwen et al., 2018).
Dry or Hot	• Berries are less sensitive to drought during ripening, and generally profit from reduced fungal and rot risks, and increased solar irradiation through reduced vegetative growth (Strack and Stoll, 2022), though water deficit stress in the early period of ripening can impact negatively on berry quality (Okamoto et al., 2004).	• Deep soils (with associated deep vine rooting) help prevent severe water deficit through increased available water. • Soils with high albedo help prevent severe water deficit through reduced evaporation.

Soil – in particular its texture, rooting depth, bulk density, organic matter content and proportion of coarse elements (Zito et al., 2024) – is just one inter-related component of vineyard water balance. Simultaneous consideration of the other components is therefore important to understanding vine water status. These are, i) weather-related water availability (precipitation and evaporation), ii) topography and geology (which determine local and regional sources, flows, and storage), iii) grapevine planting density (Gambetta et al., 2024), iv) exposed leaf area (affected by vine training system and vineyard management practices, (Gambetta et al., 2024)), v) grapevine cultivar (particularly stomatal behaviour, (Gambetta et al., 2024)), and vi) water use by cover crops or weeds (Zito et al., 2024).

In Chablis, the Kimmeridgian marls are thought to produce higher quality wines than the adjacent Portlandian limestone (Biss and Ellis, 2024). The reasons provided by producers and merchants often allude to the extensive presence of fossilised oyster shells (*Exogyra virgula* Goldfuss, 1833) in the Kimmeridgian soils, though the processes by which these affect the vines, grape berries and the final wine are not clearly explained. The superior quality could instead come from the higher clay content of the Kimmeridgian soils or possibly from the stoniness of the soil (explained in part by the presence of the fossils) which are important factors for soil water holding capacity and soil warmth (van Leeuwen et al., 2018).

Calcareous soils are often preferred for Chardonnay vineyards because of, i) their ability to drain well (van Leeuwen et al., 2018) yet still hold and absorb water within pore spaces, ii) the displacement of potassium with calcium to maintain higher acidity levels in berries for any given level of sugar (Kodur, 2011; Tablas Creek, 2020), iii) their relatively soft and fissured substrate that allows deep root penetration (van Leeuwen et al., 2018), and iv) the contribution of calcium to the formation of strong berry cell walls, increasing resistance to attack by disease and pests (Sexton, 2002). Some clay content, however, may be good for grapevines. Ideally, soils should have enough clay (or organic matter) for cation exchange (van Leeuwen, Schmutz, et al. 2024), but not too much that it impairs drainage.

Skelton (2020a) argues that while soils are important, they are not normally the major factor in vineyard siting. This is because vines can grow in a wide variety of soil types and because there are various ways to improve soil or increase the suitability of the grapevine to soil conditions through rootstock, cultivar and clonal choice. Chardonnay is clearly able to grow successfully in a wide range of geological and soil settings – including, among others, the chalk soils of Champagne and southern England, the gravelly alluvial soils of Sonoma in California, the ironstone and quartzite clay-rich soils of Adelaide Hills, South Australia and the varied soils found on the basaltic lava flows and marine sediments of Willamette Valley, Oregon – albeit wine characteristics and wine typicity may differ. Consistent with this idea, Anastasiou et al. (2023) found that cultivation practices largely eliminate the effect of soil on table grape quality.

While soils are secondary to climate and weather in determining wine quality, their impact on wine characteristics remains a topic of debate (Koundouras, 2022). Recent research into microbial assemblages in soil and their role in grapevine health and reproduction (Liu and Howell, 2021; Borghi et al., 2024; Lailheugue et al., 2024) suggest soil microbes may also have an influence on grape quality that is yet to be fully explored. For example, Liu and Howell (2021) suggest water availability may be a major influence on the microbiota present within vineyards, and that this may be an additional mechanism for understanding how water status affects wine quality.

5.1.4 Study aims

In this study, areas in England that have similar topography to Chablis, together with suitable soils and drainage for viticulture are mapped. The findings are combined with climate suitability data for both the current period (2010-19) and the mid-Century (2040-59) using data output from the Biss and Ellis (2022) Weather Model, to identify areas in England where Chardonnay vineyards for premium still white wine production may be established. The hypothesis tested is that a combination of climate, topography and soils (Combined Model, as identified by this study) can identify areas likely to produce premium Chardonnay still wine. The findings are evaluated through a survey of wine experts.

The overall aim of the study is to integrate research to date into a practical model that has utility for prospective producers and investors regarding where to site Chardonnay vineyards for the production of premium still wine in England. The findings could also be useful for other emerging cool climate wine regions, such as in Canada, China and Scandinavia.

5.2 Materials & Methods

5.2.1 Topography for England

Topographic data for England was obtained from the LIDAR Composite Digital Terrain Model (DTM) provided by the Environment Agency (2023a), comprising elevation data at 10-metre resolution. A Geographic Information System (QGIS 3.28.13) was then used to generate two topography derivatives: slope gradient and aspect.

The 10-metre LIDAR resolution selected aligns closely with the 9-metre resolution recommended for slope gradient analysis by Miller & Schaetzl (2015). Testing higher resolution data (at 1 and 2 metres) resulted in anomalous results, particularly in fields with pronounced ridges, furrows or tramlines (Appendix 5B).

This study is focused on England, as comparable LIDAR data of similar resolution was unavailable for both England and Wales.

5.2.2 Soils for England

Soil classification followed the methods of Nesbitt et al. (2018) and Vinescapes (2019), using Cranfield University's LandIS Soilscapes data (Farewell et al., 2024a and 2024b). The dataset contains 27 soil classes, of which eight were identified as suitable for viticulture, based on agricultural potential and drainage characteristics. Additionally, four soil types were deemed suitable but with impeded drainage, necessitating further inspection (Appendix 5C) (Nesbitt et al., 2018; Vinescapes, 2019). For mapping purposes in this study, these four soil types were only considered suitable on slopes exceeding 5% gradient, allowing for overland flow and drainage.

Soil variability, however, is considerably greater than that represented by the Soilscapes data and this may impact vineyard suitability. Thorough on-site soil analysis would be required before making any investment decisions.

5.2.3 Identification of Exclusion Areas for Viticulture in England

Several datasets were employed to delineate areas unsuitable for viticulture due to existing land-use (Appendix 5D), flood risk or legal protections (Appendix 5E). These include datasets from the UK Centre for Ecology & Hydrology (2023) for land-use, the Environment Agency (2023b, 2023c) for flood risk, and protection status from Historic

England (n.d.) and Natural England (n.d.). This approach follows that of Nesbitt et al. (2018), with minor adjustments in the Historic England and Natural England data (Appendix 5E).

5.2.4 Generalised Topographic Categories for Chablis Appellations

Topographic data for the Chablis vineyards in Burgundy, France, was obtained from Biss (2020) for the three main Chablis appellations: Chablis ("Village"), Premier Cru and Grand Cru (Table 5.2).

Table 5.2. Percentage of Chablis appellation vineyard land in various aspect and slope gradient categories (from Biss, 2020). Note: mean elevation of Village vineyards is 210.4 m (range 120 – 322m, SD 34.6), Premier Cru 193.2 m (range 123 – 291m, SD 29.6), and Grand Cru 166.1 m (range 128 – 219m, SD 20.2). Elevation of Chablis weather station 141 m.

Aspect categories	Village	Premier	Grand	**Slope categories**	Village	Premier	Grand
North (0-22.5°)	7%	1%	0%	Level (0-0.5%)	0%	0%	0%
Northeast (22.5-67.5°)	8%	3%	0%	Nearly level (0.5-2%)	3%	1%	0%
East (67.5-112.5°)	10%	16%	1%	Very gentle (2-5%)	16%	5%	2%
Southeast (112.5-157.5°)	14%	36%	11%	Gentle (5-9%)	27%	18%	15%
South (157.5-202.5°)	12%	18%	30%	Moderate (9-15%)	30%	32%	27%
Southwest (202.5-247.5°)	9%	13%	30%	Strong (15-30%)	22%	38%	46%
West (247.5-292.5°)	13%	11%	21%	Very strong (30-45%)	2%	6%	9%
Northwest (292.5-337.5°)	19%	3%	7%	Extreme (45-70%)	0%	0%	1%
North (337.5-360°)	7%	0%	0%	Steep (70-100%)	0%	0%	0%

Solar irradiation charts were also generated to investigate the interaction between slope aspect and gradient for Chablis (Figure 5.2). This analysis was then used alongside the abovementioned Chablis topographic data to define slope aspect / gradient categories for the three wine quality levels, such that as the category of slope steepness increases, the acceptable range of aspect narrows (Figure 5.2). The categories identified were i) Unclassified, ii) Village quality (very gentle slopes with good drainage), iii) Premier Cru quality (gentle, moderate or strong slopes facing East to South-East) and iv) Grand Cru quality (gentle, moderate or strong slopes facing South to West) (Figure 5.3).

5.2.5 Application of the Generalised Topographic Categories to England

Using the generalised topographic categories for Chablis, land in England was similarly classified into these same four categories – Unclassified, Village, Premier Cru and Grand Cru (Figure 5.3).

Slopes greater than 30% in gradient may be suitable for manually-worked vineyards or specialist tracked equipment, as is the case for 6 % and 10 % of Premier Cru and Grand Cru vineyard land in Chablis respectively (Table 5.2), but is widely considered dangerous for machinery work (Vigoroso et al., 2019). As such, it has been treated in this study as sub-optimal and so is unclassified.

Slopes ≤ 2 % are considered unsuitable here because they are often too flat for efficient drainage of rainwater and cold air. They are rare in Chablis accounting for only 3 % and 1 % of Chablis Village and Premier Cru vineyard land area (Table 5.2) and have therefore been excluded as potential areas in this study.

Land at the top and bottom of hills is usually sub-optimal for viticulture (see section 5.1.2). By only identifying slopes with gradient greater than 2 %, these problematic Summit and Toeslope areas (Miller & Schaetzl, 2015) were effectively excluded.

Although 1-100 or 1-150m elevation have been suggested by Nesbitt et al. (2018) and Skelton (2020a) as the limits for cultivation, elevation was not used as a limiting factor here to identify potential vineyard sites given i) HadUK-Grid climate data already accounts for elevation, ii) current observed elevation limits to viticulture will not necessarily apply in a future warmer climate, and iii) the elevation of Chablis vineyards are much greater than 150m (to a maximum of approximately 322 m).

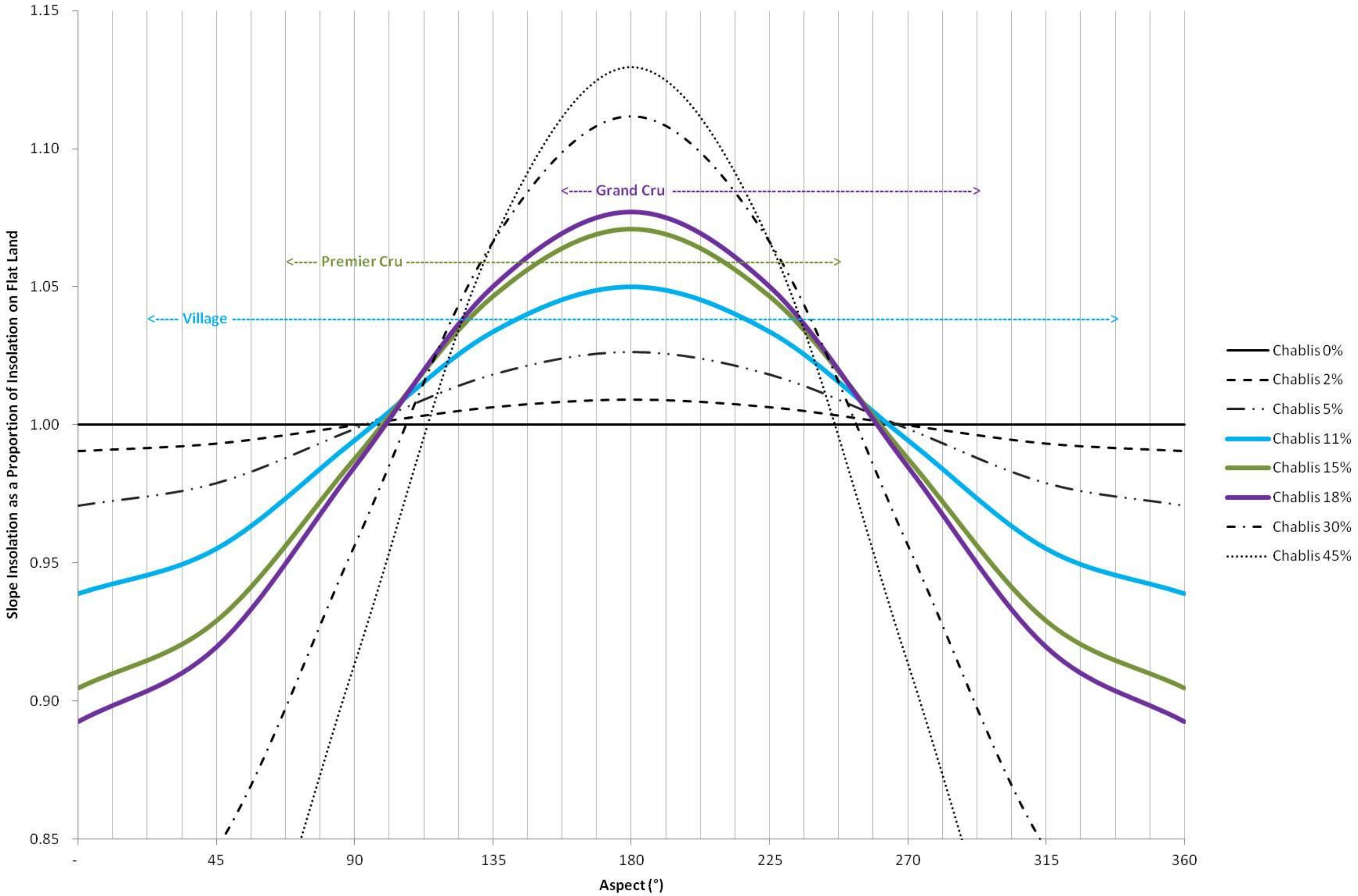

Figure 5.2. Insolation on Chablis slopes (from 0 to 45% in gradient) as a proportion of that on flat land (0% slope). Note aspect ranges for Village, Premier and Grand Cru (dashed horizontal lines in blue, green and purple) denote the range of aspects within which 80%+ of vineyards in that appellation can be found. Mean gradient for Village, Premier Cru and Grand Cru appellations are 11, 15 and 18% respectively (Biss, 2020). Plots calculated from meteoexploration (n.d.), based on latitude 47.815°, longitude 3.801°, elevation 200m, and relative humidity 50%.

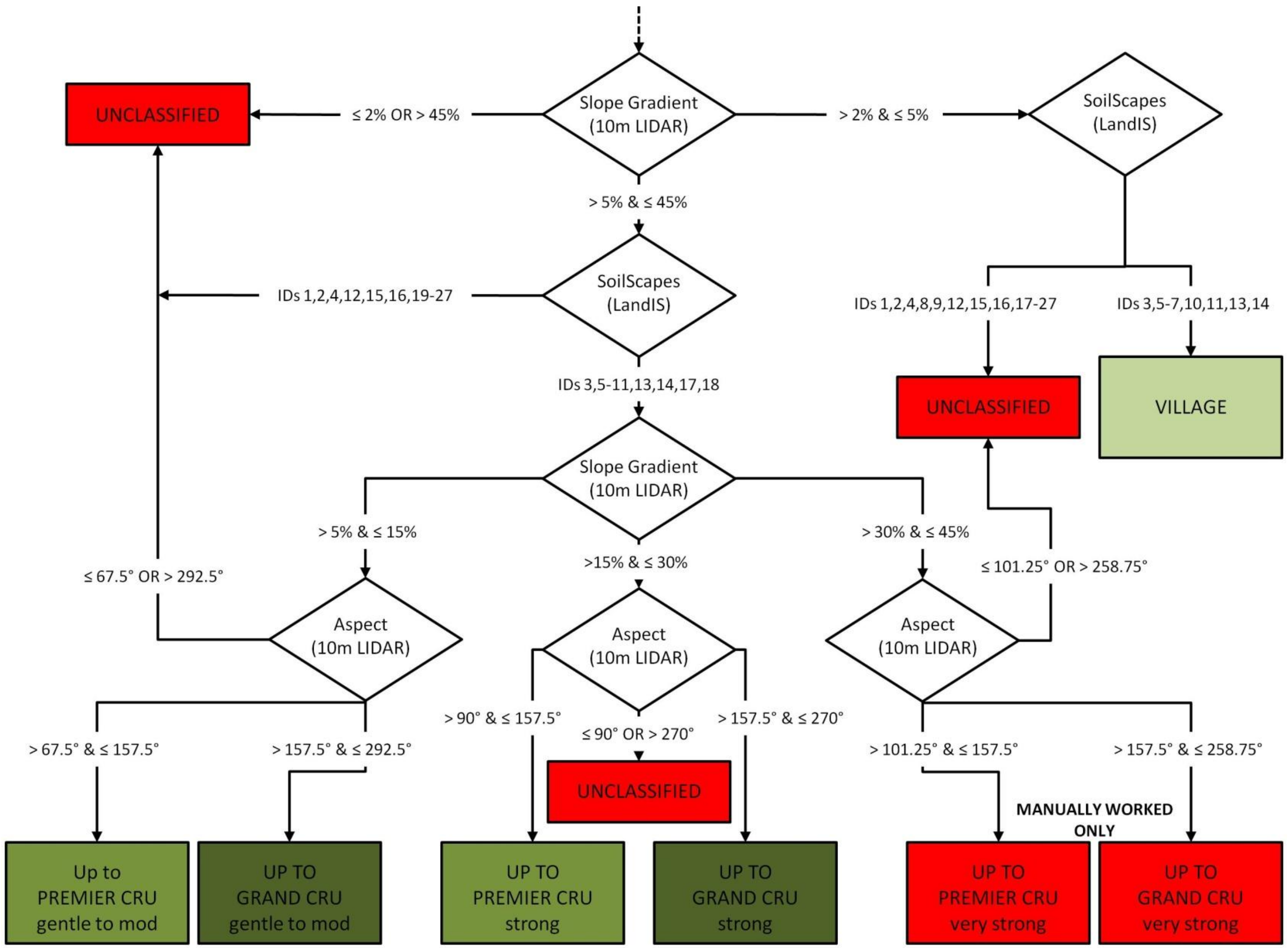

Figure 5.3. Generalised model to identify suitable land in England for Chardonnay viticulture for still wine, based on topography and soils. Note the topmost arrow represents the input of LIDAR 10 m data for England less areas excluded because of existing land use (Appendix 5D), flood risk (Appendix 5E) and protected designation (Appendix 5E). The limits shown are discussed in the text.

5.2.6 Integration of Climate Data for England (2010-19 and 2040-59)

Potential vineyard locations were overlaid with output from the Weather Model of Biss & Ellis (2022) based on climate data only for mean vintage quality for 2010-19 and 2040-59 under three scenarios: i) 2010-19 as a proxy for the current climate (which is also similar to the 5th percentile RCP 4.5 projection for 2040-59), ii) 2040-59 RCP 4.5 50th percentile, which represents vintage scores for the median and most likely climate scenario, and iii) 2040-59 RCP 4.5 95th percentile with an alternative method for calculating the Cool Night Index (*CNI2*) (see Chapter 3). These scenarios represent the lower, middle and upper end of vintage quality predictions for mid-Century arising from an approximate 0.5, 1.5 and 2.5 °C rise in mean April to September temperatures respectively, relative to 1981-2000.

5.2.7 Adjusting for Elevation Differences in England between LIDAR and HadUK-Grid cells

A complication arose because the topography model was built on LIDAR cells with a resolution of 10m, whereas the climate data came from HadUK-Grid cells with a resolution of 5km (that already account for elevation) (Met Office et al., 2020). In other words, the mean elevation of an identified land parcel may be higher or lower than the mean elevation of its HadUK-Grid cell and can therefore be expected to be cooler or warmer, respectively, than the climate data upon which the vintage ratings were calculated; by approximately 0.65 °C per 100 metres based on the mean adiabatic lapse rate (Royal Meteorological Society, 2024). Areas in England where the elevation discrepancy was greater than 25 m were identified (Appendix 5F), which may require greater caution in the interpretation of their expected vintage score.

5.2.8 Proof-of-concept for the Combined Model

The Combined Model was evaluated by comparing two datasets.

5.2.8.1 Dataset 1: Land classification for existing producers

Vineyards in England with Chardonnay grapevines (> 1 ha; from Skelton, 2024) and known for production of still Chardonnay wine were digitised in QGIS. In all, 24 producers were identified as making single cultivar still Chardonnay wine from grapes grown in either their own vineyards or explicitly stated sources in England (Appendix

5G). For these vineyards, i) the percentage of their land (or the land from which the grapes were sourced) classified as Village, Premier Cru and Grand Cru quality by the current study based on topography and soils (Figure 5.3), and ii) their mean vintage rating in 2010-19 according to the Weather Model based on climate alone (Biss & Ellis, 2021) were calculated. These statistics were then compiled into a relative index (from 0 to 1) to give an overall expected quality of still Chardonnay wine, based on a weighting of 40% topography and soils (this study) and 60% climate. This is consistent with previous research about the influence of climate (Biss and Ellis, 2021). Other weightings, however, were also checked to ensure there was a robust and monotonic relationship between them (Appendix 5H).

5.2.8.2 Dataset 2: Survey of wine experts

A total of 229 wine experts (writers, journalists, bloggers, and UK wine merchants) were extracted from a media database and emailed on 1 December 2024 requesting completion of a survey (Appendix 5G). Of these, 35 completed the online survey using the Qualtrics XM platform (Appendices 5I and 5J). The survey had received ethical clearance from the University of Reading prior to the study.

Respondents were asked to choose up to five of their favourite wines from the list of 24 English wines. They were also asked to select their *most* favourite wine and say which of the wines, if any, were most like Chablis wine. Answers were weighted by their self-declared level of knowledge regarding the 24 still Chardonnay wines listed on the survey; “Limited familiarity” (x 1 weighting, 1 response), “Familiar with a handful only” (x 2 weighting, 9 responses), “Familiar with around half” (x 3 weighting, 9 responses), “I know most of the wines” (x 4 weighting, 15 responses), and “I know all the wines well” (x 5 weighting, 1 response) (Appendix 5G).

5.2.8.3 Statistical analyses

Finally, non-parametric correlation analyses (Spearman’s rank and Kendall Tau) were carried out on the two datasets, to test whether the expected quality of the 24 still Chardonnay wines according to the research presented here and in Biss and Ellis (2022) was consistent with the relative quality of the wines as perceived by the experts.

5.3 Results

GIS files are available at https://doi.org/10.17864/1947.001389 (Biss, 2025).

5.3.1 Classification of English Land based on Topography and Soils

Approximately 21.5 % (2.7 million hectares) of all land in England was classified as being suitable for producing high quality Chardonnay still wine based on the model described in Figure 5.3 which accounts for soils and topography but not climate: the individual quality thresholds were Grand Cru (8.6 %, 1.1 million hectares), Premier Cru (5.7 %, 0.7 million hectares) and Village quality (7.2 percent, 0.9 million hectares).

These areas were distributed across the country (Figure 5.4), generally in the lowland hill and lower upland areas. Major upland areas, such as the Lake District (North West England) and Dartmoor (South West England), tend to have been excluded because of unsuitable soils or existing land use. Large areas in the North West, Midlands and South East (and notably much of Greater London) were excluded because of urban and suburban land use, whilst large areas in Lincolnshire and Cambridgeshire were excluded because they were too flat (≤ 2%).

5.3.2 Integration of Climate Data for 2010-19 and 2040-59

Once climate data (from Biss & Ellis, 2021) was added, the distribution of suitable land shifted considerably towards the East of England and South East England (Table 5.3), particularly so for today's climate (2010-19 proxy) where Chardonnay viticulture for still white wine is generally not advisable beyond these two regions currently.

For 2040-59, the regions of South West England, West Midlands and East Midlands are projected to become more favourable, on average, for Chardonnay viticulture. Under the 95th percentile projection, the area of suitable land identified in the Combined Model is greater in South West England than in the East of England or South East England (Table 5.3), although vintage scores are projected to remain generally higher in the East of England and South East England than in South West England (see Figure 6 and Table 4 in Chapter 3).

The top six counties projected to have the largest areas (ha) of suitable land receiving ≥ 6 in predicted vintage score for mid-Century (RCP 4.5, 50th percentile) are Hampshire,

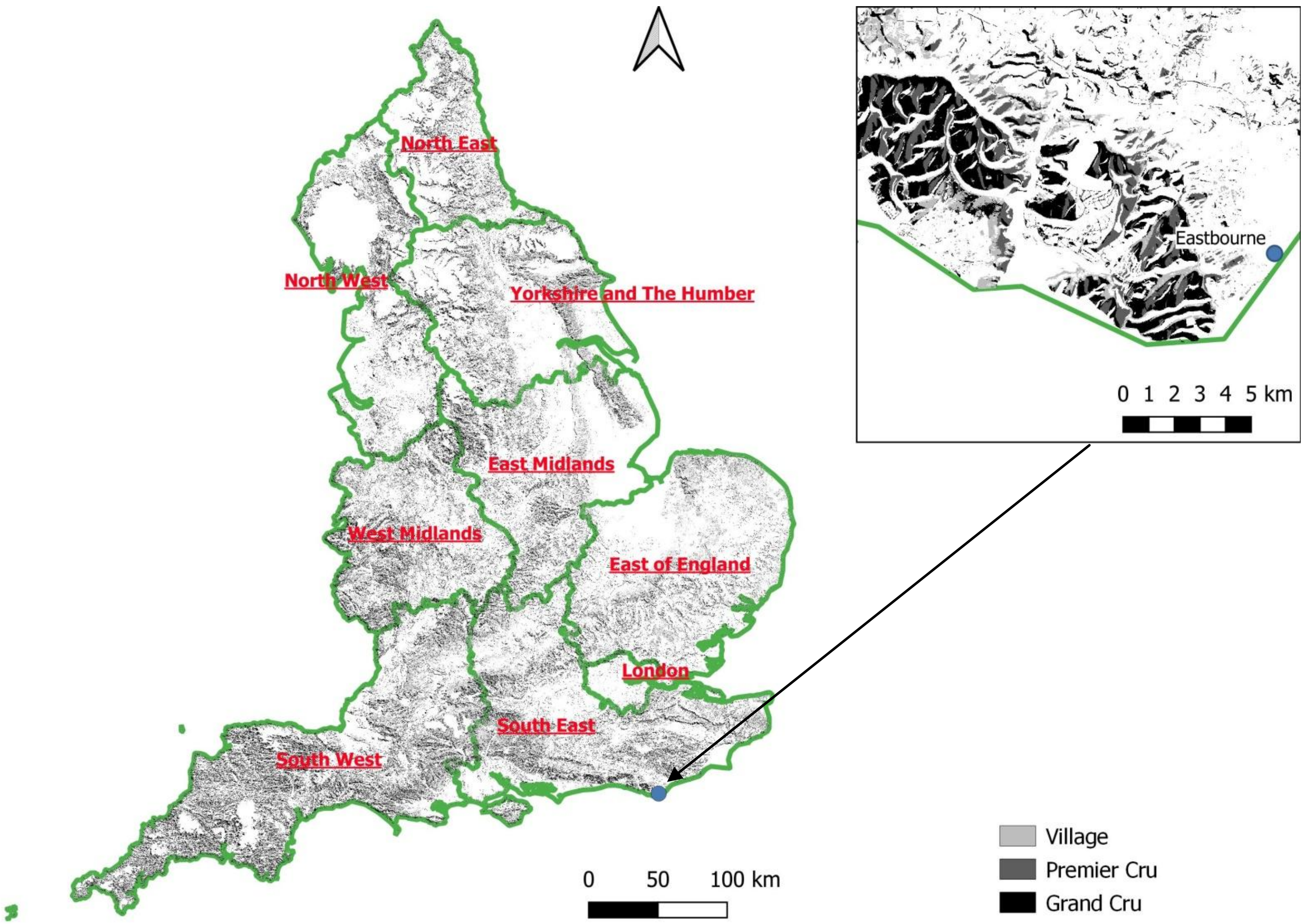

Figure 5.4. Identification of suitable areas in England for still Chardonnay wine production, based on topography and soil, and classified by Chablis appellation equivalent. Inset: Sample close-up of area around Eastbourne, East Sussex. Climate is unaccounted for in these maps.

Table 5.3. Combined Model results: Area of land (ha), by region of England, with suitable topography and soils that achieves a mean vintage score ≥ 6 for three climate scenarios (representing the current climate, and the middle and upper projections for mid-Century) for still Chardonnay wine quality. These areas are further divided into Village, Premier or Grand Cru quality land (in terms of topography and soils; Figures 5.3 and 5.4). Climate derived vintage ratings are based on the Weather Model output from Biss and Ellis (2022). (GST = mean temperature from 1 April to 30 September).

		2010-19 (Current climate) (GST +0.5 to +0.8 °C from 1981-2000) Area of land (ha) with vintage score ≥ 6			**2040-59 (RCP 4.5 50th percentile)** (GST +1.3 to +1.6 °C from 1981-2000) Area of land (ha) with vintage score ≥ 6			**2040-59 (RCP 4.5 95th perc., CNI2)** (GST +2.3 to +2.8 °C from 1981-2000) Area of land (ha) with vintage score ≥ 6		
Region	Total Ha	Village	Premier	Grand	Village	Premier	Grand	Village	Premier	Grand
East Midlands	1,565,817	0	0	0	24,756	8,806	13,769	92,232	62,572	93,273
East of England	1,915,513	5,659	2,435	4,383	126,455	44,249	70,743	170,526	50,365	82,161
London	158,547	1,713	1,496	2,225	3,730	2,694	3,611	4,020	2,792	3,672
North East England	860,994	0	0	0	0	0	0	202	1,214	1,474
North West England	1,417,852	0	0	0	51	76	132	11,492	9,063	19,014
South East England	1,911,592	8,492	3,205	3,948	149,705	104,992	139,135	179,881	128,792	171,831
South West England	2,397,831	0	0	0	56,953	42,225	63,108	201,701	183,958	294,778
West Midlands	1,298,714	33	120	136	17,550	19,367	24,536	78,714	96,600	125,139
Yorkshire and Humber	1,509,626	0	0	0	1,317	492	728	79,403	31,548	47,174
Total	**13,036,485**	**15,896**	**7,256**	**10,693**	**380,517**	**222,900**	**315,763**	**818,172**	**566,904**	**838,517**

Table 5.4. Combined Model results: Area of land (ha), by Ceremonial County of England, with suitable topography and soils that achieves a mean vintage score ≥ 6 for mid-Century (2040-59, RCP 4.5 50th percentile) for still Chardonnay wine quality. These areas are further divided into Village, Premier or Grand Cru quality land (in terms of topography and soils; Figures 5.3 and 5.4). Climate derived vintage ratings are based on the Weather Model output from Biss and Ellis (2022). (GST = mean temperature from 1 April to 30 September).

			2040-59 (RCP 4.5 50th percentile) (GST +1.3 to +1.6 °C from 1981-2000) Area of land (ha) with mean vintage score ≥ 6				
County	Region	Total County Area (ha)	Village	Premier	Grand	Total	% of County Land[1]
Hampshire	South East England	385,424	52,677	21,723	27,603	102,003	26%
Kent	South East England	390,825	33,608	22,552	26,734	82,894	21%
Suffolk	East of England	385,337	32,104	10,435	17,845	60,385	16%
Essex	East of England	394,720	23,653	11,245	18,565	53,463	14%
West Sussex	South East England	202,354	11,332	13,038	21,058	45,428	22%
East Sussex	South East England	181,052	3,045	19,032	23,134	45,211	25%
Norfolk	East of England	550,909	31,912	3,613	7,250	42,774	8%
Oxfordshire	South East England	260,585	25,674	6,366	9,649	41,689	16%
Somerset	South West England	425,575	12,289	11,373	17,335	40,996	10%
Dorset	South West England	269,483	16,065	8,760	13,774	38,600	14%

Wiltshire	South West England	348,534	15,806	7,178	11,063	34,047	10%
Hertfordshire	East of England	164,302	10,995	9,253	12,954	33,203	20%
Cambridgeshire	East of England	339,742	20,050	4,862	7,948	32,860	10%
Gloucestershire	South West England	324,103	8,142	8,225	11,142	27,509	8%
Buckinghamshire	South East England	187,355	7,587	7,856	11,613	27,056	14%
Herefordshire	West Midlands	217,967	7,665	7,434	9,410	24,509	11%
Surrey	South East England	167,006	6,946	6,617	9,908	23,471	14%
Worcestershire	West Midlands	174,051	6,416	7,478	9,044	22,938	13%
Devon	South West England	683,978	4,311	6,309	9,272	19,892	3%
Bedfordshire	East of England	123,539	7,712	4,880	6,309	18,901	15%
Northamptonshire	East Midlands	236,696	8,663	3,424	4,845	16,931	7%
Berkshire	South East England	126,386	6,019	4,567	5,225	15,811	13%
Lincolnshire	East Midlands	718,194	8,900	1,346	2,634	12,880	2%
Isle of Wight	South East England	39,494	2,867	3,252	4,186	10,305	26%
Warwickshire	West Midlands	197,747	1,763	3,449	4,781	9,992	5%
Nottinghamshire	East Midlands	216,153	4,324	2,027	3,618	9,969	5%
Greater London	London	159,467	3,690	2,634	3,527	9,851	6%
Rutland	East Midlands	39,374	1,787	664	670	3,122	8%
Staffordshire	West Midlands	271,677	1,347	553	703	2,602	1%

Leicestershire	East Midlands	215,709	310	844	1,123	2,277	1%
Derbyshire	East Midlands	262,881	804	529	863	2,197	1%
West Midlands	West Midlands	90,162	356	428	592	1,376	2%
South Yorkshire	Yorkshire and Humber	155,208	935	147	226	1,308	1%
West Yorkshire	Yorkshire and Humber	202,925	378	344	501	1,223	1%
Cornwall	South West England	363,603	119	235	333	686	0%
County of Bristol	South West England	23,535	212	149	191	552	2%
Cheshire	North West England	238,027	51	76	132	259	0%
East Riding of Yorkshire	Yorkshire and Humber	257,634	5	1	1	6	0%
Merseyside	North West England	81,751	0	0	0	0	0%
Cumbria	North West England	718,254	0	0	0	0	0%
Durham	North East England	269,226	0	0	0	0	0%
Greater Manchester	North West England	127,599	0	0	0	0	0%
Lancashire	North West England	326,321	0	0	0	0	0%
North Yorkshire	Yorkshire and Humber	867,991	0	0	0	0	0%
Northumberland	North East England	507,847	0	0	0	0	0%
Shropshire	West Midlands	348,759	0	0	0	0	0%
Tyne and Wear	North East England	55,115	0	0	0	0	0%
Total		**13,294,579**	**380,516**	**222,900**	**315,762**	**919,179**	**7%**

[1] Total Village, Premier Cru and Grand Cru suitability as % of all land in County.

Kent, West Sussex, and East Sussex in South East England and Suffolk and Essex in the East of England (Table 5.4). In terms of Premier and Grand Cru classification only (excluding land classified as Village), the counties of Hampshire, Kent and East Sussex were projected to have the largest areas of suitable land (Table 5.4).

Two areas are shown for the three periods as examples – East Sussex (South East England) and the Crouch Valley in Essex (East of England) – with a simple overlay showing topographically favourable land that could be used to produce premium quality Chardonnay wine (Figure 5.5), potentially experiencing more favourable local and micro-climates than the general climate for the area. In both areas the change from today's climate (2010-19 proxy) to the RCP 4.5, 50th and then 95th percentile improved predicted scores. The Crouch Valley provided the higher vintage scores based on general climate but the highlighted area of East Sussex offered a comparably greater area of suitable land based on topography and soils.

5.3.3 Combined Model proof-of-concept

There was a significant, moderate positive correlation between the results of this study (i.e. land quality incorporating climate, topography and soils) and how wine experts perceived the relative quality of still Chardonnay wine from existing producers in England (Spearman's rank r_s = 0.47, $P = 0.020$; Kendall's tau T = 0.36, $P = 0.018$). This finding was robust (Appendices 5H and 5K).

A plot of the wine experts' favourite wines against the expected quality of land showed a fan shape (Figure 5.6), suggesting poor quality land (as identified in this study) is unlikely to produce grapes of the necessary quality for premium wine. As the quality of land increases, however, the *potential* for premium wine also increases, though is not necessarily achieved in the judgment of all experts.

Of the existing producers who currently make still Chardonnay wine, five stood out according to the surveyed wine experts: Chapel Down Wines Kit's Coty Vineyard in Kent (relative land quality rating 0.74, weighted votes 70); Danbury Ridge Wine Estates in Essex (0.58, 63); Gusbourne Vineyard in Kent (0.70, 63); Martin's Lane Vineyard in Essex (0.76, 45), and Simpson's Wine Estate – The Roman Road in Kent (0.76, 75) (Figure 5.6 and Appendix 5J).

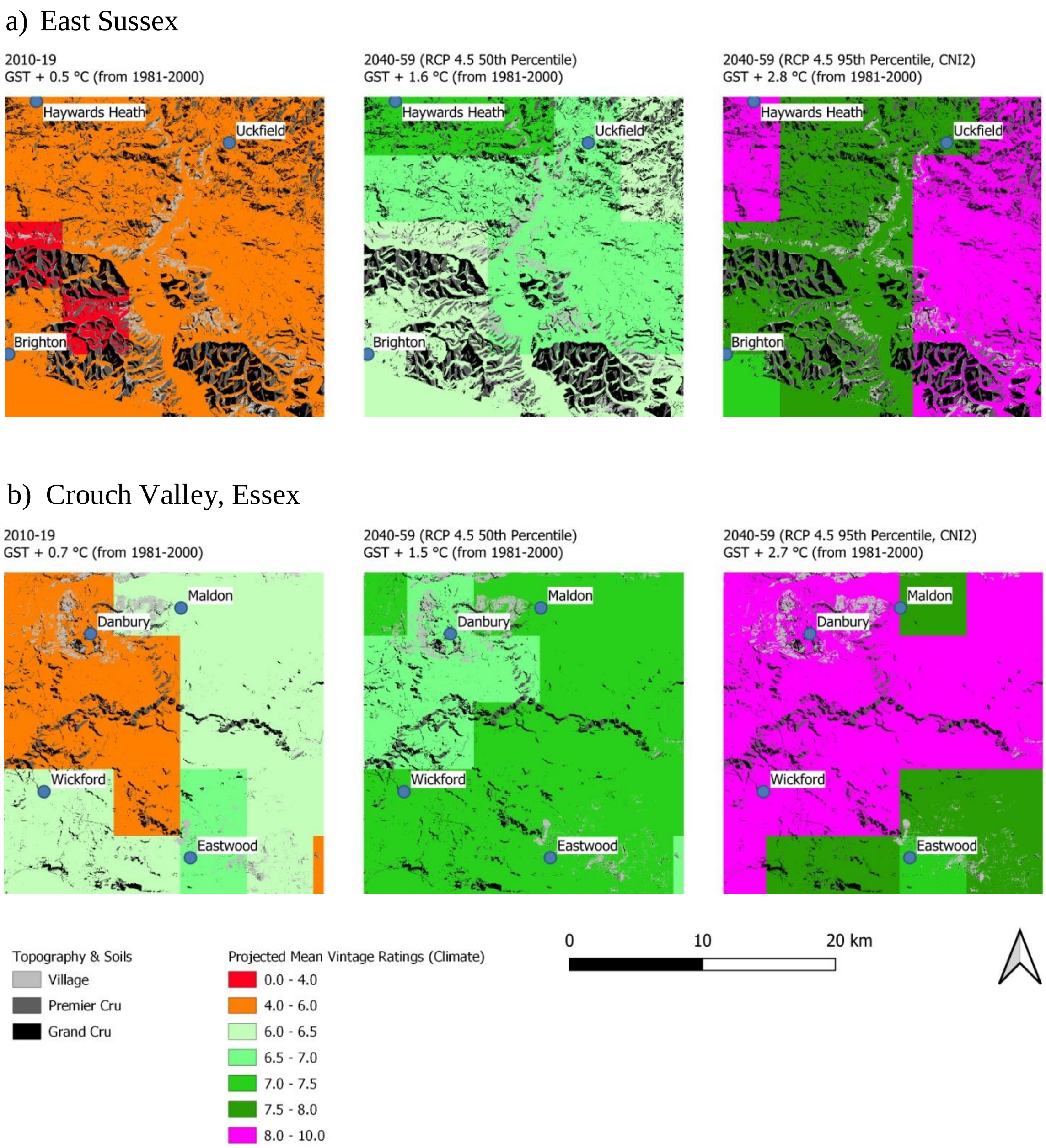

Figure 5.5. Sample close-ups of two areas in England: a) part of East Sussex to the North and East of Brighton, and b) the Crouch Valley in Essex. Samples show mean vintage score predictions (0 to 10) for Chardonnay still wine based on the climate for 2010-19 (left column), 2040-59 (50^{th} percentile) (middle) and 2040-59 (95^{th} percentile with an alternative projection for the Cool Night Index (*CNI2*)) (right) (from Biss and Ellis, 2022). These are overlain with the expected quality of land based on topography and soils from this study (Village, Premier Cru and Grand Cru; Figures 5.3 and 5.4).

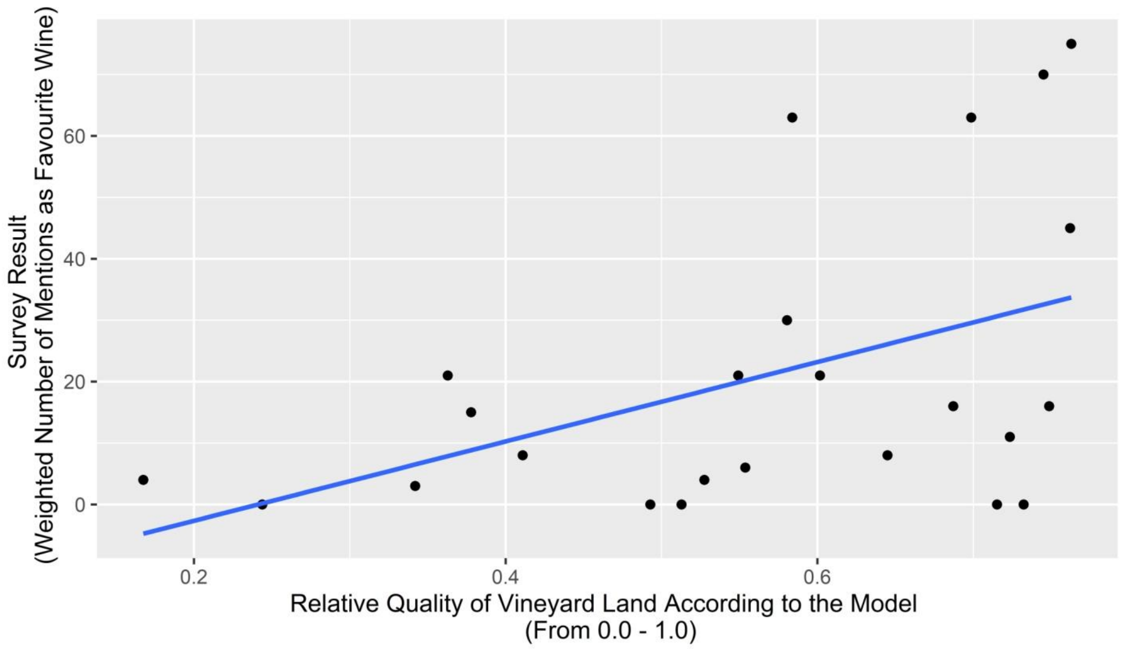

Figure 5.6. Survey results from 35 wine experts (Appendix 5I) asked to name up to five of their favourite English still Chardonnay wines (from a list of 24 wines, Appendix 5G), plotted against the relative quality of the vineyard land (weighted 60% climate, 40% topography and soils). Survey responses were weighted according to the experts' self-declared knowledge of the wines, from "limited familiarity" (x 1) to "I know all the wines" (x 5) (see Section 5.2.8.2).

One producer, Danbury Ridge Wine Estates, was notable for its outperformance. Its wine received a weighted score of 63, second only to Simpson's Wine Estate – The Roman Road, though it ranked only 12th for relative land quality rating (0.58) in this study (Figure 5.6). It was also chosen as the respondents' *most* favourite wine (Q2, Appendix 5G) more times than any other, receiving a total weighted score of 55, compared to the second most cited favourite wine (Gusbourne Vineyard) which received a weighted score of 14.

In terms of identifying the wine most like Chablis wine, Simpson's Wine Estate – The Roman Road received the highest weighted votes (41), well above the second-place choice Gusbourne Vineyard with only 11 weighted votes. Simpson's Wine Estate – The Roman Road was also the highest ranked vineyard in terms of topography and soils, with 96% of its land classified as Grand Cru in this study (Figures 5.3 and 5.4).

However, the relationship between land quality and Chablis-like typicity could not be more fully explored given the extreme asymmetry of the data. Twelve wines received no votes, and only eight wines received > 3 weighted votes. Nine respondents did not answer this question, saying that English wine was unlike Chablis wine or citing vintage variation and recent climate change in Chablis as reasons to prevent comparison.

Notably, of the top five vineyards, only Chapel Down Kit's Coty includes a vineyard area with soils that could be viewed as similar to those of Chablis based on a preliminary assessment of the LandIS National Soil Map (Appendices 5L and 5M).

None of the mean vineyard elevations were more than 32 m higher than the mean elevation of the HadUK-Grid cell upon which vintage scores were predicted (mean difference 3.4 m, standard deviation 18.0 m). Thus no adjustment was required for the purposes of this first-approximation study (see section 5.2.7).

Overall, there is sufficient evidence to suggest that a combination of climate, topography and soils (as identified by this study) can lead to a significant increase in still Chardonnay wine quality (Figure 5.6).

5.4 Discussion

This study provides a method and first approximation approach for where in England to site Chardonnay vineyards for the purposes of producing premium quality still wine reliably.

Building on the findings of Biss and Ellis (2022), suitable land was classed into three potential quality levels (in ascending order of quality) - Village, Premier Cru and Grand Cru - using the Chablis region in France as an analogous model.

Overall, the South East and East of England have the greatest amounts of suitable land for Chardonnay viticulture for the current climate (2010-19) and for mid-Century (2040-59) (Table 5.3), broadly consistent with previous research (Georgeson and Maslin, 2017; Nesbitt et al., 2018). The top six counties projected to have the largest areas of suitable land based on topography and soils, and receiving ≥ 6 (out of 10) in mean vintage score for mid-Century (RCP 4.5, 50th percentile), are Hampshire, Kent, East Sussex, and West Sussex in South East England and Suffolk and Essex in the East of England (Table 5.4). Projected mean vintage scores, however, are slightly higher in Essex and Kent by approximately 0.3 points than in East Sussex, Hampshire, Suffolk and West Sussex (Biss & Ellis, 2022).

Vintage score predictions for 2010-19 and 2040-59 were based solely on climate and weather data, and have already been discussed (Biss & Ellis, 2022). Here the addition of topography and soils to the model (Figures 5.3 and 5.4) and the inclusion of Chablis quality levels are considered.

5.4.1 The influence of topography

While Biss (2020) found no evidence for a topographic effect on wine quality among the Premier Cru areas of Chablis, he found differences in quality at the appellation level. Grand Cru wines (from steep slopes with predominantly south and south-western aspect) scored more highly than Premier Cru wines (less steep, predominantly south-east facing) which in turn scored more highly than Village Chablis (less steep still, more widely orientated), albeit there may have been a consumer bias associated with their expectations of quality from the wine classification.

Additionally, Biss (2020) suggested that topography may have played a more important role in Chablis for historical periods (until around 1990 (Biss & Ellis, 2021)) when climate was more marginal, hence enhancing the reputation of the topographically superior locations of the Premier and Grand Cru vineyards. Certainly, the emerging wine regions of England are marginal in climate for Chardonnay (Nesbitt et al., 2016), and as such the topography of the vineyard may play a more important role in determining the quality of the wine than if the region was more safely located within the suitable temperature range for Chardonnay viticulture. Vineyard topography can play an important role in making viticulture less marginal and more reliable. While there is no firm evidence to prove the extent of temperature uplift for a southerly facing steep slope in Chablis compared to a piece of flat land (given the lack of publicly available small-scale climate data and there only being one Météo-France weather station in Chablis), it could be expected to be a few degrees Centigrade over the growing season based on observations from other regions at similar latitudes (Behr, 2022; Huang et al., 2008; Manley, 1944). Moreover, differences in insolation are greater in spring and autumn than summer, which may be crucial for achieving temperatures for optimum flowering and fruitset, and berry ripening – important periods for determining quality in still Chardonnay wine (Biss and Ellis, 2021).

Slopes with gradient ≤ 2% were categorised as unsuitable in this study. Although some producers might argue that viticulture is evidently possible on such land, this avoided summits and toeslopes of hills (Miller & Schaetzl, 2015) where drainage (of cold air and water) is potentially, though not always, problematic, and which (for summit areas) may be affected by high winds. The objective was to find the most suitable land. It is accepted, however, that certain measures are available to improve drainage and reduce frost-risk (Skelton, 2020a).

The impact on yields (though likely positively correlated with advantageous topography) and production costs were not considered here. Steep-slope viticulture can be up to 2.6 times more expensive than viticulture on flat land (Strub and Loose, 2021), because of increased labour costs and/or use of specialist machinery, and the costs associated with measures to reduce or prevent soil erosion. Accidents with machinery are also more common on steeper slopes (Vigoroso et al., 2019), though for this reason the model excluded land as suitable if it had a gradient greater than 30%. This value is commonly quoted as the limit to operating a tractor safely in the academic literature (e.g., Pereira et al., 2011) and on online forums, depending on tractor type, ground conditions, and load type, and with many provisos on safe handling (Eather and Fragar, 2009).

5.4.2 The influence of soils

Grapevines can grow in a wide variety of soil types (García-Navarro et al., 2023), provided they have access to available water, nutrients, aeration, warmth and sunlight. Crucially, they should be unaffected by waterlogging. The extent to which they can tolerate anaerobic conditions varies by rootstock, cultivar and clone, and the phenological stage they are at, though generally 3 to 7 days is seen as the upper limit before growth is affected (Australian Wine Research Institute (AWRI), 2022). In effect, this means that soil texture and organic matter content are of primary importance, determining levels of permeability. As such, soil data that prioritised permeability and drainage properties were used, consistent with Nesbitt et al. (2018) and Vinescapes (2019).

Additionally:

- Grapevines are perennial plants that are expected to survive in commercial production for around 30 years (Skelton, 2020a), and thus need to develop deep roots to survive occasional and extended periods of drought.
- A soil with clay and organic matter tends to provide more available nutrients, through increased cation exchange capacity.
- Too much clay, however, reduces permeability (though increases porosity and available water).
- Deficiencies in nutrition and/or soils that are too acidic or alkaline can be managed, to some extent, through choice of rootstock, cultivar, clone and/or soil improvement measures.
- Microbial assemblages in soil play an important role in grapevine health and reproduction (Liu and Howell, 2021; Borghi et al., 2024; Lailheugue et al., 2024), though their influence on wine grape quality is yet to be explored fully.

The importance of calcareous soils in viticulture, particularly for cool climate Chardonnay wines, has been widely discussed within the wine industry and in the academic literature (Sexton, 2002; Eslava-Lecumberri and Jiménez-Ballesta, 2024). A strict analogy that says only Kimmeridgian or similar marl-based soils (as found in Chablis) should be used to produce premium quality Chardonnay may be unwise however. Grapevines can grow on many different soil types and various decisions can be taken regarding choice of rootstock and/or clone, or soil improvement and drainage measures put in place that may ameliorate certain undesirable conditions such as low nutrient availability or low/high pH (Skelton, 2020a). Moreover, the characteristics of Kimmeridgian soils are themselves highly variable at the local, regional and country scale (Biss, 2020; Gallois, 2005).

If calcareous soils with high clay content were needed, then the hectarage of Premier and Grand Cru quality land would be considerably reduced (111,295 versus 538,663 hectares) and refocused towards the East of England (all counties except Norfolk), as well as certain counties in South East England (Kent and Buckinghamshire) and South West England (Somerset) (RCP 4.5, 50th percentile) (compare Table 5.4 with Appendix 5N).

A preliminary comparison between the weighted number of mentions of a producer as a favourite of experts (Figure 5.6 and Q1, Appendix 5G) and the distribution of calcareous clay soils similar to the Kimmeridgian soils of Chablis (Appendix 5L), however, revealed no relationship. Only one of the top five wines is from vineyards located on similar soils to those of Chablis.

5.4.3 Is Chablis an appropriate analogy?

The aim of this study was not to engineer a replica of Chablis wine. The premise is that the Chablis topography serves as a guide for cool climate Chardonnay viticulture, as these vineyard areas have generally supported successful Chardonnay cultivation for centuries.

Other regions may also provide insights into the climate, topography and soils conditions necessary for successful Chardonnay viticulture in England. Chablis is, however, geographically the closest comparable region. Southern England and south-central England already have a similar climate to that of Champagne from 1961 to 1990 (Droulia and Charalampopoulos, 2022) and are now producing high quality sparkling wine using the traditional Champagne grapevine cultivars. This suggests further warming would put Chablis (located in northern Burgundy, just 160 km south-southwest of Reims in Champagne) the next logical reference point for viticulture development in England.

There may be differences in certain weather variables (cloud cover, wind, humidity, precipitation intensity) that were not captured in the data used by Biss and Ellis (2021, 2022) and differences in latitude that affect hours of daylight, which mean the analogy is not perfect. In terms of weather variability, however, an analysis of growing season temperature and precipitation shows that inter-annual variability in southern, central and eastern England is comparable to the Chablis region (Biss and Ellis, 2022).

5.4.4 Influence of winemaker and vineyard management

Though not a part of this study, producers make many decisions that affect grapevine yield and grape quality. These arise from long-term planting decisions (trellising type, row orientation, grapevine density, and land amelioration) and shorter-term agronomic practices (pruning, green harvesting, pest and weed control, leaf stripping and harvest timing) (van Leeuwen et al., 2019; Skelton, 2020a).

Likewise, the winemaker's decisions regarding vinification and storage have considerable impact on final wine quality and have been widely researched (Jackson, 2014). Decisions regarding yeast also impact on quality (Celis et al., 2023). Interestingly, this does not just relate to use of commercial yeast species, typically *Saccharomyces cerevisiae* Meyen ex E.C. Hansen. Naturally-occurring yeast assemblages in the vineyard and winery evolve differently around the world, potentially adding a unique regional character to the wine, often without the producer's intervention (Szymanski, 2023).

Despite these many influences, most producers and researchers agree that the quality of the grapes – in terms of pH and concentrations of sugars, acids, and secondary metabolites – is a crucial and limiting factor to the potential quality of the final wine (Gambetta et al., 2016).

5.4.5 Proof-of-concept results

Correlation coefficients between expectations of wine quality for existing producers of English still Chardonnay (from the Combined Model) and the opinions of wine experts were significant, albeit moderate, providing proof-of-concept for the results presented here. The moderate correlation is likely due to the fan shape of the relationship (Figure 5.6), where higher model scores result in a wider range of expert opinions.

Several reasons could explain the fan shape of Figure 5.6: i) differences in vineyard management and winemaking practices mean wine quality is not necessarily maximised despite 'good' quality land (Section 5.4.4), ii) there is less agreement among experts on wine quality particularly at the 'better end' (Hodgson, 2008), and/or iii) the model is missing an important environmental factor or lacking in resolution (particularly for the weather and climate data).

The data showed no preference for wines from larger producers among the wine experts (Appendix 5K).

5.5 Conclusions

This study presents and evaluates a methodology for identifying potential sites for Chardonnay viticulture for production of premium quality still wine, using the Chablis region as an analogous model.

The method involves two-steps. First, calculation of climate-based vintage scores for the current climate and out to mid-Century using the Chablis Vintage Model (called here the Weather Model; Biss and Ellis, 2021). Second, assessment of the land for topography and soils, classifying the land into either Unclassified, Village, Premier Cru or Grand Cru quality using the methodology set out in this Chapter (Figure 5.3). Suitable land for further investigation would score highly in both steps.

Proof-of-concept results suggest a combination of climate, topography and soils (as identified by this study; Combined Model) can lead to a significant increase in still Chardonnay wine quality. While soils are important, particularly regarding water balance and drainage, there is no evidence to suggest that soils should be similar to the Kimmeridgian soils of Chablis in order to produce premium quality still Chardonnay wine.

The methodology has been created for and applied to England, but could also be adapted for other emerging cool climate viticulture regions, such as in Canada, China, and Scandinavia. Given the greater distance from Chablis, however, applying this analogy to other regions should be carried out with caution.

Chapter 6. General Discussion

This investigation probed whether climate change will allow the UK to become a reliable producer of premium-quality still Chardonnay wine and, if so, where within the UK's diverse regions. It used the Chablis region in Burgundy, France, as an analogy for UK viticulture; to understand what weather, topography and soils are associated with premium quality still wine and to understand the limits to producing good to excellent wine vintages from Chardonnay, a major cool climate French grape cultivar.

The findings presented here may be used to inform site selection for new Chardonnay vineyards, primarily in the UK and possibly in other emerging cool climate wine regions. The methodology was consistent with the approach of Ashenfelter (2017), who said that knowing the relationship between weather and grape quality in existing growing areas allows us to predict the quality of grapes that could be grown in other locations (or the same location with a changed climate) and allows optimisation of grape type selection. It was also consistent with the UK's Agriculture and Horticulture Development Board's (AHDB) action plan for climate change adaptation (2025 – see section 6.9.3 on "horizon-scanning").

Findings from this thesis showed that i) weather is the primary determinant of Chardonnay wine quality in Chablis, ii) topography plays an important role in modulating warmth and soil drainage, and iii) that a model built on the Chablis region provides an excellent analogy for identifying potential vineyard sites in the UK.

By the mid-21st Century, many parts of South-East and Eastern England will be suitable for Chardonnay vineyards to produce high quality still Chardonnay wine under a middle-of-the-road climate projection scenario. This area would extend further into the Midlands and the South-West under a greater warming scenario. On the other hand, meeting, or approaching, the Paris Agreement emissions targets, though unlikely, would mean that the climate in South-East and Eastern England would continue to be more suitable for sparkling wine production.

The importance and contributions of the thesis are discussed in greater detail below.

6.1 New analogous approach

This thesis presented a new quantitative approach to identify suitable Chardonnay viticulture sites in the UK for the purposes of producing premium quality still wine reliably (Chapter 5), using the Chablis region in France as an analogous model in terms of climate (Chapters 2 and 3) and topography and soils (Chapter 5).

The approach was designed to consider wine quality, not yield, and it may be useful to combine the approach with existing yield-based assessments such as those of Nesbitt et al. (2018). However, yield and quality are often well correlated especially in cooler wine regions like England (Nesbitt et al., 2022), except if extreme damage to crops occurs through frost and/or hail. These risks are particularly high in the weeks after budburst when buds are delicate, typically from April to May. Note that the potential damage from hail or other extreme events was not accounted for in the Weather Model developed in Chapter 2.

Some consideration was given to frost risk. Only slopes with gradient greater than 2% were included for land classification, thus excluding problematic summit and toeslope areas where cold air drainage is impeded (Chapter 5). Other barriers, however, such as hedges, woods, etc., may serve as barriers to cold air drainage, and/or dips in the land may create cold air pooling. Any site would need to be fully investigated to estimate frost risk and decide on mitigation measures.

6.2 Modelling of Chablis vintage quality

In Chapter 2 it was shown that vintage quality in Chablis varies in a predictable manner with weather. A regression model was devised to model the relationship. Chablis had not previously been looked at in this way separately to the rest of Burgundy. It showed that weather is key for Chablis quality, particularly i) warmth from April to September, ii) night-time temperatures during ripening (*CNI*), and iii), precipitation from June to September (approximately the period from flowering & fruitset to harvest). Moreover, the average temperature from 1 May to 31 July (peri-flowering) provides a good early estimation of likely still wine quality there (Chapter 2).

This thesis examined the effects of weather variables on Chablis wine quality, but not the intermediate stages of (a) the effects of weather on grape biochemistry and (b) the relationships between variation in grape biochemistry and Chablis wine quality. The effect of *CNI* on Chablis wine quality is especially interesting and novel given that *CNI* was not found to affect other white Burgundy wines (Davis et al., 2019), but then *CNI* values are appreciably cooler in Chablis than other white wine growing areas of the region (Table 5, Chapter 2). As already noted in that chapter, acidity is more important for Chablis than other white wines from Burgundy (George, 2007).

The variable *CNI* in the multiple regression model was a strong driver of vintage score (Table 2, Chapter 2). The late ripening period, which now typically falls in September in Chablis, is key to the development of flavour and aroma compounds in the grapes (Guillaumie et al., 2011). Meteorological drivers of cool nights are several and include, for example, high-pressure systems associated with clear sky days and nights and large diurnal temperature ranges, as well as northerly winds that provide both cool days and cool nights. These differences affect the light incident on the berries and, in turn, the concentrations of flavour and aroma compounds in the grapes (Alem et al., 2019; Blancquaert et al., 2019). The negative effect of precipitation ($P_{Jun\text{-}Sep}$) on vintage score (Table 2, Chapter 2) is consistent with a benefit to wine quality from clear skies.

Independently of associated daytime conditions, a low *CNI* (i.e. cool nights) reduces respiration rates, so berries lose less malic acid (the main acid degraded during ripening) and, to a lesser extent, sugars overnight (Jackson, 2014; Arrizabalaga-Arriazu et al., 2020; Keller, 2020). It may also affect the concentration of other secondary metabolites, as suggested by work on low night temperatures increasing anthocyanin accumulation in Corvina grapes, albeit at veraison (Gaiotti et al., 2018). As such, when combined with adequate daytime warmth and sunlight, cool nights during ripening can lead to slower, more even berry maturation and thus more balanced wines (van Leeuwen & Darriet, 2016).

6.3 Minerality

Chapter 4 reported an investigation into how minerality of Chablis wine varied with weather, soils and topography. This research involved textual analysis of tasting notes from CellarTracker. Minerality is a key characteristic of Chablis wine, thought to be closely tied to its terroir.

This textual analysis was a new way to investigate minerality. Prior research had looked at biochemistry and used small expert panels, whereas Chapter 4 took a “wisdom of crowds" approach similar to that of Biss (2020). The findings showed that minerality is likely linked to weather, not soils and geology, consistent with Maltman (2013), and that analysis of tasting notes can provide useful insights into wine quality. The implication of this research is that if weather drives a key defining characteristic of Chablis wine, then climate change can effectively transfer the wine characteristics of one region to another one (subject only to the winemakers' skills).

This issue of minerality is tied to the concept of terroir, which says that the interaction between the environment, the grapevine and viti- and vini-cultural techniques in any geographic area or region produces a wine that is unique and distinct from wines from other regions. The difficulty is that terroir, by OIV definition, includes everything that affects the wine up to and including bottling. However, some factors are more transferrable and changeable than others. For example, climate change is resulting in changes to growing season temperatures and precipitation, whereas geology does not change (at least, not on the timescales important to viticulture). Vineyard and winery practices can also be replicated from one region to another; and indeed winemakers often move from region to region and across national boundaries to develop their careers.

As such, it is important to define and quantify the contribution of individual factors to a terroir objectively (Anesi et al., 2015), especially when considering whether an emerging wine region such as England will be able to produce still Chardonnay wines that are comparable in quality to those of Burgundy. Van Leeuwen et al. (2020) argue that even with standardised vineyard and winery practices, terroir variables cannot be fully controlled or replicated, and they imprint distinct chemical signatures in the wine. However, the findings of Chapter 4 suggest that at least one distinct property of Chablis wine (i.e., minerality) is driven by weather and the typicity of the wine may therefore be less fixed to its geographical location than if geology and soils were the primary drivers, especially with climate change.

6.4 Application to the UK, now and with Climate Change

In Chapter 3, the Weather Model (Chapter 2) was applied to the UK to see where it is possible climatically to produce premium quality still Chardonnay wine now, and where it will be possible by mid-Century with climate change. Previous research had used general cool climate viticulture thresholds with yield, not quality, as the criteria. We now know how areas of the UK compare to Chablis, climatically. The UK has generally not been suitable for reliable production of premium quality still Chardonnay wine in recent times. By mid-Century, several areas will be suitable climatically, particularly in South-East and Eastern England, extending further into the Midlands and the South-West under a greater warming scenario. The distribution of suitable land identified by the model differs slightly from prior yield-based research (Nesbitt et al., 2018). Specifically, in Nesbitt et al.'s work high suitability areas were i) concentrated along coastal areas and ii) stretched further south-westwards (Chapter 3).

6.5 Extending the Analogy with Topography and Soils

Topography will have the effect of modulating climate, weather and drainage at the local level. In Chapter 5, Chablis topography and soils data (from Biss, 2020) were used in combination with the Weather Model (Chapters 2 and 3), to further narrow down the most-suitable sites in England for Chardonnay vineyards. This research continued the Chablis analogy to its logical conclusion, dividing suitable land into three wine quality levels at a 10m resolution. The result is that we now know how areas of England compare to Chablis, climatically and topographically and, in general structural terms, soils. When taking into account topography and soils, and excluding areas because of land use, protected status or flood risk, suitable areas by mid-Century (RCP 4.5 50th percentile) are concentrated in South-East and Eastern England, but also extend to the Midlands.

6.6 Unique Survey to Evaluate Findings

Wine experts were surveyed to investigate which UK producers are currently making the highest quality still Chardonnay wine (Chapter 5). The findings from this survey were used to test the findings of this thesis. No such academic survey had previously been carried out looking explicitly and solely at still Chardonnay wine quality in the UK. A comparison between the survey results and the Combined Model results showed that the approach described in Chapter 5 identified premium quality potential in the UK well.

6.7 Practical Use

The Combined Model provides a simple and inexpensive first approximation for identifying potential sites for Chardonnay vineyards in the UK for production of premium quality still wine. Appendix 6A provides an example of the kind of report that can be produced by applying the research reported in this thesis.

6.8 Extending the Combined Model's Utility

Although this thesis is concerned with Chardonnay, for the reasons outlined in Section 1.4, the Combined Model could be extended to other cool climate cultivars (especially Pinot Noir) and other emerging viticulture regions.

The model was designed with the production of premium still Chardonnay wine in mind, using the Chablis region of France as an analogue. Chardonnay, Pinot Noir, and Pinot Meunier share broadly similar climate requirements (Figure 1.1; Jones, 2006) and are extensively grown, more or less alongside each other, in Champagne and (excluding Meunier) Burgundy. Therefore, the Combined Model can serve as a first-approximation for all three cultivars. However, production of sparkling wine can tolerate a slightly cooler climate compared to still Chardonnay wine, which is why many English sparkling wine producers have performed well in the current climate. As such, as a rule of thumb, it may be useful to look for mean vintage scores ≥ 4.0-5.0 for sparkling wine and ≥ 5.0-6.0 for still wine when applying the Weather Model, depending on land classification (i.e. lower scores in the range can be tolerated for sites with better topography and soils). To maintain flexibility, producers may consider planting Chardonnay and Pinot Noir clones that can be used for both still and sparkling wine. It may then be possible to use weather and crop conditions for the May to July period to help plan whether, or in which proportion, to produce still or sparkling wine (Chapters 2 and 3).

For intermediate or warmer cultivars (Figure 1.1) such as Cabernet Sauvignon, Merlot, Syrah and Zinfandel, however, the Combined Model is of little relevance to UK viticulture and any intended wine production. These cultivars are presently unsuitable for the UK and their adoption would be highly risky given that the current climate is still marginal for the cool climate cultivars, even in the South-East and East of England. Adoption of these warmer climate cultivars would likely require temperature increases associated with very high GHG emissions projections (SSP3-7.0 to SSP5-8.5) and, even then, would not be practicable until the final quarter of the 21st Century at the earliest.

As an illustration, the IPCC's best estimate (and very likely range) for global surface temperature change for 2041-2060 and 2081-2100 (from the 1850-1900 base) using SSP2-4.5 (the projection used in this thesis) is +2.0°C (1.6 to 2.5°C) and +2.7°C (2.1 to 3.5°C) respectively (IPCC, 2023) (Table 1.3). The warmer grapevine cultivars require roughly an additional 2°C in GST compared to Chardonnay (Figure 1.1), yet the best estimate (and very likely range) for SSP5-8.5 for 2041-60 is +2.4°C (1.9 to 3.0°C), not significantly higher than SSP2-4.5. It is only towards the end of the Century (2081-2100) that SSP3-7.0 and SSP5-8.5 provide the kind of temperature increases required for growing these warmer cultivars in the UK (+3.6°C (2.8 to 4.6°C) and +4.4°C (3.3 to 5.7°C) respectively) (Table 1.3).

The methodology was developed for and applied to England, but could be adapted for other emerging cool climate viticulture regions, such as in Canada, China, and Scandinavia. Given the greater distance from Chablis, however, applying this analogy to other regions should be carried out with caution, taking care to account for any significant differences to the growing environment. For example, choice of Chardonnay clone for a vineyard in Ontario, Canada - a region that experiences severe winters - would likely prioritise cold hardiness (Kemp et al., 2017) and may therefore favour a different combination of clones from those typically used in Chablis and the UK. Precedence exists, however, for applying European-derived guidelines to non-European regions (Ashenfelter, 2017; Jones et al., 2004; Takow et al., 2012).

6.9 Thesis Limitations and Areas for Further Research

6.9.1 Topography

An apparent inconsistency arises between the use of topography data in Chapter 5 and the conclusion of Biss (2020) who said that, "No strong evidence was found that topography plays a role in determining differences in wine quality within Chablis." The latter, however, does not prove the opposite, i.e. that topography is not important. Biss (2020) could not rule out appellation as a confounding factor (i.e. consumers may have scored a wine higher based on an expectation of appellation wine quality) and so his research (and the above conclusion) was based on the Premier Cru wines alone. In fact, differences in quality and topography were found among the three main Chablis appellation levels (basic Chablis (or "Village"), Premier Cru and Grand Cru) and so consistent with the idea that aspect, slope gradient, elevation, and relative elevation of the appellations impact on wine quality.

Moreover, 96% of the data used by Biss (2020) came from vintages between 1995 and 2016. This was a period when the weather in Chablis produced consistently good or excellent vintages (Biss and Ellis, 2021). The findings may have been different had data prior to 1992 been used, when vintages were sometimes poor because of cool temperatures and/or high precipitation, such that vineyards on superior topography (in terms of aspect, slope gradient and elevation) may have produced distinctly superior wines to those on inferior topography. The proof-of-concept presented in Chapter 5 suggests topography is indeed important to areas that are marginal for Chardonnay viticulture, such as England. Future research, however, should investigate the impact of topography in Chablis and England using a network of vineyard weather sensors to capture topographic differences and associated biochemical differences in berry composition.

One other potential issue is that a resolution discrepancy exists between the digital elevation models (DEMs) used for the source and target regions: the Chablis region was represented by 1 arc-second Shuttle Radar Topography Mission (SRTM) data (~25 m resolution) (Biss, 2020), while England was analysed using a 10 m resolution DEM derived from LIDAR (Chapter 5). This mismatch introduces potential bias, particularly in terrain-derived variables such as slope and aspect, which are known to be resolution-dependent (Miller and Schaetzl, 2015). Specifically, the coarser DEM may smooth out fine-scale topographic features, leading to an underestimation of slope gradients and less precise aspect delineation. As a result, comparisons between regions may understate topographic variability in the source region. However, since the analysis focused on identifying broad-scale patterns of topographic suitability rather than microsite selection, the resolution difference is not expected to fundamentally alter the general conclusions of site comparability. Nonetheless, future work should consider harmonizing DEM resolution across regions to ensure a consistent analytical scale, especially if extending this method to finer-scale viticultural zoning.

6.9.2 Climate Data

In Chapter 3, several methodological decisions were made regarding climate and weather data that could be refined in future research:

- *Emission scenarios:* Climate projections for the UK were based on RCP 4.5. It would also be informative to consider the more extreme "business-as-usual" scenario, RCP 8.5, in which little action is taken to reduce greenhouse gas emissions. Nesbitt et al. (2022), for example, used RCP 8.5 when assessing Pinot Noir suitability in the UK. Nonetheless, because the main challenge for UK viticulture lies in its position at the cooler margin of grape-growing climates, less extreme warming projections (e.g. RCPs 2.6, 4.5 or 6.0) are more appropriate for testing suitability.
- *Spatial resolution:* This study used 5km resolution data from the UK Met Office to map recent and mid-Century climates. This choice reflected both computational constraints and the exploratory aim of providing a first approximation for vineyard suitability. However, finer-resolution data would be valuable for local-scale decision-making.

Further research might also incorporate into the approach the impact of: i) increased atmospheric carbon dioxide on grapevine development, ii) small scale extreme weather events on final berry composition, and iii) increased warmth and changes in precipitation patterns on the distribution of pests and pathogens.

6.9.3 Appropriateness of Chablis Analogy

A larger question that is fundamental to this thesis is whether it is optimal, or even appropriate, to use the Chablis region as an analogy for production of still Chardonnay wine in the UK. The arguments set forth in the thesis can be summarised as follows:

- The climate of Southern England is already comparable to that of Champagne (Droulia and Charalampopoulos, 2022), which is only around 150 km north of Chablis. Further warming will likely move the climate of Southern England closer to that of Chablis.
- Chablis has traditionally been the most northerly producer of still Chardonnay wine (at significant commercial quantities) and is geographically the closest to Southern England (currently the main viticulture area of England).
- As the most northerly producer of premium-quality still Chardonnay wine, the Chablis region marks the base climate which the UK would need to reach in order to maintain reliable still high-quality Chardonnay wine production.

- The wines of Chablis, and Burgundy in general, have a long-standing reputation for premium quality.
- The main cultivars grown in the UK are currently Chardonnay and Pinot Noir (Chapter 1), albeit mostly to produce sparkling wine. Further warming would allow for more reliable production of still wine from these cultivars.

This approach is consistent with the AHDB (2025) report on Climate Change Adaptation for the UK. The AHDB report states that one of the three main categories of action for AHDB and the industry is a “Scoping, scanning and strategy”, which comprises, “horizon scanning of countries and regions which may be climate analogues for the UK in the future” and “modelling and analysis to help determine how risks and opportunities may change in the future, and therefore the implications for action”.

Nonetheless, differences exist between Chablis and the UK (and also within the UK) with regard to photoperiod (Parker et al., 2013) and weather systems (Nesbitt et al., 2018). Certain factors related to weather systems, such as cloudiness, hours of sunshine, light quality, and humidity, are not captured directly in the Weather Model but may be important to viticulture in the UK. Photoperiod (the duration of daylight from dawn to dusk, i.e. including twilight) is one of the key signals that plants use to adjust to seasonal changes (George et al., 2018; Roberts et al., 1997), yet it is rarely accounted for in research that compares one viticulture area to another (Prats-Llinàs et al., 2020). As such, future research regarding the importance of photoperiod and light quality (i.e. spectral composition) for grapevine phenology and berry composition would be instructive, especially in relation to how light quality may also be modified by topography and canopy structure.

6.9.4 Extend Scope of Research – Geographically and for Other Cultivars

It would be valuable to extend the analogy-based research to other parts of Burgundy, particularly the Côte d’Or, for both Chardonnay and Pinot Noir, as well as to other popular cool climate cultivars such as Sauvignon Blanc from the Loire Valley. For example, it would be worth exploring whether the *CNI* - identified as significant in the Chablis Weather Model - also emerges as an important predictor of still Chardonnay quality elsewhere in Burgundy. Developing a suite of models using consistent and comparable methodologies across different cultivars and regions would provide a more holistic understanding of climatic influences on wine quality and would further support site and cultivar selection in emerging wine regions.

6.9.5 Impact of Clones and Rootstocks

In Chapter 3 it is suggested that "… new vineyards planted henceforth in areas that are expected to be suitable for good-quality still Chardonnay wine in 2040–2059 could be planted with Chardonnay clones that can be used to produce sparkling wine (either as a blend or as a blanc de blanc) but will also work well for still wine in the future. For example, clones 75, 76, 95, 121, 131 and 548 are good for both types of wine (Skelton, 2020a)." Box 6.1 provides an example of the advantages and disadvantages of one of these clones (548).

There are 31 certified Chardonnay clones in France (PlantGrape, 2025). The models developed in this thesis did not account for differences in clones. Data on clonal usage in vineyards, both in Chablis and in England, are unevenly available and often incomplete. If the clones used in Chablis differ markedly from those used in England, this could affect the strength of the analogy, given Chardonnay clones exhibit some differences in growing requirements, physiology, disease tolerance, ripening, yield and sensory profiles (Dry, 2016).

A preliminary investigation, however, indicates the clones used are broadly similar; notably Dijon clones 95, 96 and 76 (Rathfinny, n.d.), which are valued for their balance of yield, sugar, acidity, and secondary metabolites, and are well suited to cool climate conditions; though also in England clone 121 (Whitewolfe Estates, 2024). Where England currently diverges, such as the additional use of clone 121, it may introduce stylistic variations that are worth further exploration.

In contrast to scion clones, the evidence that rootstocks impart a direct influence on grape and wine composition is mixed (Allebrandt et al., 2024). Nonetheless, appropriate rootstock selection plays a key role in enabling grapevines to adapt to site-specific conditions and will therefore affect the grapevine's ability to produce berries with an optimal balance of sugars, organic acids (Mehofer et al., 2025), flavour and aroma compounds – such as flavonoids (Allebrandt et al., 2024) and phenolic compounds in general (Ozden et al., 2010) – and yeast assimilible nitrogen (YAN) (de Souza et al., 2022). For example, some rootstocks help vines tolerate alkaline soils and reduce the

BOX 6.1. CLONE 548

Chardonnay clone 548 (ENTAV-INRA®) is an earlier ripening clone known for producing high quality, concentrated, balanced wines with complex aromas (PlantGroup, n.d.) and good ageing potential (Foundation Plant Services - UC Davis (FPS), n.d.). Its grapes are capable of high sugar concentration with good acid balance, and – because of the loose, small-berry bunches – good disease tolerance (Dry, n.d.). Several premium domaines in Chablis are reported to use it, including Vincent Dauvissat and Jean-Paul et Benoît Droin (Cannavan, 2016). Despite its qualities, clone 548 is not currently widely planted in England.

Several factors contribute to this limited adoption:

1. **Lower Yields**: Clone 548 is a very low-yielding clone. In comparative trials over 5 years in the AOC of St Véran, Burgundy, clone 548 produced approximately 30 to 45% less yield than the most commonly used ENTAV-INRA® Dijon clones 76, 95 and 96 (ENTAV-INRA, cited by Dry, n.d.). In England's cooler climate, where achieving full ripeness can be challenging, higher-yielding clones are often preferred for their reliability and economic viability.
2. **Early Ripening**: While early ripening is usually advantageous in cooler climates, especially for still wine, it may not always align with the desired harvest times for English sparkling wine producers, who are usually looking for higher acidity levels at harvest.
3. **Limited Availability and Familiarity**: Clone 548 was certified in France in 1978 but was only more recently introduced to regions outside France, such as California (FPS registered in 1997). Its relatively recent introduction means that English producers may have limited experience with this clone, leading to a preference for more established clones.
4. **Focus on Sparkling Wine Production**: England's wine industry has traditionally focused on sparkling wines, which require grapes with higher acidity and lower sugar levels. Clones such as 76 and 95 are well-suited for this style, whereas clone 548's characteristics are more aligned with still wine production.

However, some English producers are beginning to experiment with clone 548 for still wine production; for example, Simpson's The Roman Road (in Kent) is made entirely from 548. As the English wine industry continues to evolve and diversify, it's possible that clone 548 will see increased usage, particularly in regions focusing on premium still Chardonnay wine.

This may include blending clone 548 wines with those of other Chardonnay clones, such as 76, 95 and 96, to add "freshness and tension" (Sullivan, 2020), especially given clone 548 can become over-ripe if not monitored closely at harvest (Dry, 2016). For example, Gusbourne Estate's Guinevere Chardonnay (Kent) is made from 95 and 548 and Riverview's Crouch Valley Chardonnay (Essex) is a blend of clones 76, 548 and Fr 155 (a German registered clone from Freiburg).

Despite its greater association with production of still wine, clone 548 still has flexibility to be used for sparkling wine in the UK (Skelton, 2020a). For example, Yotes Court in Kent uses clone 548 for its 'Benie Des Dieux' Blanc de Blancs sparkling wine.

risk of chlorosis (e.g. Fercal, 41B, and SO4), promote earlier ripening (e.g. Fercal and SO4), or adapt to freely draining sandy soils (e.g. 5BB) (George, 1984; Rathfinny, n.d.; Simpsons' Wine Estate, n.d.; Trotton Estate Vineyards, n.d.).

Rootstock choice also affects vine vigour (Clingeleffer et al., 2022) and different rootstocks offer varying degrees of resistance to abiotic stresses (Cheng et al., 2020; Keller, 2020), such as flooding (Kawai et al., 1996) and drought (de Souza et al, 2022), and have different suitabilities based on soil nutrient availability (Chen et al., 2024; Kodur, 2011) and soil pH (Chen et al., 2024), perhaps related to their strong influence on the soil microbiome (Anand, 2024). There is also a wide range of rootstocks commercially available with different resistances to biotic stresses such as phylloxera and root-knot nematodes (Chen et al., 2024; Walker and Cox, 2011), making optimal selection a complex but important task, often involving some compromise.

Like most plants, under hot conditions with a high evaporative demand grapevines face a trade-off between closing the stomata to avoid water stress, and keeping the stomata open to maintain photosynthesis and evaporative cooling (Albasha and Bartlett, 2024). Rootstocks can influence how grapevines manage this balance (de Souza et al., 2022).

To illustrate the point, Ozden et al. (2010) investigated the impact of two rootstocks (SO4 and 1103P) on grape quality for a Shiraz cultivar in a water limited area of Turkey. They looked at a range of berry composition parameters (total anthocyanins, total phenolics, total antioxidant activity, total soluble solids (TSS), total acidity, pH, total sugar content, etc.) under five irrigation conditions and found that grape quality response to irrigation levels was altered by rootstock. The quality of grapes harvested from vines grafted on SO4 was higher compared to those from 1103P under all irrigation treatments. Thus they recommended the SO4 rootstock under non-limiting water conditions (i.e. irrigated), but 1103P for water-limited conditions.

Accordingly, optimum rootstock choice in the UK likely varies between sites, depending on local soil properties and environmental conditions. In Chablis, where soils are rich in active lime and chlorosis is a major concern, the most commonly used rootstocks are SO4 and 41B (George, 1984; 2007). SO4 gives grapes with high sugar content and can ripen as much as 14 days earlier than 41B, but 41B can, in some producers' opinions, provide better wine in good years (George, 2007). The other rootstocks used in Chablis tend to be 3309C (for soils with lower lime content), 161-49 (early ripening, but early spring development can increase frost risk), and Fercal (more resistant to chlorosis than 41B) (George, 1984; 2007).

With regard to the UK, a WineGB report for 2019 (WineGB, 2020) showed that 50% of UK vines were grafted on SO4 rootstocks, with 10.6% on Fercal, 8.4% on 3309C, 7.8% on 41B, and 3.1% on 5BB. Notably, 12.6% had unknown rootstocks and 2.8% were growing on their own roots. This data suggests that rootstock usage in the UK and Chablis is broadly similar, likely reflecting the initial concentration of English viticulture on chalk-rich soils, such as those of the South and North Downs.

Looking ahead, even if rootstock diversity in UK Chardonnay vineyards increases - as viticulture expands beyond chalk into areas such as the Crouch Valley (Essex) or the Weald (South-East England) - the analogous methodology employed in this thesis remains valid. This is because rootstocks function to support the scion's adaptation to environmental constraints, facilitating its potential to express varietal character. Crucially, there is little evidence to suggest that rootstocks themselves impart distinct aromatic or flavour profiles to the resulting wines.

6.9.6 Impact of Planting Decisions

Differences in planting density and vine training systems between Chablis and the UK are also not accounted for in this thesis. Once again, such data is unevenly available and not collected by any central agency in a consistent manner.

Most Chablis producers use a single or double Guyot training system in which, after pruning, a one-year-old cane is retained and positioned horizontally along a fruiting wire to one side of the trunk (or both sides, in the case of double Guyot). Shoots then grow vertically upwards from the cane, forming what is known as a Vertical Shoot Positioning (VSP) system.

The same system is used in most UK vineyards - particularly for Chardonnay, Pinot Noir, and Meunier - though some differences exist. Vineyards in the UK (typically in the South of England) tend to: i) use single Guyot rather than double, as it puts less demand on the vine and produces a smaller crop that is more likely to ripen; ii) train vines on a higher fruiting wire (c. 90 cm vs. 40 cm in Chablis) to reduce frost risk; and iii) maintain a taller canopy, to maximise photosynthesis during the shorter, cooler growing season. Further research is needed to identify and quantify how these differences may affect berry quality, if at all.

Training a grapevine is a manipulation of vine form (Reynolds and Vanden Heuvel, 2009) in order to achieve a desired production objective. In warmer climates, trellis designs tend to be chosen for their shading potential (Danko et al., 2024). In cooler climates, like Chablis and the UK, training systems are adopted for maximising exposure to sunlight (to optimise photosynthesis and berry ripening) and to improve airflow and spray penetration through the canopy (to reduce the incidence of mildew and rot) (Bavougian et al., 2012; Danko et al., 2024). The ultimate goal is to achieve a balance between vine vigour and yield, while also achieving optimum fruit quality and composition (Reynolds and Vanden Heuvel, 2009).

The literature consistently supports the selection of an optimum training system for given grapevine cultivars and site conditions to maximise yield and fruit condition (Bavougian et al., 2012; Junquera et al., 2015; Simonetti et al., 2021; Somkuwar et al., 2025; Vanden Heuvel et al., 2013). Vanden Heuvel et al. (2004) found that training system affected yield and berry sugars (°Brix) for Chardonnay clone 96 and Cabernet Franc clone 331, with the lowest yielding systems achieving the highest concentrations of sugars, but did not affect pH or titratable acidity. However, evidence for a direct effect on berry or wine quality and composition is generally mixed (Guerrero et al., 2017; Reynolds and Vanden Heuvel, 2009), potentially reflecting differences in climate, cultivar, vine age, vineyard management, and the criteria used to assess quality.

For the purposes of this thesis, any differences in training systems between Chablis and the UK are unlikely to undermine the analogy. Both regions employ similar clones of Chardonnay and share comparable cool-climate challenges, notably the need to balance vine vigour with fruit production and ripening, while ensuring healthy fruit free from mildew and rot.

The differences between Chablis and the UK are more considerable with regard to planting density (a function of row width and inter-vine distance), which can impact both yield and possibly berry quality. Skelton (2020a) discusses the impact of planting density on yield. He suggests an optimum row width of 2.0 m, with an inter-vine spacing of 0.85-1.00 m for single Guyot, and 1.20 m (maximum 1.40 m) for double Guyot Chardonnay and Pinot Noir vineyards in Britain.

The primary reasons for higher-density plantings are increased yield and improved vigour control, due to greater root competition (Skelton, 2020a). This helps minimise shading and the need for intensive canopy management, while maintaining levels of light, air flow, and spray penetration. However, overly high planting densities can lead to excessive shading between rows and intensified root competition for nutrients and water, ultimately reducing yield. This underlines the importance of an optimum range, which may vary depending on regional environmental conditions. Overall, Skelton's preferred planting density (plants spaced 2.0 m × 1.2 m) suggests a typical configuration in Britain of around 4,200 vines per hectare, using a double Guyot training system.

Planting densities tend to be higher in Chablis. AOC regulations mandate a minimum of 5,500 vines per hectare (a requirement in place since the early 20th century), with row spacing no more than 1.20 m (except on slopes with gradient of 40% or over) and intra-row spacing at least 0.80 m (European Commission, 2025). Many Chablis domaines, particularly those focused on higher quality, plant between 6,000 and 8,000 vines/ha (for example, Camille & Laurent Schaller domaine (Bourget Imports, n.d.)), with some Grand Cru vineyards reaching up to 10,000 vines/ha to encourage vine competition. This is associated with smaller berries and more concentrated flavour.

As such, a question remains: is it possible or even desirable for the UK to achieve planting densities similar to those of Chablis and would it have a positive impact on both yield and quality? Climate change may allow vineyards in the UK, particularly Southern and Eastern England, to increase planting density, provided the incidence of diseases (particularly downy and powdery mildew, and rot) does not rise significantly as a result.

This is certainly an interesting area for future research. In the WineGB Yield Survey Report of 2020, Skelton (2020b) states that, "The average yield for the top 25 per cent of performers at 11.36 t-ha (4.60 t-acre) is comfortably in the 'sustainable' zone. These are vineyards that both cover their costs and produce a return for their owners and the other 75 per cent are lagging behind. The industry badly needs to learn some lessons from the best producers, with the middle 50 per cent averaging only 6.03 t-ha (2.44 t-acre). Is it the site, the altitude, the orientation, the exposure to wind? Is it the varieties, the clones, maybe even the rootstocks, or is it the vine density, management, or disease control that makes some producers better than others? If growing vines in Britain is to become truly (financially) sustainable, then these questions need answering."

6.9.7 Vineyard Management

Vineyard management will be key to maintaining yields, quality, and wine typicity in traditional wine regions around the world that are, or will be, experiencing periods of extreme heat and/or water stress (Faralli et al., 2024). However, for emerging wine regions such as the UK, little can be done once a vineyard is established to compensate for growing season temperatures below those required for ripening Chardonnay (and other cultivars). That said, certain targeted practices can still help to maximise fruit quality and mitigate environmental limitations and disease pressures.

Soils influence vine development and grape ripening through their effects on soil temperature, water supply, and nutrient availability (van Leeuwen et al, 2018). In the UK context, vineyard management often focuses on encouraging deep rooting and avoiding compaction to maintain good soil structure, thereby enhancing resilience in both cool and variable seasons. Cover crops between the rows can also be used to create competition for water (often in excess in UK soils) thereby helping to prevent excessive vine vigour and shading at the expense of berry development (Abad et al., 2021; Wheeler and Pickering, 2003).

Canopy management techniques such as shoot positioning, leaf stripping, and timely pruning regulate sunlight exposure, promote airflow, and improve spray penetration, all of which reduce fungal disease risk and encourage even berry ripening (Vance et al., 2013). In cooler climates, maintaining an open canopy is especially important for maximising heat interception.

Producers can also adjust the crop load (also known as green harvesting). This involves removing under-ripe bunches during the season to help concentrate sugars, flavours, and phenolics in the remaining fruit (King et al., 2015; Somkuwar et al., 2014). This practice, along with careful winter pruning, allows growers to balance yield and ripening potential under short or variable growing seasons.

Finally, by determining the optimum harvest date through regular monitoring of °Brix, acidity, pH, and flavour development, producers can influence the desired wine style and quality (Coombe & McCarthy, 2000). In cooler years, this may mean accepting lower sugar levels to preserve acidity, while warmer years may require earlier picking to avoid over-ripeness. Extended periods of cool, wet weather, however, and sudden or increased pressure from diseases and pests at harvest period (such as birds and wasps), can limit the extent to which optimal timing is achievable.

None of these variables are explicitly considered in this thesis or its models. The assumption is that all vineyard managers, whether in Chablis or in the UK, will similarly choose, on average, the most suitable practices to optimise yield and fruit quality. The adoption of organic or regenerative practices, however, would bring further challenges to cool climates such as Chablis and the UK, where the use of fungicides has historically proved an effective measure against powdery mildew, downy mildew, and certain fruit rots such as *Botrytis cinerea* (Mundy, 2022; Pedneault and Provost, 2016)

6.9.8 Using Yield as a Lever to Manage Quality

Although yield was not explicitly modelled in this thesis, it is acknowledged that yield can be used as a ‘lever’ to manage fruit composition and wine quality. The traditional view is that decreasing yield per vine leads to an increase in fruit quality (Keller, 2020), though Keller warns this is an oversimplification.

The relationship between yield and wine quality is not always linear, clear, or even consistently negative (Reynolds & Vanden Heuvel, 2009; King et al., 2015), and is complicated by many other intervening environmental and agronomic factors. In fact, considerable research suggests that it is only very high yield that can impact negatively on quality parameters and that there is little or no benefit from yield reduction once a reasonable crop load is achieved (Kliewer et al., 2005; Walter-Peterson, 2013; Coia & Ward, 2014; King et al., 2015). In some cases, very low yields (undercropping) can even lead to poor quality fruit (Keller, 2020). Even if lower yield accelerates sugar accumulation in grape berries it does not necessarily lead to greater quality (Keller, 2020).

Importantly, the effect of yield on quality is considerably smaller than the inter-annual effect of weather on both quality and yield (Jones & Davis, 2000; Baciocco et al., 2014; Davis et al., 2019). That said, longer-term yield management for the sake of improving berry quality can be achieved through choice of clone and rootstock (Dry, 2016; Mehofer et al., 2025), planting density (Skelton, 2020a), and vine training systems

(Vanden Heuvel et al., 2004; Reynolds & Vanden Heuvel, 2009), whereas inter-annual management can be achieved through pruning choices (Vance et al., 2013; Goldammer, 2015), i.e. decisions on the number of buds to leave for the following season. Reynolds & Vanden Heuvel (2009) conclude, however, that with the appropriate training system and the associated increase in exposed leaf area, yield can often be increased with no detrimental impact on fruit quality.

Additional within-season methods for fine-tuning crop load and, indirectly, quality include green harvesting and irrigation. The quality benefits of green harvesting are mixed, with many studies showing limited or no improvement when fruit thinning is carried out late or when crop load is already reasonable (King et al., 2015; Marbach et al., 2025). Irrigation decisions, particularly in warmer climates, also affect vine water status and therefore impact both yield and berry composition, and excess water can compromise quality in vines that have been heavily thinned (Ozden et al., 2010; Bellvert et al., 2016; Keller, 2020).

Crop load is more important than crop size or yield; as a general rule, 1 to 1.5 m2 leaf area is required to fully ripen 1 kg of fruit, although this depends on cultivar, training system, and environmental conditions (Keller, 2020). If the crop load is lower than this, grapevines are said to be undercropped or sink-limited. Such vines invest more resources in vegetative growth, which can delay ripening and reduce fruit quality via the effects of a dense canopy and, in some cases, larger berries. Conversely, if the crop load is so high that there is insufficient leaf area to ripen the fruit, grapevines are said to be overcropped or source-limited, and ripening is slow, with attendant effects on fruit composition. In practice, vines of intermediate vigour often produce both higher yields and better quality fruit than vines at either end of the vigour spectrum; such vines are described as balanced, with crop size matching vegetative growth (Keller, 2020).

For wine styles such as Chablis that aim to retain relatively high acidity and moderate alcohol, managing crop load can shift the timing at which the desired ripeness is achieved, even if inter-annual weather remains the dominant driver of phenological timing. In contrast, in the UK, where Chardonnay ripening is still marginal in many seasons, yields are more constrained by climate, and crop load adjustments are used primarily to ensure ripeness is achieved rather than to shift the ripening window for stylistic reasons.

In the Chablis context, EU legislation in part recognises the relationship between yield, grape composition and wine quality by imposing maximum yield caps (European Commission, 2025). This is intended to protect the reputation, typicity and quality of Chablis wine from the effects of overcropping, but also to prevent market oversupply. More specifically, the system provides target regulatory yields ("rendement") for each appellation – Chablis (Village) 60 hl/ha; Chablis Premier Cru 58 hl/ha; Chablis Grand Cru 54 hl/ha. It also provides limits for maximum yield ("rendement butoir") - Chablis (Village) 75 hl/ha; Chablis Premier Cru 73 hl/ha; Chablis Grand Cru 64 hl/ha. Producers are allowed to allocate wine between the "rendement" and "rendement butoir" as VCI (Volume Complémentaire Individuel), i.e. stored as reserve for poor years (though it still has to be sold as the vintage it is from). Any wine above the rendement butoir cannot be marketed as appellation (AOC) wine.

It is not a perfect system (Jefford, 2023). In a bad weather year, yield is likely to be low and therefore the caps have little impact on maintaining quality. In a good weather year, vineyard yields can be well above the rendement butoir while quality is also high, and producers may end up selling very good wine under a different non-appellation label.

As such, while yield can be used as a lever to manage fruit quality to some extent, in emerging cool-climate regions such as England and Wales inter-annual weather variability and its modulation by topography remain the dominant constraints.

Average vineyard yields in the UK are substantially lower than those in Chablis, at around 30 hl/ha (2014–23; WineGB, 2024) compared with around 51 hl/ha for Chablis as a whole over 2019–2023 (BIVB, n.d.), ranging from c. 45 hl/ha for Grand Cru vineyards to c. 52 hl/ha for Village Chablis. This is primarily because the UK is still marginal for Chardonnay viticulture and the industry is still relatively young. Only in an excellent vintage such as 2023 do the yields of southern and eastern England (the highest yielding areas) approach the regulatory yield caps used in Chablis. Thus, preventing the production of dilute, over-cropped wines is not yet a primary concern in the UK, at least not one that can be addressed via yield caps.

6.9.9 Winemaking and Yeasts

This thesis examined the environmental conditions necessary for wine quality and, with the exception of Chapter 4, excluded consideration of Chablis winemaking and storage practices, which, while having a considerable influence on the final wine quality and sensory profile, are transferable to other regions.

One relevant factor in winemaking is the choice of yeasts for alcoholic fermentation. Most fermentations are initiated by inoculating the must with a commercial *Saccharomyces cerevisiae* strain, but some producers instead rely on naturally occurring yeasts from the vineyard and/or winery, a practice currently concentrated among a small group of natural winemaking practitioners. However, even when commercial yeasts are used, there is evidence that indigenous yeasts remain active during fermentation, potentially imparting a distinctive local or regional influence on the final sensory profile of the wine (Brawner, 2018; Castrillo and Blanco, 2024; König et al., 2017).

As such, indigenous yeasts may represent an unaccounted-for component of terroir, potentially imparting a high-quality influence on Chablis wines that distinguishes them from wines produced elsewhere. This possibility warrants further research.

6.9.10 Economics

Further data is required regarding the long-term economic viability for production (and sale) of still Chardonnay wine produced in the UK. Estimation of the size of the market by mid-Century is beyond the scope of this thesis, though some commercial research suggests there will be increasing demand for premium, rather than low-quality high-volume, still wine (360iResearch, n.d.; Future Market Insights, 2025). Also beyond the scope of this thesis is any forecast regarding what will happen to the supply of still Chardonnay wine from existing traditional producers, such as those in Australia, France, Italy, New Zealand, Spain, and the USA, or any projection regarding the popularity of the Burgundian cool climate cultivars (Chardonnay and Pinot Noir) compared to other cool climate cultivars such as Riesling, but also notably the PIWIs. The PIWIs (see Section 1.1) may develop greater appeal to producers (and consumers) because of their increased disease resistance and their consequent reduction in fungicide applications, especially if final quality is shown to be at least as good as that from traditional cultivars. Also, there are the other emerging wine regions to consider, such as in Canada, China, and Scandinavia.

There are numerous factors that would need to be taken into account for any economic model of demand and potential profitability with climate change. Establishing a vineyard typically requires a capital outlay of around £30,000 per hectare (Skelton, 2020a) and full cropping is not usually achieved until year 4, a delay of several years before an income is generated. Unlike the major horticultural crops in England, the profitability of vineyards is not in the public domain. This is because DEFRA's annual Farm Business Survey only includes three vineyards currently, which small sample size prevents the publication of the data (Richard Crane, personal communication, 2025).

Achieving reliable high grape yields is still an issue (see Section 6.9.6), and planting a perennial crop, such as a grapevine, which typically produces a commercial crop for 25 to 30 years (Skelton, 2020a), does not provide the same flexibility to respond to climate change as annual crops. Viticulture also comes with disease and pest pressures that are associated with monocultures, as well as seasonal labour requirements similar to those of other soft fruits (though mechanized harvesting is improving). It is for these reasons, and the inertia that may come with learning to grow and market a new crop, which may prevent existing farmers from switching to viticulture. In addition, there are competitive crops (such as durum wheat) that may become suitable to UK conditions (Redhead et al., 2025) and offer superior returns. Such economic modelling would be an interesting area for further research, especially if it were to inform national and local government policy to encourage (or not) viticulture as part of an adaptation strategy to climate change.

6.10 Conclusions

This thesis has developed a method to assess and map land suitability in the UK for Chardonnay viticulture to produce premium quality still wine now and out to mid-Century. The research has shown that:

- Weather is the primary determinant of Chardonnay wine quality in Chablis. *(Hypothesis A supported; evidenced in Chapter 2)*;

- A weather-quality model built on Chablis region data is an excellent analogy to identify potential vineyard sites in the UK. *(Hypothesis B supported; Chapter 3)*;
- Minerality in Chablis wine is associated with weather, rather than soils and geology. *(Hypothesis C supported, although a complication exists in the changing definition of "minerality"; Chapter 4)*;
- Topography (and soil drainage) play an important role in site selection. *(Hypothesis D supported; Chapter 5)*;
- A model that combines weather with topography and soils can be used to map and further refine suitable sites in the UK for Chardonnay vineyards. *(Hypothesis E supported; Chapter 5)*;
- The UK is generally unable to produce high-quality still Chardonnay wine reliably under current climate conditions (2010-19). *(Hypothesis F unsupported; Chapter 3)*;
- The scale of future warming driven by climate change will affect the extent to which UK Chardonnay viticulture will be able to produce premium quality still wine. Areas projected to be suitable under a median projection include much of South-East and Eastern England, extending to Central England under a more extreme (95th percentile) projection. (*Hypotheses G broadly supported; Chapters 3 and 5*).

Since starting the research in 2020, the argument for producing still wine from Chardonnay grapevines in the UK has strengthened and some producers are now regularly making single cultivar Chardonnay still wine, albeit a few wine experts remain sceptical about the quality (Chapter 5). The relevance and utility of this PhD is therefore yet firmer than thought likely at the outset, potentially helping new entrants or existing producers to assess land suitability for Chardonnay (and potentially Pinot Noir) using a simple approach that compares their land to that of Chablis, traditionally the most northerly major producer of premium quality still Chardonnay wine. Further refinements to the methodology would include a comparison between growing conditions and wine characteristics in Chablis and the Côte d'Or (further south in Burgundy), and an extension of the methodology to explicitly include Pinot Noir.

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Appendices

APPENDIX 1A

Impact of vineyard topography on the quality of Chablis wine

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Abstract

Background and Aims: 'Terroir' is a term used to describe how climate, microclimate, geology, soil, topography and vitivinicultural history affect the taste and aroma of a wine produced from a vineyard. This study investigates one aspect of terroir—the topography—for Chablis, a white wine-producing region of France.

Methods and Results: A digital elevation model was used to produce topographic data for the vineyard areas of Chablis ('Climats'). Correlation and regression analyses were used to compare topography with 6850 wine scores extracted from CellarTracker, an online crowdsourced database of wine-tasting notes.

Conclusions: No strong evidence was found that topography plays a role in determining differences in wine quality within Chablis. There is, however, a reason to think that slope gradient may have an influence on wine quality, but the evidence is insufficient, and data limitations prevented further analysis.

Significance of the Study: The findings suggest that, provided a vineyard falls within a range of topographic, soil and climatic parameters, it is possible for a good winemaker to produce high-quality wine no matter where the land is located and that, provided certain thresholds are not crossed, the influence of topography is too small to be detected in the final wine.

Keywords: *CellarTracker, Chablis wine, Chardonnay, terroir, topography*

Introduction

'Terroir' is cited by winemakers and consumers alike as crucial in determining the characteristics of a wine. The definition of terroir according to the Organisation Internationale de la Vigne et du Vin (OIV), an intergovernmental organisation concerned with the vitiviniculture sector, is that it is "a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied vitivinicultural practices develops, providing distinctive characteristics for the products originating from this area" (Organisation Internationale de la Vigne et du Vin 2010).

The concept of terroir is important to the winemakers of Chablis, who claim that its white wines produced from Chardonnay are distinct from Chardonnay wines produced elsewhere. This, they claim, is primarily down to the terroir, a key feature of which is the Kimmeridgian marl geology and the relatively northerly latitude of Chablis (George 2007). In fact, the name 'Chablis' is registered by the European Union as a Geographical Indication (GI), a system set up to protect agricultural food and drink products where the quality or reputation of a product is attributable to its geographical origin (European Commission 2016).

Terroir is also used to distinguish wines within Chablis. Because the geology and macro-climate are relatively homogeneous, wines from different Premier and Grand Cru 'Climats'—a specific Burgundian term that delineates a vineyard area based on microclimate, geology and viticultural history (United Nations Educational, Scientific and Cultural Organization 2020)—are distinguished largely by their topographical location and its assumed impact on microclimate and soil (Droin 2014, Rupnik et al. 2016). As such, differences in wine characteristics and wine quality between the Climats of Chablis may be largely attributable to the influence of topography or the winemaker, or both.

This study is the first to systematically investigate the impact of topography on Chablis wine quality, one of the world's most important areas for the production of Chardonnay wine, to determine if there are topography-related effects at the local scale.

Terroir and topography

While climate and soil are widely accepted as key components of terroir at the regional scale (van Leeuwen et al. 2004, Prata-Sena et al. 2018), there have been many papers that suggest topography—specifically elevation, slope and aspect—play a key role in determining wine characteristics at the local level (Bavaresco et al. 2007, Bramley et al. 2011, Roullier-Gall et al. 2014, Scarlett et al. 2014, Anesi et al. 2015, Rupnik et al. 2016, Fraga et al. 2017).

Most recently, research has focused on the chemical analysis of grape berries, the idea being to see if there are differences in berry composition prior to vinification and whether these differences can be related to terroir (Roullier-Gall et al. 2014). Many of the compounds found in the berries have been associated with aromas and flavours, such as 'red berry' and 'flowery' (Bramley et al. 2011), although some compounds when found in excess produce unpleasant sensations, such as sourness and bitterness (Rodrigues et al. 2017).

Anesi et al. (2015) examined berries taken from seven vineyards in three Italian wine regions—Soave, Valpolicella and Lake Garda. They found that the metabolites within the berries [which were picked at veraison (onset of ripening), mid-ripening and full ripening] showed terroir-related features and that these were related to certain environmental factors, such as strong light/shading, low/high temperature,

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elevation and water deficit, thus showing how topography can influence the biochemical make-up of the grapes.

Bavaresco et al. (2007) investigated a vineyard area of 3500 ha in northwest Italy and attempted to relate the concentration of stilbenes in grape berries to environmental factors. Stilbenes are a family of bioactive molecules, some of which are thought to have antioxidant health benefits, that are normally produced in plants in response to stress (Shen et al. 2009). Aside from the importance of grape cultivar, Bavaresco et al. (2007) found that grape stilbene concentration increased with land elevation up to 320 m but, interestingly, decreased thereafter.

Other research has looked more explicitly at the smaller scale. Scarlett et al. (2014) found within-vineyard variations in berry rotundone concentration (a compound associated with a 'peppery' character), which they found to be 'spatially structured' and Bramley et al. (2011) found differences in wine characteristics, over a small study area (8.2 ha), for sites only 3.43 m apart in elevation.

Rupnik et al. (2016) presented an interesting case study that is analogous to Chablis. It involved an investigation of two vineyards in Slovenia that share the same vine cultivar, geology and macro-climate but are located in different topographic settings, one in the valley bottom and one on a terraced slope. Rupnik et al. found that the wines differed significantly, especially regarding TA and pH, and they related these to three factors: (i) slope gradient; (ii) aspect; and (iii) soil depth. The authors pointed out that topography is the key driver for wines from their study area.

The processes by which topography impacts wine characteristics are complex and involve an interaction with climate (thereby modifying local levels of solar irradiation, drainage and air circulation) and soils (thereby modifying local soil conditions) (Jones 2015).

Stafne (2015) suggests that aspect is a key consideration for vineyard location: in cool climates, south, south-west and southeast orientations allow maximum heat accumulation for grapes to ripen, producing wines with greater alcohol and concentration. Stafne also points out that: (i) southern and western exposures are warmer than eastern ones, although during warm years, this can lead to overheating of the berries and diminished acidity levels; and (ii) eastern aspects receive the early morning sun, which helps dry out overnight dew (or rain) and warm soils sooner than western-facing slopes, perhaps reducing the susceptibility of the vines to rot and mildew.

Advice on vineyard siting often warns against hillside tops or valley bottoms, preferring instead a 'thermal belt' along the hillside (Goldammer 2015). Reasons for this relate to protection from high winds and cold air drainage into valley bottoms and prevention of flooded soils (which destroy vine roots). Goldammer also points out that, for every 100 m rise in elevation, there is an approximate 0.61°C decrease in temperature, having an overall effect of shortening the growing season.

Brillante et al. (2018) thinks the impact of slope gradient on soil water status is one of the key drivers of vine physiology; steeper slopes lead to greater water deficit by increasing runoff and reducing the amount of water that penetrates the soil. The authors point out, however, that there is some disagreement regarding the effect of water deficit on wine quality—some vineyard areas of moderate water deficit in summer appear to produce high-quality wine, yet some research suggests water stress should be negative for wines (because water stress reduces the abundance of some aromatic compounds and because water stress is normally associated with high temperature that degrade acidity levels).

Goldammer (2015) considers gently sloping land ideal for viticulture as this allows for good air drainage that prevents frost and promotes drying of the canopy, reducing the risk of disease such as mildew and rot, which can have a deleterious impact on wine quality. He does not, however, discuss the effect of slope on water status.

Slope gradient also affects the amount of solar radiation received at the ground (Erley and Jaffe 1979); a steep south-facing slope will receive more energy per unit area than a flatter south-facing slope because the sun's rays are concentrated into a smaller area. This has clear implications for: (i) berry ripening; and (ii) drying of berries after rainfall.

Wine assessment

Of direct relevance to this study, Rodrigues et al. (2017) investigated whether Chablis wines from the 'right' bank (east side) of the river Serein contained a different concentration of compounds associated with 'minerality', a widely used sensory descriptor that has nothing to do with the actual mineral content of a wine (Maltman 2013), compared to the 'left' bank (west side). Their chemical analysis of the wines found that the concentration of methanethiol, a compound associated with shellfish aroma and minerality, was significantly higher in left-bank wines. Their panel of 32 wine experts, however, could discern a difference only by orthonasal olfaction (sniffing) and not from full tasting (of the 1-year-old wine).

There may be, however, an added complication to the terroir debate, suggesting grape berry analysis or tasting of early-stage wines may not be the best way of assessing terroir effects. Roullier-Gall et al. (2014), working with four vineyards in Burgundy, failed to find any obvious terroir-related chemical fingerprint in the grapes analysed immediately after harvest and for the early-stage wine. The researchers, however, found that the same wines, after bottle ageing for 3–5 years, demonstrated a 'perfect separation' between vineyards, during which time molecular diagenesis had occurred in the bottle.

In this regard, it may be worth including a large sample size of wine consumers to find whether these topographic effects are apparent in the finished, and ready-to-drink, wine. In other words, rather than relying on the chemical analysis of grape berries or questioning a panel of wine experts (Bramley et al. 2011, Priori et al. 2019), can the market, en masse, detect any difference in the quality of the wines between the different vineyards of Chablis? CellarTracker, an online crowdsourced database of wine-tasting notes, provides an opportunity for this type of quantitative analysis.

Materials and methods

Study area

The Chablis area (Figure 1)—located in the northern part of Burgundy—is the second largest producer of Chardonnay wine in France, second only to the Côte d'Or (also in Burgundy). Its wines are produced by around 460 winemaking estates ('domaines') and make up 20% of the volume of total Burgundy wine production (Bureau Interprofessionnel des Vins de Bourgogne 2017).

Most wine commentators agree that: (i) Chablis wine has a distinctive aroma and taste, variously described as flinty or mineral, although with ageing, the Premier and

APPENDIX 1A

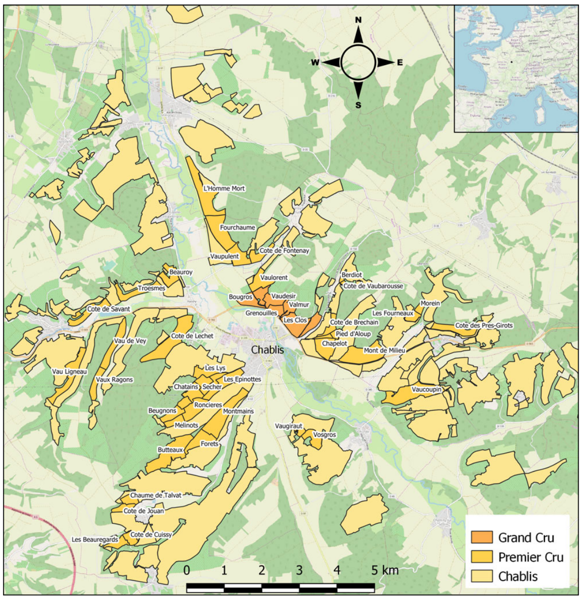

Figure 1. Map of study area showing the location of vineyards for the three main appellation d'origine contrôlée (AOC) of Chablis: Chablis Grand Cru (■), Chablis Premier Cru (■) and Chablis (■) (also referred to as 'Village Chablis'). The fourth appellation and most junior Chablis appellation, Petit Chablis (■), is not included in this study. From Bureau Interprofessionnel des Vins de Bourgogne (2016).

Grand Cru wines can become softer, honeyed and intense; (ii) that the Climats produce wines with their own characteristics, and these characteristics are driven by differences in topography and differences in the agricultural history of the land (which affect the soil); and (iii) that some winemakers (and some vintages) are better than others in revealing these Climat characteristics (George 2007, Biss 2009, Droin 2014).

Chablis wines are divided into four appellation d'origine contrôlée (AOC), referred to here as the 'appellations'. In decreasing order of quality, these are Grand Cru Chablis [102 ha under production (Bureau Interprofessionnel des Vins de Bourgogne 2016)], Premier Cru Chablis (790 ha), Chablis (3560 ha) and Petit Chablis (1010 ha).

The town of Chablis—latitude 47°48′49″ N, longitude: 3°47′54″ E, 140 masl—lies at the heart of the vineyard area. The surrounding topography is hilly, rising to around 320 m, and the vineyards lie on both sides of the river Serein, which runs broadly north–south through the town. The Chablis Grand Cru Climats are all located on the east side of the Serein, occupying a hillside overlooking the town. The land is considered to be the best for viticulture in the area, with steep, west- to south-west-facing slopes producing outstanding wines of remarkable longevity (Robinson 2020).

In contrast, the Premier Cru Climats are located on both sides of the Serein, stretch several km away from the town and cover a wider range of topographic settings (Figure 1). The vineyards are still considered well-sited and produce Chablis' most reliable buys (Robinson 2020).

Most of the remaining vineyards (that are not designated Petit Chablis) qualify for basic Chablis, which is highly variable in quality according to Robinson (2020). The basic Chablis appellation is restricted to the communes of Beine, Béru, Chablis, Fyé, Milly, Poinchy, La Chapelle-Vaupelteigne, Chemilly-sur-Serein, Chichée, Collan, Courgis, Fleys, Fontenay-près-Chablis, Lignorelles, Ligny-le-Châtel, Maligny, Poilly-sur-Serein, Préhy, Villy and Viviers (Bureau Interprofessionnel des Vins de Bourgogne 2020).

The Petit Chablis vineyards lie mostly on soils derived from hard Portlandian limestone and patches of sandy silt (Bureau Interprofessionnel des Vins de Bourgogne 2020), unlike the main underlying geology of the other three appellations, which is Kimmeridgian marls and limestones. Its wines are known for their freshness and are drunk young (typically after 2 years), although Robinson (2020) says they are often vapid and are the product of plantings on the outskirts of Chablis when the Chablis growers found they were unable to keep up with international demand.

The Grand Cru and Premier Cru appellations are divided into 7 and 40 vineyard areas, respectively, called 'Climats' (Figure 1), and as an added complication, the 40 Premier Cru Climats are grouped into 17 larger principal Climats (Figure 2). (La Moutonne is an unofficial eighth Grand Cru

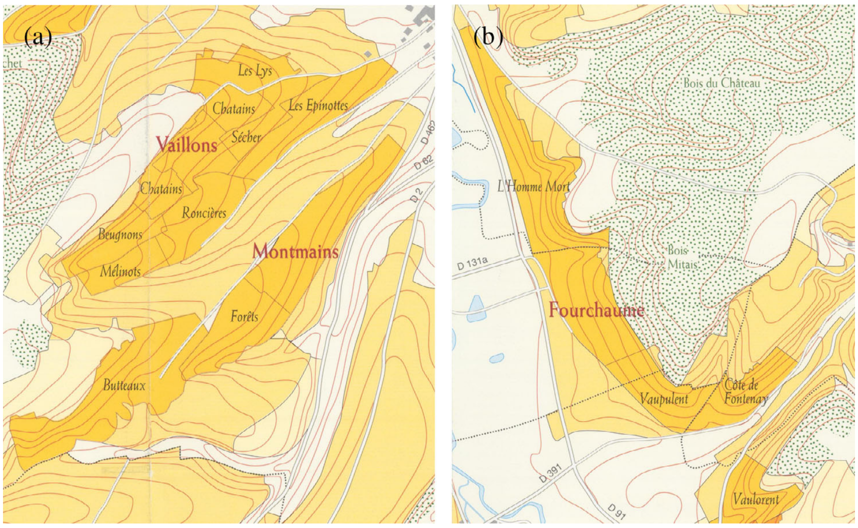

Figure 2. Close-up of the principal Premier Cru Climats of (a) Vaillons and Montmains and (b) Fourchaume. Note how the principal Climat is made up of several smaller Climats. From Bureau Interprofessionnel des Vins de Bourgogne (2016).

Climat, which lies mostly in Vaudésir, although partly in Preuses. For the purposes of this study, its wines have been included within Vaudésir.)

Appellation regulations govern certain quality criteria, such as the minimum alcohol level and maximum yield, and these are successively stricter from Petit Chablis to Grand Cru.

The climate of Chablis is mid-latitude maritime. It can suffer from spring frost and hailstorms, although these events tend to affect yield rather than quality, and winemakers have some means for combatting frost (George 2007). Climate change appears to have had an impact on the region; the date at which harvesting begins has changed by around 20 days since 1980, moving from around early October to mid-September (Figure 3).

Why Chablis?

Several factors make Chablis an ideal choice for study area.

- The cultivated area is relatively compact—only 16 km (north–south) by 18 km (east–west) in size—meaning there is little regional-scale climatic variation.
- Wine is 100% produced from one grape cultivar, Chardonnay (Bureau Interprofessionnel des Vins de Bourgogne 2017).
- The geology is relatively homogeneous. The Premier Cru and Grand Cru appellations, and most of the basic Chablis appellation, are underlain by Kimmeridgian marls and limestones. (This compares to the Petit Chablis appellation, which is mostly underlain by Portlandian limestone, and is therefore omitted from this study.)
- For the Premier Cru and Grand Cru appellations, wines are bottled and labelled according to their Climats, which means a direct link can be investigated between wine quality (from wine-tasting scores) and vineyard topography.

As such, because the climatic and geological factors are relatively well controlled for, it may be possible to detect the effect of topography on wine quality.

Certain factors, however, cannot be controlled for. Most crucially, this includes the winemaker—in terms of both viticultural and vinification practices—and also natural processes operating at the smaller scale, such as microclimate (albeit this is inter-related with topography). The question for this study is whether, despite these complications, the topographic signal is large enough to be detected.

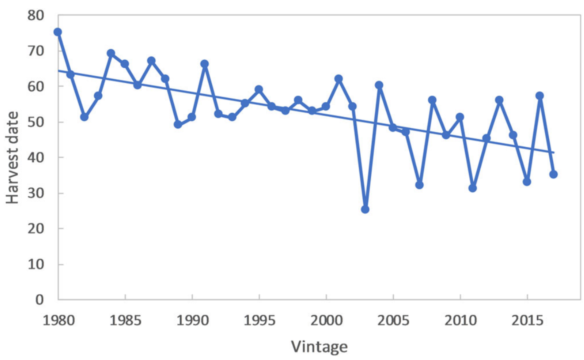

Figure 3. Chablis harvest dates from 1980 to 2017. Harvest dates are given in number of days from 31 July, where 1 August = 1 and 30 September = 61. Until 2007, the harvest date (Ban de Vendange) was officially declared by the Institut National de l'Origine et de la Qualité (INAO). Since 2008, winemakers have been allowed, on application to INAO, to begin harvesting when they choose. Estimates for harvest dates from 2008 onwards are based on vintage reports from wine merchants and wine writers.

Topographic variables

Four topographical variables were derived from a digital elevation model (DEM). The Chablis vineyards were then digitised as a layer over the DEM, and zonal statistics and histograms were produced in ArcGIS 10.4.1 (ArcGIS) (Esri, Woodlands, CA, USA) to provide topographical summaries for those vineyard areas.

The DEM was derived from elevation data taken from the Shuttle Radar Topography Mission (SRTM), which was obtained through the USGS Earth Explorer website (https://earthexplorer.usgs.gov/). The SRTM data were acquired on 11 February 2000 and published on 23 September 2014 (Entity ID SRTM1N47E003V3) and have a resolution of 1 arc-s (approximately 30 m, although this is closer to 25.6 m for the Chablis study area).

The map projection used for this study was the Universal Transverse Mercator (UTM), a commonly used projection for regional studies that are contained within one of the 60 UTM zones, each of 6° longitude; the Chablis area falls entirely within UTM Zone 31, and distortion was minimised by the selection of this projection. As such, scale error does not exceed 0.1% (Esri 2016, GISGeography 2018).

Two maps—from Bureau Interprofessionnel des Vins de Bourgogne (2016) and Pitiot and Servant (2016)—were scanned, georeferenced and used as a guide for digitising the Chablis appellations and Climats in ArcGIS, using basemap satellite images for placement of exact vineyard boundaries. Where boundaries were unclear or the two maps did not agree, vineyard photographs were referenced (Droin 2014).

The following topographic variables were calculated from the DEM using the ArcGIS Spatial Analyst (SA) toolbox (Esri, for discussion of algorithms): aspect, slope gradient, elevation and relative elevation (Tables S1–S5, Figure S1). Relative elevation, which describes the magnitude of one cell's elevation in relation to the cells around it, was calculated according to Goings (2015). This method involves calculation of drainage density to derive the average length of overland flow, which is then used as a neighbourhood setting for the calculation of relative elevation. For this study area, drainage density is 1.10, resulting in an average length of overland flow, and neighbourhood setting, of 550 m. Relative elevation is expressed as an index between 0 and 100, where 0 means it is the lowest cell within the 550 m radius (e.g. a valley bottom) and 100 means it is the highest cell within the 550 m radius (e.g. an exposed hilltop).

Soils

The Premier Cru and Grand Cru Climats of Chablis (and some of the basic Chablis vineyards) are underlain by Kimmeridgian marls and limestones. According to the Chablisienne, this subsoil is the most important defining characteristic of the Chablis terroir, giving the wines their defining purity and mineral character (Bureau Interprofessionnel des Vins de Bourgogne n.d., Biss 2009). Because the geology involves, however, alternating bands of marls and limestones, and because of other factors such as geomorphology and microclimate, there is still local variation in the subsoils and soils. As such, despite the broad assumption of relatively homogenous soils for this study, a decision was made to digitise a soil map to gauge variation (in broad classification terms) between the Climats to check the extent to which this assumption is true.

To do this, an electronic image of a soil map was extracted from the website of the Chambre d'Agriculture de Bourgogne (n.d.) 'Sols de Bourgogne' and georeferenced and digitised in ArcGIS. ArcGIS was also used to convert the image from RGF 93/Lambert 93 map projection, a projection that is used for the whole of France, to UTM31 in order to ensure alignment with the rest of the data used for this study.

The map showed that the Chablis vineyards are distributed over eight cartographic soil units [Unités Cartographique de Sol (UCS)] (Table S6), each of which comprise between 3 and 10 different soil types (Unités Typologique de Sols). The unit of most importance to this study is UCS n°30 (UCS30), the soil unit associated with the Kimmeridgian slopes (Table S7).

Weather

Over 30 years of simulated daily weather data, from 1 January 1985 to 2 November 2017, for the town of Chablis (47.81°N3.8°E) were obtained from Meteoblue. Meteoblue is a Swiss company that provides historical weather data based on model simulations (Meteoblue n.d.). The use of Meteoblue data has two advantages over traditional weather station data: (i) it provides data that are consistent and complete for the full study period; and (ii) it is centred around the town of Chablis compared to the nearest weather stations, which are Auxerre (19.0 km away) and Troyes-Barberey (58.0 km away). The data, however, suffer from several potential issues: (i) it is unable to capture extreme localised events; (ii) it uses data from just one location, which means it is unable to capture microclimatic effects (although this would be true for any data based on one weather station); and (iii) a level of trust is required regarding the integrity of the data and the accuracy of the models they use. Nevertheless, there is precedent for the use of Meteoblue data in the academic literature (Vidmar et al. 2016, Shkarupilo et al. 2017, Panassiti et al. 2018).

A range of indicators was calculated, based on a survey of the literature [including Ashenfelter et al. (1995); Byron and Ashenfelter (1995); Corsi and Ashenfelter (2001), Bavaresco et al. (2007), Ashenfelter (2008)], to capture the key characteristics of weather that are important for viticulture. This includes temperature [average, minimum, maximum, average minimum and average maximum (°C)], rainfall (mm) and sunshine (h).

Calculations were made for the following periods to characterise the full growing season and the final phenological stage of berry ripening (Bavaresco et al. 2007): 1 April to 30 September; 1 April to 31 October, monthly (August, September and October); and the 42- and 61-day period leading up to the harvest.

Wine scores

Wine scores (6850) were extracted from CellarTracker, an online crowdsourced database of tasting reviews. This was made up of scores for 1483 Grand Cru, 3224 Premier Cru and 2143 basic Chablis ('Village') wines. Although the scores relate to vintages as far back as 1942, over 99% of them are for vintages from 1980 and over 96% for vintages from 1995 (Table 1). Table S8 provides further details of the database, including sample size, median score and interquartile range for each principal Climat.

Table 1. Number of wine scores per Chablis appellation, grouped by wine vintage.

	Wine scores†		
Vintage	Chablis	Premier Cru	Grand Cru
1946–1979	5	3	14
1980–1994	24	98	97
1995–2016	2114	3123	1372

†Scores extracted from CellarTracker between October and December 2017.

The pros and cons of using CellarTracker data

There are numerous issues involved with using CellarTracker data. These include the following:

- CellarTracker is the opposite of having a panel of experts in a controlled environment. Most contributors to CellarTracker are amateurs, come from different backgrounds and have different levels of tasting experience. They are also mostly from North America and northern Europe (Tables S9–S11, Figure S2), and this may have a cultural influence on how the wines are reviewed (Sáenz-Navajas et al. 2013).
- For the purposes of this study and to ensure sufficient data, wine scores are used regardless of whether the wines may have been tasted too old, too young or if they had been poorly stored. No attempt has been made to 'cleanse' the data or remove outliers, which would in most cases involve a subjective assessment of which reviews were unwarranted.
- The scoring system may not be consistent between different tasters. For example, one taster may consider price an important factor and judge a wine according to value, whereas another may consider this unimportant. Some tasters may prefer more floral wines, others more mineral.
- Each score is an average figure. Some wines (a wine in this case referring to a particular vintage of a wine from a specific producer and from a particular Climat) may have been tasted by tens or even hundreds of tasters on several occasions, whereas others may have a wine score that is based on only one tasting carried out by one person. The average number of bottles tasted per wine score is 32.5 (Tables S9–S11, Figure S2).

There are, however, equally serious issues that surround the use of wine experts and panels. Hodgson (2008) examined the performance of judges for a US wine competition and found that only 10% of wine judges were able to replicate their wine scores when secretly given three samples of the same wine. Another issue is that the number of experts on a wine panel tends to be small, and findings may not be statistically significant.

In contrast, CellarTracker is the largest consumer-submitted database of wine ratings in the world (Marks 2015) and the closest thing available to a market judgement for wines, especially for wines that do not have a traded secondary market, such as Bordeaux (Ashenfelter 2008).

Nonetheless, it is well documented that there are many issues relating to wine-tasting notes that cast doubt on their usefulness. These include the effects of storage (Skouroumounis et al. 2005), food (Nygren et al. 2001) and the taster's age (Fukunaga et al. 2005, Methven et al. 2012), not to mention differences in experience and ability. The approach taken here, however, is that, en masse and on average, the tasting scores should reach a good level of 'accuracy' in a process described by Surowiecki (2005) as the wisdom of crowds. Moreover, the advantage of using existing tasting notes is that they were written free from any bias that may have occurred had they known their notes would be used to examine the concept of terroir.

Statistical analyses

XLSTAT 2018 (Addinsoft, Paris, France) was used for all statistical analyses.

Results

Comparing the appellation wine scores

Table 2 shows the average CellarTracker scores for each appellation. There is a noticeable improvement in score per step-up in appellation, equivalent to 1.5 points in the median. Using the non-parametric Mann–Whitney *U*-test, the differences in medians were found to be statistically significant ($P < 0.0001$ for each pair, which is lower than $P < 0.05/3$ as per the Bonferroni method for multiple pairwise comparisons [Townend 2002]). These differences in score may reflect real differences in quality, although they may be based on biases that arise from labelling information, that is, CellarTracker users expect the Grand Cru wines to be of higher quality than the Premier Cru and Village wines, and thus, they provide a higher rating for these wines; see Pohl (2004) for a discussion of the labelling effect. (It is unclear how much of the labelling bias impacts the scoring in this study, and the study later focuses on the Premier Cru appellation to obviate this potential effect.)

The Premier Cru and Grand Cru scores also exhibit less variance and negative skew compared to those of Village Chablis, with Village Chablis having the longest fat tail into the lower scores. This suggests that basic Chablis is not as consistent in quality as the Premier and Grand Cru wines.

The observed differences are relatively robust. Figure 4 plots the median average scores for rolling periods of 5 years from the 1994 to 2016 vintage and shows that the difference between the appellation scores has remained substantially stable over the period. The earlier vintage scores for the Premier Cru Climats are slightly closer to the Grand Cru scores than for later vintages, although this may be because of survivorship bias in the Premier Cru wines—that is, CellarTracker has only been in existence since 2003, and only the best Premier Cru wines of those early vintages were likely to have been available when CellarTracker began, whereas it is normal for Grand Cru wines to last for 10 years (Robinson 2020). This may have the effect of understating the difference in quality between the Premier Cru and Grand Cru wines, but it should not affect the interpretation; it is an issue of magnitude and not of direction. It may also indicate that the labelling effect is not as large as feared because CellarTracker users recognise that the surviving Premier Cru wines were closer in quality to the Grand Crus despite the difference in appellation labelling. Alternatively, the observation could simply be the result of insufficient sample numbers for the earlier vintages and a lack of true sampling representation (Figure S2). Overall, however, the difference in quality between the appellations appears stable.

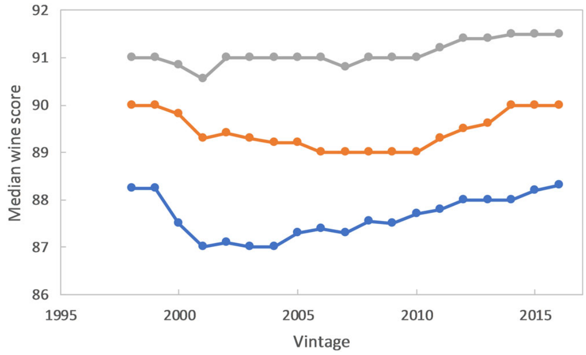

Figure 4. Five-year moving average for appellation median scores for Chablis Grand Cru (——), Premier Cru (——) and Village wines (——).

The question, for this study, is whether these differences in score can be explained by variations in topography. Table 3 lists the key topographic variables for each appellation. This is the mean average figure unless otherwise stated.

From Table 3, a clear trend is apparent in all the variables, with the variables either increasing or decreasing monotonically as the quality of the appellation rises. Most notably, moving from basic Chablis, through Premier Cru to the Grand Cru appellations, there is:

- a decreasing proportion of northerly slopes and an increasing proportion of south- and south-west-facing slopes;
- an increase in steepness;
- a decrease in elevation;
- a decrease in relative elevation, that is, a decrease in slope exposure; and
- an increase in the proportion of UCS30 soils.

Correlation analysis

To test the significance of the above observations, the appellations were broken down into 20 observations (seven

Table 2. Appellation scores across all vintages of Chablis in CellarTracker.

		CellarTracker score					
	No. of samples	Median	10th Percentile	25th Percentile	75th Percentile	90th Percentile	Skew
Chablis	2143	88.0	83.7	86.0	89.0	90.0	−0.66
Premier Cru	3224	89.5	86.0	88.0	90.8	92.0	−0.49
Grand Cru	1483	91.0	88.0	90.0	92.2	93.3	−0.22

Skew is the Pearson 2 skewness coefficient measure [3 × (mean − median)/SD]. The skewness coefficient suggests that the basic Chablis and Premier Cru samples are probably not from a normally distributed population (Doane and Seward 2011), which was confirmed by the failure of four statistical tests for normality (Shapiro–Wilk, Anderson–Darling, Lilliefors and Jarque-Bera). Non-parametric tests were therefore chosen for analysis of the wine scores.

APPENDIX 1A

Table 3. Topographic and soil summary at the Chablis appellation level.

	Chablis	Premier Cru	Grand Cru
Aspect, % of land facing			
Northwest to north-east	41	7	8
East to south-east	25	52	12
South	12	17	29
Southwest to west	22	24	51
Slope gradient (%)	11.1	15.3	17.6
Elevation (m)	210	193	166
Relative elevation (0–100)	54	41	34
Soils (% UCS30)	48	72	84

Grand Cru Climats, 12 principal Premier Cru Climats and one observation for Village Chablis) that were used for Spearman's rank correlation of wine score versus aspect, slope gradient, elevation, relative elevation and proportion UCS30 soils (Table 4).

Spearman's rank correlations confirmed that some of the topographic relationships with wine quality are significant. Table 5 shows that a moderate negative correlation was found between wine scores and (i) elevation and (ii) the proportion of slopes facing east, south-east and east to south-east. A positive correlation (albeit at a lower confidence level, $P < 0.1$) was found between wine scores and slopes facing south-west and the proportion of UCS30 soils. The relationships for elevation can be seen more clearly in the scatter plot (Figure 5).

As such, there appears to be a moderate relationship between topography and soil versus wine score when viewed across the appellations, and this could, at first glance, provide an argument for topography and soils being a key driver in determining differences in wine quality within Chablis.

Appellation is a confounding factor

The problem with the above analysis is that appellation may be (and probably is) an influence on wine quality. In other words, appellation, possibly because of the Grand Cru's greater association with producers of superior winemaking skill and stricter appellation laws regarding viticulture and vinification (and likewise Premier Cru relative to Village), appears to be a confounding variable and should be controlled for. Moreover, as mentioned earlier, it may be that drinkers are scoring the Grand Cru wines higher than the Premier Cru wines and Premier Cru wines higher than Village wines because of the labelling effect.

For example, Figure 6 illustrates what originally looks like a relationship between median score, and elevation in Figure 5 breaks down when considered within each of the Grand and Premier Cru appellations. Figures 7 and 8 show how the relationships identified for soil and aspect similarly break down when viewed at the individual appellation level.

Table 4. The 20 Climats used for correlation analysis.

Principal Climat†	Appellation	Area (m^2)
Village	Chablis	36 288 609
Beauroy	Premier	639 721
Côte de Léchet	Premier	529 063
Fourchaume	Premier	1 380 278
Les Fourneaux	Premier	356 856
Mont de Milieu	Premier	462 275
Montée de Tonnerre	Premier	431 501
Montmains	Premier	1 226 405
Vaillons	Premier	1 359 980
Vau de Vey	Premier	401 381
Vau Ligneau	Premier	313 640
Vaucoupin	Premier	523 170
Vosgros	Premier	233 102
Blanchot	Grand	125 063
Bougros	Grand	158 457
Grenouilles	Grand	89 050
Les Clos	Grand	290 068
Preuses	Grand	117 861
Valmur	Grand	110 003
Vaudésir	Grand	165 660

†Principal Premier Cru Climats of Berdiot, Chaume de Talvat, Côte de Jouan, Côte de Vaubarousse and Les Beauregards could not be used due to their insufficient number of wine-tasting scores in CellarTracker.

Table 5. Spearman's rank correlations between wine score and certain topographic and soil variables in Chablis.

	Correlation (r_s)	Significance (P)
Elevation	−0.56	0.011
% Slopes facing east	−0.62	0.004
% Slopes facing southeast	−0.52	0.021
% Slopes facing east to southeast	−0.63	0.004
% Slopes facing southwest	0.43	0.058
% UCS30 soils	0.44	0.055

The list includes only the relationships found to be significant.

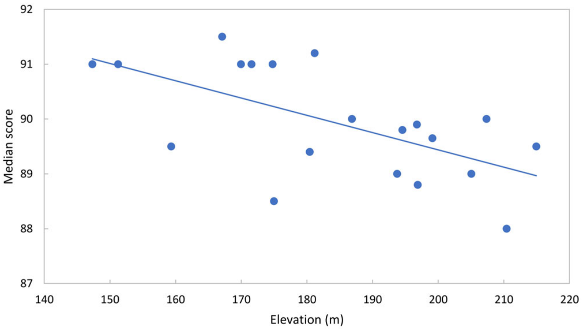

Figure 5. Median wine score versus mean elevation for Chablis wine.

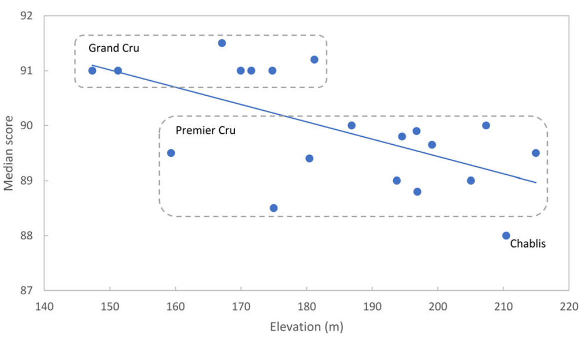

Figure 6. Median wine score versus mean elevation of Grand Cru, Premier Cru and Chablis appellations, with demarcation of appellation observations. Note how the Spearman's rank correlation (r_s = −0.56) and regression line suggest a relationship that does not hold at the individual appellation level.

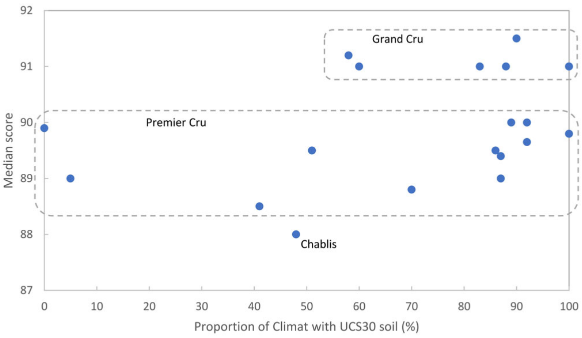

Figure 7. Median wine score versus the soil type UCS30 of Grand Cru, Premier Cru and Chablis appellations. Note how the Spearman's rank correlation (r_s = 0.44, $P < 0.10$) suggests a relationship that does not hold at the individual appellation level.

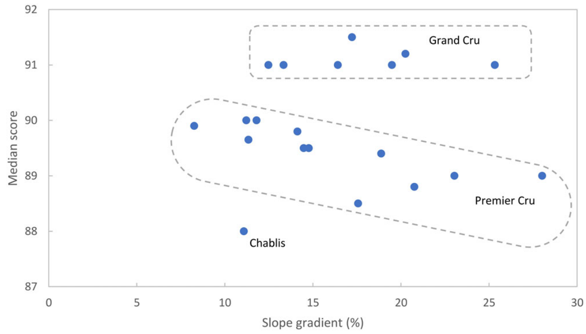

Figure 9. Median wine score versus mean slope gradient of Grand Cru, Premier Cru and Chablis appellations. Taken altogether, there appears to be no relationship between slope gradient and wine score. When separated by appellation, however, there appears to be a significant inverse relationship for the Premier Cru Climats.

The exception is slope gradient, which appears to be working in the opposite way: when viewed across the appellations, there appears to be no relationship (and no significant correlation), but closer inspection suggests there may be an inverse relationship between slope gradient and wine scores within the Premier Cru appellation (Figure 9). In fact, a strong inverse relationship ($r_s = -0.851$, $P < 0.05$) was found between median wine score and slope gradient for the Premier Cru dataset (Table S12).

The negative correlation between wine quality and slope gradient for the Premier Cru Climats is interesting because it is contrary to the general trend found at the appellation level (Table 3). Given that the Grand Cru Climats are steeper than those of the Premier Cru Climats, which are themselves steeper than the basic Chablis vineyards, it is surprising to find that, within the Premier Cru appellation, the gentler slopes appear to produce higher-scoring wines (Figure 10). A linear regression model for the relationship gives an R^2 of 0.57 and root mean square error (RMSE) of 0.34 ($P = 0.005$).

Wine quality, weather and slope gradient

It is widely acknowledged that vintage weather is a crucial factor in determining wine quality (Ashenfelter et al. 1995, Byron and Ashenfelter 1995, Corsi and Ashenfelter 2001).

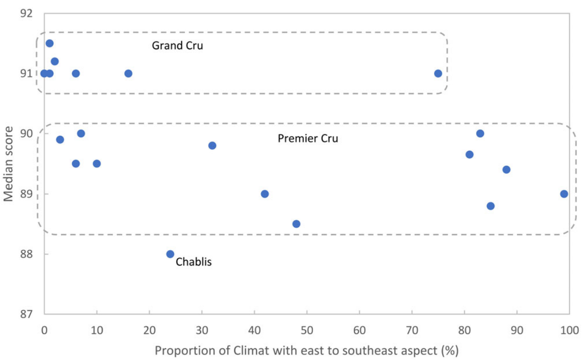

Figure 8. Median wine score versus the proportion of vineyard land facing east to south-east of Grand Cru, Premier Cru and Chablis appellations. Note how there appears to be two clusters of observations, each negatively correlated, that gives an overall Spearman's rank correlation coefficient of $r_s = -0.63$ ($P = 0.004$). This relationship, however, breaks down at the individual appellation level.

Ashenfelter et al. (1995), for example, found that auction prices for Bordeaux wine, a proxy for quality, could be well explained by growing season warmth and the amount of rainfall immediately before and during harvest.

To investigate the relationship between slope gradient and wine quality, it may be necessary to understand the role that slope gradient plays in how weather is transmitted to the grape berries and final wine quality. For example, does Vau de Vey, a Climat with the steepest slopes, produce superior wines in relatively wet years when drainage is important but underperform compared to other Climats in dry years?

To investigate this, the principal Premier Cru Climats were divided into two groups based on their mean gradient—(i) a low incline group and (ii) a steep incline group—omitting a medium buffer group comprising Mont de Milieu (mean gradient 14.1%), Fourchaume (14.5%) and Vaucoupin (14.8%) (Figure 11).

Figure 12 shows that there are notable differences between the two groups. On average, the low-incline Climats score 0.59 higher than the steep Climats. Using the non-parametric Mann–Whitney *U*-test, the difference between the groups was found to be statistically significant ($P = 0.023$). Spearman's rank correlation between the two groups is moderately high ($r_s = -0.73$), suggesting the two groups move broadly in unison between vintages. The ovals in Figure 12 point to vintages where the difference between the two groups move away from the average by more than

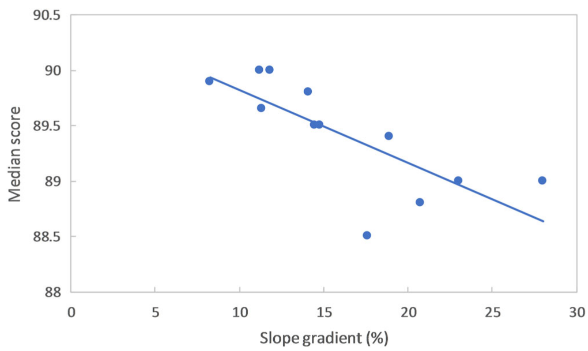

Figure 10. Median wine score versus mean slope gradient for Premier Cru Climats only. $y = -0.0656x + 90.483$, $R^2 = 0.569$.

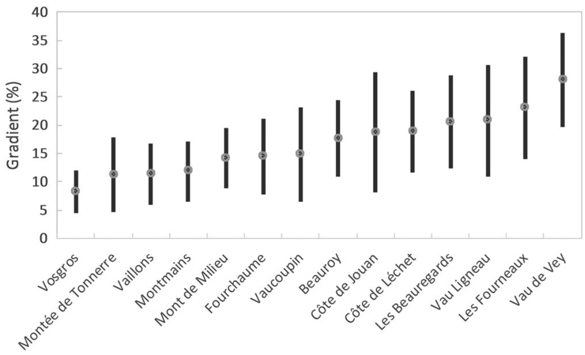

Figure 11. Slope gradient of Premier Cru Climats, where each bar illustrates the mean –1 SD (bottom of bar), mean (middle mark) and mean +1 SD (top of bar). Fourteen of the 17 principal Premier Cru Climats were involved in the analysis, excluding Berdiot, Chaume de Talvat and Cote de Vaubarousse, which have zero tasting scores in CellarTracker.

0.34 (which was the RMSE for the linear regression between slope gradient and Premier Cru median wine score). The vintage in which steep Climats performed worse than usual is 2009. Vintages in which the steep Climats performed better than usual are 2006, 2010 and 2012.

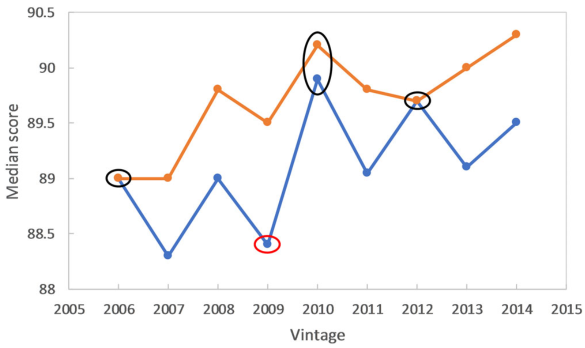

Figure 12. Steep Premier Cru Climats (●) versus low-incline Premier Cru Climats (●). The years 2006, 2010 and 2012 stand out as vintages when steep Climats performed better than usual, whereas steep Climats underperformed in 2009. The low incline group comprises: Vosgros (mean gradient 8.3%), Montée de Tonnerre (11.2%), Vaillons (11.3%) and Montmains (11.8%). The steep group comprises: Beauroy (mean gradient 17.6%), Côte de Jouan (18.7%), Côte de Léchet (18.9%), Les Beauregards (20.5%), Vau Ligneau (20.75%), Les Fourneaux (23.0%) and Vau de Vey (28.0%). It was not possible to extend the analysis beyond 2006 to 2014 due to insufficient sample numbers.

To determine if these observations are random or represent an indirect influence of slope gradient on wine quality, a closer inspection was carried out to see whether any aspect of vintage weather correlates to these years of relative under- and overperformance.

Correlation with vintage weather

The observation that the steeper Premier Cru Climats generally underperform compared to the low-incline Premier Cru Climats may simply be related to the greater proportion of superior winemakers farming the low-incline Climats. This appears especially likely given the steep group does not include any of the widely acknowledged finer Climats, such as Montée-de-Tonnerre, Fourchaume, Mont de Milieu, Montmains and Vaillons (Biss 2009). If there was evidence, however, that the steep- and low-incline groups react differently to vintage weather, this could provide evidence of slope gradient playing a role in determining wine quality rather than the winemaker.

Figure 12 shows how the steep Climats performed relatively well in 2006, 2010 and 2012, equalling or almost equalling the median score of the low-incline group, and performed relatively poorly in 2009. From Table 6, 2006 is identifiable as hot, wet and cloudy, and it is unsurprising that it is one of the lowest-ranked vintages of the range according to the CellarTracker scores.

In comparison, the 2010 vintage fell into the sweet spot of temperature, rainfall, sunshine and average minimum temperature and is ranked as one of the best Chablis vintages by CellarTracker scores. The only other vintage of the range to achieve this joint highest score is the 2014 vintage.

The 2012 vintage is a relatively successful vintage, ranked fourth by CellarTracker scores. It differed from 2010 in two respects: (i) it experienced, by far, the lowest rainfall in the 61 day period prior to harvest (47 mm vs an average of 115 mm); and (ii) it experienced the highest average and maximum wind speed during the April to September period, perhaps leading to some further dehydration of the berries.

The 2009 vintage was like 2012 in terms of its low August and September rainfall but was far hotter than 2012 (average April to September temperature of 17.5°C compared to 16.1°C). It was, in fact, the second hottest vintage

Table 6. Summary weather statistics for vintages from 2006 to 2014.

		Temperature (°C)			Rain (mm)			Sunshine (h)
		Average	Ave min	Ave min				
Vintage	CellarTracker vintage rating	April–September	April–September	61-days	April–September	42-days	61-days	April–September
2006	8.8	17.8	11.9	14.7	141	104	149	707
2007	8.8	16.8	11.0	13.1	129	97	154	731
2008	9.5	16.1	10.1	11.7	110	75	113	728
2009	9.0	17.5	10.9	13.1	69	33	72	854
2010	10.0	16.3	10.1	12.3	115	78	85	802
2011	9.5	17.0	10.7	12.8	100	76	99	833
2012	9.7	16.1	10.3	13.1	69	35	47	757
2013	10.0	16.3	10.3	12.6	116	79	128	782
2014	10.0	16.6	10.7	13.5	92	73	120	783
Average	9.4	16.6	10.7	13.0	107	70	115	767

Note: '42 days' and '61 days' refer to the 42- and 61-day period leading up to the harvest.

APPENDIX 1A

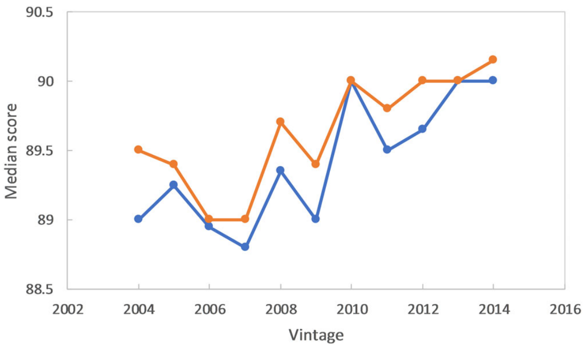

Figure 13. Comparison of the scores for the left (●) and right (●) bank Chablis Climats. The left bank group comprises Beauroy, Côte de Jouan, Côte de Léchet, Les Beauregards, Montmains, Vaillons, Vau de Vey, Vau Ligneau and Vosgros. The right bank group comprises Fourchaume, Les Fourneaux, Mont de Milieu, Montée de Tonnerre and Vaucoupin.

for the 2006–2014 period. The high temperature and low rainfall suggest the vines would have come under water stress and potentially become overripe or even cooked.

Some questions emerge from these findings:

- Did the steeper Climats perform better than usual in the wet 2006 because of superior drainage?
- If so, why did they also perform as well as the low-incline group in the excellent vintage of 2010 and the good, but dry, vintage of 2012? Was it because of the 'adage' that lesser winemakers can make good wine in good years?
- Did the steeper Climats perform worse than usual in the hot and dry 2009 because of poor water retention and excessive solar insolation?

Unfortunately, the only other excessively wet or excessively hot and dry vintages that can be examined are found prior to the 2006 vintage, where CellarTracker sample numbers are too low.

Thus, to further test the relationship between slope gradient and wine quality, more data are required, specifically more vintage observations and a greater number of wines scored within those vintages.

Left versus right bank

The 'left bank/right bank' differentiation is not an important feature in Chablis as it is for Bordeaux. It is still sometimes referred to in the wine market, although more often as a locational reminder that the widely regarded better Climats, such as Montée de Tonnerre, and the Grand Cru Climats are situated on the right bank (Biss 2009). Following a paper by Rodrigues et al. (2017), however, which found some chemical differences in the wines produced in the two areas, it is interesting to investigate whether there is also a difference in wine scores between them.

Figure 13 shows how the two groups vary with vintage. On average, right-bank Climats score 0.22 higher than the left-bank Climats. The Mann–Whitney *U*-test found, however, that there is no significant difference between the median scores of the two groups ($P = 0.14$), despite the appearance providing no statistical evidence for a clear left-bank/right-bank distinction. There is also no evidence of a divergent reaction to vintage weather as the two groups move in almost perfect unison while maintaining a difference of between 0.00 and 0.50 in score (Spearman's rank; $r_s = 0.96$).

Multiple regression

Perhaps no single topographic variable is strong enough to impact wine quality alone, but when taken together with other variables, a topographic effect may be clearer. Multiple regressions were carried out between median wine score and various combinations of two predictor variables—for example, slope gradient and aspect and slope gradient and elevation. In no case, however, was there sufficient evidence (i.e. $P < 0.10$ for the second factor) to suggest two factors together exert a greater, and statistically significant, influence on differentiating wines scores between the Premier Cru Climats than one factor alone. The single correlation between slope gradient and wine score remained the strongest relationship.

Discussion

There is little evidence that topography has played a role in determining differences in wine quality between the appellations and Climats of Chablis over the study period.

Traditionally, any unofficial ranking (in the sense that one Climat is seen as superior to another) has been explained by differences in terroir, of which topography is a major component (Droin 2014). An alternative view, however, is that differences result instead from the proportion of 'good' winemakers who farm land within the Climat. In other words, there may be a positive feedback mechanism where the older well-established Climats are perceived as superior (by winemakers and drinkers alike), and prices for that land are such that only the better more established winemakers can afford them (Storchmann 2018).

That said, it must not be forgotten that land and winemaking are inter-related and that superior winemaking may indeed lead to superior wines over time through viticultural practices that enhance the soil.

Certainly, the differences in scores at the appellation level (Chablis, Premier Cru, Grand Cru) could be explained by superior winemaking practices, some of which are required by appellation law. There are certain rules and regulations that must be adhered to regarding viticulture and winemaking between the basic Chablis, Premier Cru and Grand Cru appellations (e.g. yields). It may therefore look like a south-west aspect and greater steepness lead to superior wines, but this may simply reflect the superior viticultural practices and winemaking of the Grand Cru domaines. Conversely, the difference in scores may result from a labelling effect where CellarTracker drinkers mark their scores up or down based on their expectation of appellation quality.

There is perhaps some evidence for slope gradient playing a role as this appears to be a factor that explains some of the differences in wine quality within the Premier Cru appellation. This could be for genuine topographical reasons, for example, superior drainage, enhanced solar radiation, but may be random and coincidental; more data are required to test this relationship.

In other words, within the parameters considered generally acceptable for growing Chardonnay grapes in Chablis, and contrary to the findings of several other studies (Bavaresco et al. 2007, Bramley et al. 2011, Roullier-Gall et al. 2014, Scarlett et al. 2014, Anesi et al. 2015, Rupnik et al. 2016), it appears to matter little in terms of overall quality (although not necessarily characteristics) whether the vineyards are south-east or south-west facing, whether the land is at 50 m or 150 m or if the land is closer to the valley floor or hilltop.

Aside from increasing the dataset size (i.e. the sample size is too small for some Climats once they are broken down into vintages), several improvements could be made to this study:

- Qualitative wine reviews could be included to understand the impact of topography on wine characteristics, and not just wine quality.
- The winemaker could be included in the analysis to find what proportion of a Climat is farmed by good winemakers, thus answering more directly the question of how much influence the winemaker has (although agreement would be needed on who the good winemakers are).
- Instead of SRTM data, Light Detection and Ranging (LIDAR) data could be used to produce a more accurate and higher-resolution DEM.

Conclusion

Based on a comparison between CellarTracker wine scores and topographic data for the Chablis area, this study has been unable to find any clear evidence that topography plays a detectable role in determining wine quality differences within Chablis. This is not to say that topography does not play an important role in giving certain characteristics to wines within Chablis (not explored here), but there appears little evidence to suggest that topography plays a significant role in determining quality differences between the Climats in Chablis as measured by CellarTracker scores.

One general implication from this is that, providing a vineyard falls within the general topographic parameters of the vineyards studied here, and the weather and soil is appropriate, it should be able to produce quality wine from Chardonnay vines no matter the topography. Aside from a possible but unproven relationship with slope gradient, this study finds no evidence for a topographic differentiator in quality at the local scale.

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Supporting information

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Figure S1. Aspect rose diagrams for (a) Premier and (b) Grand Cru appellations. Measured in cell numbers, with each cell the equivalent to 655 m^2 of vineyard land (25.6 × 25.6 m).

Figure S2. Sample size (■) and interquartile range (——) by vintage. The chart shows the number of scored Chablis Premier Cru wines in the CellarTracker database per vintage (1995–2015). Note the low sample numbers for vintages prior to 2004.

Table S1. Proportion of Climat land with specified aspect orientation.

Table S2. Slope gradient of principal Chablis Climats.

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Table S4. Elevation of Chablis principal Climats.

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Table S6. Soil unit [Unités Cartographique de Sol (UCS)] for each principal Climat and the basic Chablis appellation (Village), Chablis.

Table S7. Description of UCS soil classifications.

Table S8. CellarTracker scores for each principal Climat and the basic Chablis appellation (Village), ordered by median score.

Table S9. Countries with over 1000 declared CellarTracker members.

Table S10. Number of Chablis wines and number of bottles tasted for vintages from 1995 to 2016.

Table S11. CellarTracking scoring system.

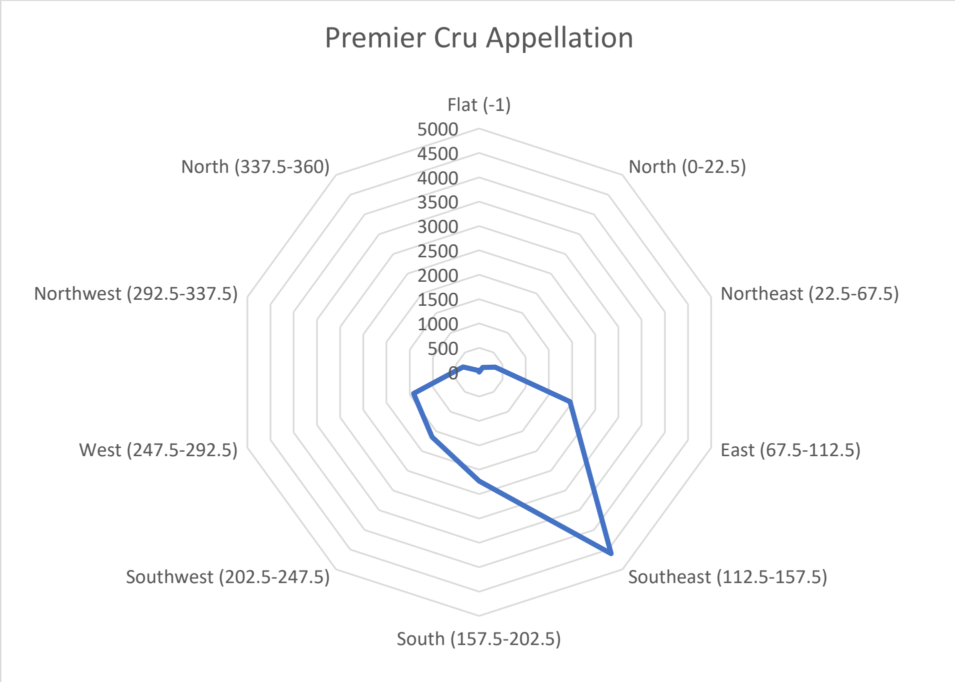
Table S12. The Chablis Premier Cru dataset used for correlation and regression analysis.

Supporting Information

Table S1. Proportion of Climat land with specified aspect orientation.

				Proportion of Climat land (%)							
Principal Climat	**Appellation**	**Area (m^2)**	**Flat**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Village	Chablis	36 288 609	0	14	8	10	14	12	9	13	19
Beauroy	Premier	639 721	0	0	0	9	39	36	15	1	0
Berdiot	Premier	19 643	0	0	0	0	0	0	40	60	0
Chaume de Talvat	Premier	108 694	0	0	1	7	80	12	0	0	0
Côte de Jouan	Premier	93 634	0	1	1	15	55	27	1	0	0
Côte de Léchet	Premier	529 063	0	6	4	26	62	2	0	0	1
Côte de Vaubarousse	Premier	14 405	0	0	0	0	0	0	82	18	0
Fourchaume	Premier	1 380 278	0	0	0	0	6	14	32	40	8
Generic Premier	Premier	8 294 109	0	1	3	16	36	18	13	11	3
Les Beauregards	Premier	200363	0	0	0	3	54	43	0	0	0
Les Fourneaux	Premier	356 856	0	0	0	7	35	40	17	1	0
Mont de Milieu	Premier	462 275	0	0	0	4	28	47	18	2	0
Montée de Tonnerre	Premier	431 501	0	0	0	0	7	13	36	39	5
Montmains	Premier	1 226 405	0	0	3	27	56	12	2	0	0
Vaillons	Premier	1 359 980	0	4	10	24	57	4	0	0	0
Vau de Vey	Premier	401 381	0	0	1	61	38	0	0	0	0
Vau Ligneau	Premier	313 640	0	1	7	33	52	5	0	1	1
Vaucoupin	Premier	523 170	0	0	0	2	8	40	22	20	8
Vosgros	Premier	233 102	0	3	1	0	3	19	28	26	19
Blanchot	Grand	125 063	0	0	0	10	65	25	0	0	0
Bougros	Grand	158 457	0	0	0	0	0	28	29	33	10
Generic Grand	Grand	1 056 161	0	0	0	1	11	30	30	21	7
Grenouilles	Grand	89 050	0	0	0	0	1	51	40	7	1
Les Clos	Grand	290 068	0	0	0	0	1	26	63	10	0
Preuses	Grand	117 861	0	0	0	2	14	9	13	52	11
Valmur	Grand	110 003	0	0	0	0	2	20	19	49	9
Vaudésir	Grand	165 660	0	3	0	0	6	49	10	11	21

APPENDIX 1B



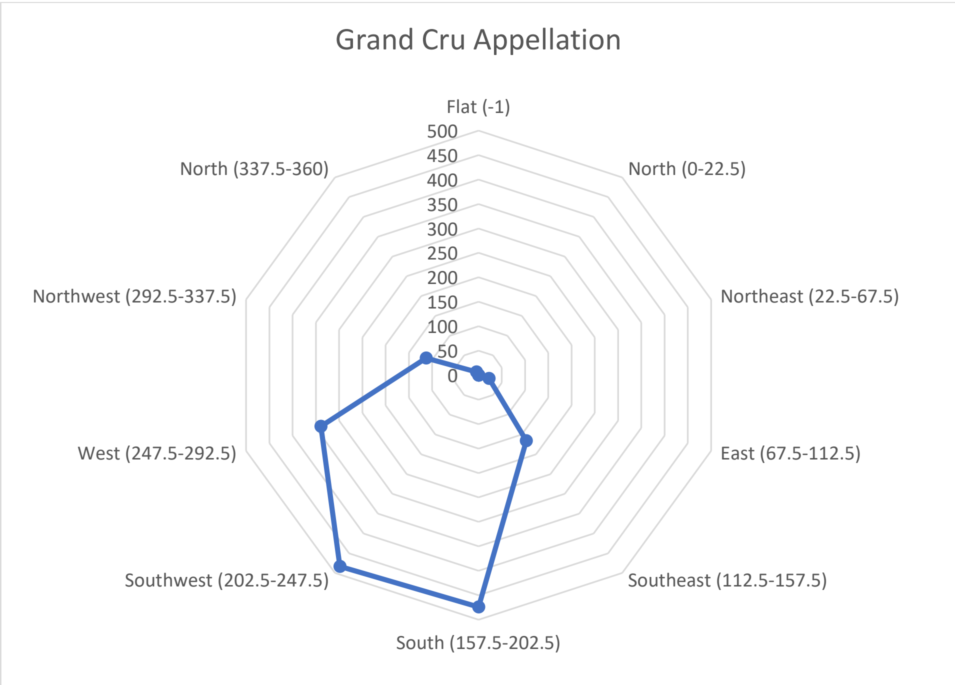


Figure S1. Aspect rose diagrams for (a) Premier and (b) Grand Cru appellations. Measured in cell numbers, each cell equivalent to 655 m^2 of vineyard land (25.6 x 25.6 m).

Table S2. Slope gradient of principal Chablis Climats.

		Slope gradient (%)			
Principal Climat	**Appellation**	**Mean**	**Min**	**Max**	**SD**
Blanchot	Grand	25.3	5.6	51.3	9.1
Bougros	Grand	12.5	2.0	34.8	7.9
Generic Grand	Grand	17.6	2.0	53.2	8.8
Grenouilles	Grand	16.4	4.9	31.3	6.5
Les Clos	Grand	17.2	4.9	35.7	6.5
Preuses	Grand	13.3	4.4	32.4	6.3
Valmur	Grand	20.2	5.4	53.2	7.3
Vaudésir	Grand	19.5	2.1	47.9	11.0
Beauroy	Premier	17.6	0.0	38.1	6.8
Berdiot	Premier	21.6	9.2	35.3	4.4
Chaume de Talvat	Premier	21.4	0.7	39.3	7.2
Côte de Jouan	Premier	18.7	0.7	51.4	10.7
Côte de Léchet	Premier	18.9	0.7	43.0	7.2
Côte de Vaubarousse	Premier	19.8	4.0	37.7	9.0
Fourchaume	Premier	14.5	0.7	45.4	6.7
Generic Premier	Premier	15.3	0.0	51.4	8.2
Les Beauregards	Premier	20.5	2.0	48.9	8.3
Les Fourneaux	Premier	23.0	3.5	47.1	9.0
Mont de Milieu	Premier	14.1	3.5	36.0	5.3
Montée de Tonnerre	Premier	11.2	0.7	41.5	6.5
Montmains	Premier	11.8	0.7	29.8	5.3
Vaillons	Premier	11.3	0.0	31.3	5.4
Vau de Vey	Premier	28.0	5.0	48.9	8.3
Vau Ligneau	Premier	20.8	0.7	47.0	9.9
Vaucoupin	Premier	14.8	1.0	42.3	8.4
Vosgros	Premier	8.3	0.0	19.1	3.7
Village	Chablis	11.1	0.0	55.7	7.0

Table S3. Proportion of Climat land that falls into slope steepness categories.

		Proportion within steepness categories (%)						
Principal Climat	**Appellation**	**N.Lev**	**V.Gen**	**Gen**	**Mod**	**Str**	**V.Str**	**Extr**
Blanchot	Grand	0	0	1	13	57	26	4
Bougros	Grand	0	8	39	24	26	3	0
Generic Grand	Grand	0	2	15	27	46	9	1
Grenouilles	Grand	0	1	12	35	51	1	0
Les Clos	Grand	0	0	10	32	55	3	0
Preuses	Grand	0	3	26	37	33	1	0
Valmur	Grand	0	0	2	21	68	8	1
Vaudésir	Grand	0	4	14	25	35	21	1
Beauroy	Premier	1	1	6	28	58	5	0
Berdiot	Premier	0	0	0	7	90	3	0
Chaume de Talvat	Premier	1	1	3	16	67	13	0
Côte de Jouan	Premier	1	3	17	17	48	9	4
Côte de Léchet	Premier	1	3	6	20	65	6	0
Côte de Vaubarousse	Premier	0	5	5	27	50	14	0
Fourchaume	Premier	0	4	18	38	37	3	0
Generic Premier	Premier	1	5	18	32	38	6	0
Les Beauregards	Premier	0	1	3	22	60	13	1
Les Fourneaux	Premier	0	0	2	15	63	19	2
Mont de Milieu	Premier	0	1	14	47	38	1	0
Montée de Tonnerre	Premier	1	6	37	37	15	3	0
Montmains	Premier	1	7	25	43	24	0	0
Vaillons	Premier	1	8	30	39	23	0	0
Vau de Vey	Premier	0	0	1	4	54	39	2
Vau Ligneau	Premier	2	5	6	16	52	19	0
Vaucoupin	Premier	1	7	22	30	35	6	0
Vosgros	Premier	2	17	42	33	6	0	0
Village	Chablis	3	16	27	30	22	2	0

N.Lev., nearly level (0.5–2%); V.Gen, very gentle (2–5%); Gen, gentle (5–9%); Mod, moderate (9–15%); Str, strong (15–30%); V. Str, very strong (30–45%); Extr, extreme (45–70%). Descriptors from Barcelona Field Studies Centre (2018).

Table S4. Elevation of Chablis principal Climats.

		Elevation (masl)			
Principal climat	**Appellation**	**Mean**	**Min**	**Max**	**SD**
Blanchot	Grand	171.6	138.0	216.0	19.1
Bougros	Grand	147.3	128.0	166.0	10.1
Generic Grand	Grand	166.1	128.0	219.0	20.2
Grenouilles	Grand	151.2	131.0	175.0	11.4
Les Clos	Grand	167.1	129.0	215.0	22.7
Preuses	Grand	174.8	136.0	211.0	14.9
Valmur	Grand	181.2	142.0	219.0	16.2
Vaudésir	Grand	170.0	136.0	200.0	14.8
Beauroy	Premier	175.0	146.0	223.0	14.3
Berdiot	Premie	191.0	173.0	208.0	9.4
Chaume de Talvat	Premie	253.7	211.0	291.0	20.4
Côte de Jouan	Premie	240.3	218.0	274.0	12.9
Côte de Léchet	Premie	180.4	143.0	228.0	19.0
Côte de Vaubarousse	Premie	186.0	174.0	198.0	6.7
Fourchaume	Premie	159.3	123.0	219.0	17.9
Generic Premier	Premie	193.2	123.0	291.0	29.6
Les Beauregards	Premie	258.6	227.0	291.0	16.4
Les Fourneaux	Premie	205.0	177.0	236.0	13.3
Mont de Milieu	Premie	194.6	158.0	234.0	17.0
Montée de Tonnerre	Premie	186.9	158.0	230.0	17.0
Montmains	Premie	207.4	157.0	269.0	26.1
Vaillons	Premie	199.1	150.0	256.0	22.6
Vau de Vey	Premie	193.8	152.0	236.0	19.9
Vau Ligneau	Premie	196.9	170.0	238.0	12.7
Vaucoupin	Premie	214.9	158.0	268.0	26.0
Vosgros	Premie	196.8	178.0	212.0	7.6
Village	Chablis	210.4	120.0	322.0	34.6

Table S5. Relative elevation index for principal Climats of Chablis.

		Relative elevation index (0–100)			
Principal Climat	**Appellation**	**Mean**	**Min**	**Max**	**SD**
Blanchot	Grand	30.5	8.0	66.0	14.7
Bougros	Grand	29.7	5.0	42.0	9.9
Generic Grand	Grand	34.1	2.0	70.0	14.8
Grenouilles	Grand	22.7	6.0	40.0	9.6
Les Clos	Grand	31.8	2.0	69.0	16.9
Preuses	Grand	45.6	10.0	70.0	11.6
Valmur	Grand	42.0	13.0	69.0	11.9
Vaudésir	Grand	37.9	10.0	66.0	11.8
Beauroy	Premier	40.2	11.0	81.0	14.7
Berdiot	Premier	29.5	12.0	45.0	9.5
Chaume de Talvat	Premier	45.1	9.0	74.0	17.2
Côte de Jouan	Premier	27.8	14.0	52.0	9.3
Côte de Léchet	Premier	38.4	10.0	74.0	16.9
Côte de Vaubarousse	Premier	22.6	13.0	33.0	5.8
Fourchaume	Premier	32.8	7.0	72.0	13.0
Generic Premier	Premier	41.0	5.0	94.0	16.5
Les Beauregards	Premier	40.5	15.0	69.0	14.1
Les Fourneaux	Premier	33.2	8.0	63.0	12.9
Mont de Milieu	Premier	40.6	19.0	66.0	10.3
Montée de Tonnerre	Premier	47.1	32.0	71.0	6.6
Montmains	Premier	50.4	12.0	84.0	14.3
Vaillons	Premier	39.3	10.0	75.0	15.8
Vau de Vey	Premier	37.5	9.0	81.0	17.8
Vau Ligneau	Premier	25.7	5.0	72.0	13.8
Vaucoupin	Premier	49.9	14.0	80.0	13.6
Vosgros	Premier	72.3	53.0	94.0	9.6
Village	Chablis	54.1	3.0	100.0	21.0

Table S6. Soil unit [Unités Cartographique de Sol, (UCS)] for each principal Climat and the basic Chablis appellation (Village), Chablis.

		Proportion of Climat land with specified soil unit (%)							
Principal Climat	**Appellation†**	**UCS_20**	**UCS_28**	**UCS_29**	**UCS_30**	**UCS_32**	**UCS_33**	**UCS_36**	**UCS_56**
Blanchot	Grand	0	0	0	**60**	0	40	0	0
Bougros	Grand	0	0	0	**100**	0	0	0	0
Generic Grand	Grand	0	0	0	**84**	9	6	0	0
Grenouilles	Grand	0	0	0	**100**	0	0	0	0
Les Clos	Grand	0	0	0	**90**	3	7	0	0
Preuses	Grand	0	0	0	**83**	17	0	0	0
Valmur	Grand	0	0	0	**58**	42	0	0	0
Vaudésir	Grand	0	0	0	**88**	12	0	0	0
Beauroy	Premier	0	0	0	**41**	57	0	0	2
Berdiot	Premier	0	0	0	**0**	0	100	0	0
Chaume de Talvat	Premier	0	0	0	**59**	41	0	0	0
Côte de Jouan	Premier	0	0	0	**100**	0	0	0	0
Côte de Léchet	Premier	0	0	0	**87**	13	0	0	0
Côte de Vaubarousse	Premier	0	0	0	**0**	0	100	0	0
Fourchaume	Premier	0	0	0	**51**	49	0	0	0
Generic Premier	Premier	0	0	2	**72**	20	6	0	0
Les Beauregards	Premier	0	0	0	**74**	26	0	0	0
Les Fourneaux	Premier	0	0	0	**5**	0	95	0	0
Mont de Milieu	Premier	0	0	0	**100**	0	0	0	0
Montée de Tonnerre	Premier	0	0	0	**92**	8	0	0	0
Montmains	Premier	0	0	7	**89**	3	0	0	0
Vaillons	Premier	0	0	1	**92**	6	0	0	0
Vau de Vey	Premier	0	0	0	**87**	13	0	0	0
Vau Ligneau	Premier	0	0	0	**70**	30	0	0	0
Vaucoupin	Premier	0	0	7	**86**	6	0	0	0
Vosgros	Premier	0	10	0	**0**	55	35	0	0
Village	Chablis	1	1	8	**48**	32	8	2	0

†Generic_Premier and generic_Grand refer to total figures for all Premier and Grand Cru Climats, respectively, that is at the appellation level. UCS_30 is the soil unit associated with the Kimmeridgian slopes (see Table S12 for explanation of UCS). Based on Chambre d'Agriculture de Bourgogne (n.d.).

Table S7. Description of UCS soil classifications.

Soil unit	description
UCS20	Hard tabular limestone plateau dominated by deep soils
UCS28	Moderate slopes on soft chalky ('Tonnerre') limestone
UCS29	Slopes on various materials (limestone, chalky limestone)
UCS30	Kimmeridgian clay-stony slopes
UCS32	Dissected plateaus and dry valleys on hard Portlandian limestone
UCS33	Steep slopes, ravines and cliffs on hard limestones
UCS36	Slopes with low to medium gradient, in wet clay meadows
UCS56	Low terraces and alluvial plains of Armançon and Serein valleys

Translated from Chambre d'Agriculture de Bourgogne's (n.d.).

Table S8. CellarTracker scores for each principal Climat and the basic Chablis appellation (Village), ordered by median score.

Principal Climat	Appellation	Sample†	Median	P10‡	P25	P75	P90	IQR§
Les Clos	Grand	448	91.5	88.5	90.0	92.5	94.0	2.5
Valmur	Grand	197	91.2	87.6	89.5	92.2	93.1	2.7
Preuses	Grand	175	91.0	88.0	90.0	92.5	93.4	2.6
Blanchot	Grand	163	91.0	88.0	89.5	92.4	93.7	2.8
Vaudésir	Grand	240	91.0	88.0	90.0	92.0	93.0	2.0
Bougros	Grand	160	91.0	88.0	89.6	92.0	92.9	2.4
Grenouilles	Grand	89	91.0	87.2	88.6	92.0	93.0	3.4
Les Beauregards§	Premier	18	90.5	88.0	89.3	91.6	93.0	2.3
Montée de Tonnerre	Premier	319	90.0	87.0	88.8	91.1	92.2	2.3
Montmains	Premier	601	90.0	86.0	88.0	91.0	92.0	3.0
Generic Grand§	Grand	11	90.0	82.0	87.0	91.0	91.0	4.0
Vosgros	Premier	50	89.9	86.5	88.0	90.8	92.0	2.8
Mont de Milieu	Premier	196	89.8	86.4	88.0	90.5	91.6	2.5
Vaillons	Premier	610	89.7	86.5	88.1	90.7	92.0	2.7
Vaucoupin	Premier	103	89.5	86.1	88.5	90.8	91.5	2.3
Fourchaume	Premier	584	89.5	86.0	88.0	90.5	91.6	2.5
Côte de Léchet	Premier	200	89.4	86.0	88.0	90.1	91.0	2.1
Vau de Vey	Premier	63	89.0	87.2	88.0	90.0	91.0	2.0
Les Fourneaux	Premier	79	89.0	83.8	87.8	90.0	91.0	2.3
Vau Ligneau	Premier	31	88.8	86.0	87.3	90.0	93.0	2.8
Beauroy	Premier	146	88.5	85.0	87.0	90.0	91.0	3.0
Generic Premier	Premier	209	88.0	82.7	86.0	89.6	91.0	3.6
Village	Chablis	2,143	88.0	83.7	86.0	89.0	90.0	3.0
Côte de Jouan§	Premier	15	87.5	84.0	84.5	91.0	91.0	6.5

†Sample refers to the number of scored wines; ‡P10, P25, P75 and P90, 10th, 25th, 75th and 90th percentile; §Climat with low sample numbers. IQR, interquartile range.

Table S9. Countries with over 1000 declared CellarTracker members.

Country	Number of members†	Proportion of total (%)
United States	99 499	17.8
Canada	10 703	1.9
United Kingdom	6458	1.2
Australia	4699	0.8
Sweden	3120	0.6
Denmark	2833	0.5
France	2334	0.4
Norway	2214	0.4
Germany	2025	0.4
Brazil	1995	0.4
The Netherlands	1944	0.3
Belgium	1832	0.3
Switzerland	1831	0.3
Italy	1167	0.2
Hong Kong	1103	0.2
Total membership	557 638	

†Approximately 70% of members do not declare their country of residence. Taken from CellarTracker on 9 September 2018.

Table S10. Number of Chablis wines and number of bottles tasted for vintages from 1995 to 2016.

	Wines†	Bottles tasted (No.)	Average bottles per wine (No.)
Chablis	3552	56 533	15.9
Premier	5551	171 978	31.0
Grand Cru	2379	144 795	60.9
Total	11 482	373 306	32.5

†Approximately 40% of wines reviewed in the CellarTracker database have not been given a score. Thus, the number of wines above is more than the number of wine scores used in this study. Taken from CellarTracker on 9 September 2018.

Table S11. CellarTracking scoring system.

Score	Definition
96 – 100	Extraordinary
90 – 95	Outstanding
85 – 89	Very good
80 – 84	Barely above average
70 – 79	Average
60 – 69	Below average
50 – 59	Unacceptable

The scoring system is based on The Wine Advocate system of 50 to 100 (The Wine Advocate, n.d.). Flawed wines (due to cork taint, for example) are normally given a score of 0, though for the purposes of this study, no zero-score tasting notes were included in the analysis.

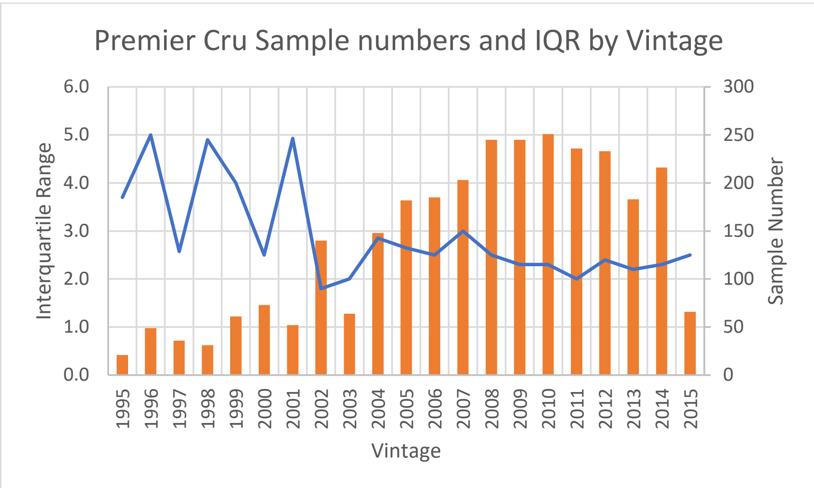


Figure S2. Sample size (█) and interquartile range (——) by vintage. The chart shows the number of scored Chablis Premier Cru wines in the CellarTracker database per vintage (1995 to 2015). Note the low sample numbers for vintages prior to 2004.

Table S12. The Chablis Premier Cru dataset used for correlation and regression analysis.

Principal Premier Cru Climats	**No. of wines†**
Beauroy	146
Côte de Léchet	200
Fourchaume	584
Les Fourneaux	79
Montée de Tonnerre	319
Montmains	601
Mont de Milieu	196
Vaillons	610
Vaucoupin	103
Vau de Vey	63
Vau Ligneau	31
Vosgros	50
Total	2982

†Numbers refer to CellarTracker sample size, that is the number of scored wines available for each Climat. Two principal Climats were excluded for low sample size: Côte de Jouan (15) and Les Beauregards (18), based on a calculated sample size requirement of 27 minimum (The University of North Carolina, 2010). Three principal Climats had no tasting scores in CellarTracker: Berdiot, Chaume de Talvet and Côte de Vaubarousse. Generic Premier Cru wines – typically wine produced by a négociant who has sourced grapes from several vineyards – have not been included.

SUPPLEMENTARY DATA

Biss, A., & Ellis, R. (2021). Modelling Chablis vintage quality in response to inter-annual variation in weather. *OENO One, 55*(3)
https://doi.org/10.20870/oeno-one.2021.55.3.4709

TABLE S1. Vintage scores, vintage scores standardized to 10-point scale, mean consensus vintage scores and overall vintage ratings for Chablis wine from 1963 to 2018.
BBR = Berry Bros. & Rudd wine merchants, DEC = Decanter magazine, WE = Wine Enthusiast, WS = The Wine Society, and WSG = Wine Scholar Guild.
QUAL = vintage score inferred from qualitative vintage reports on the Bourgogne Wine Board (BIVB) Chablis website and from George (2007).
Ratings are based on mean consensus score: Excellent (> 8), Good (6 – 8) and Poor (< 6). NA = not available

	Institution / Wine Expert Score						Institution / Wine Expert Score: 10-point scale						Mean	
Vintage	DEC	WE	WS	BBR	WSG	QUAL	DEC	WE	WS	BBR	WSG	QUAL	Score	Rating
1963	NA	NA	NA	NA	NA	4.5	NA	NA	NA	NA	NA	4.5	4.5	Poor
1964	NA	NA	NA	NA	NA	8.5	NA	NA	NA	NA	NA	8.5	8.5	Excellent
1965	NA	NA	NA	NA	NA	3.5	NA	NA	NA	NA	NA	3.5	3.5	Poor
1966	NA	NA	NA	NA	NA	8.75	NA	NA	NA	NA	NA	8.75	8.8	Excellent
1967	NA	NA	NA	NA	NA	7	NA	NA	NA	NA	NA	7	7.0	Good
1968	NA	NA	NA	NA	NA	3.25	NA	NA	NA	NA	NA	3.25	3.3	Poor
1969	NA	NA	NA	NA	NA	9.5	NA	NA	NA	NA	NA	9.5	9.5	Excellent
1970	NA	NA	NA	NA	NA	6.5	NA	NA	NA	NA	NA	6.5	6.5	Good
1971	NA	NA	NA	NA	NA	8.5	NA	NA	NA	NA	NA	8.5	8.5	Excellent
1972	NA	NA	NA	NA	NA	3	NA	NA	NA	NA	NA	3	3.0	Poor
1973	NA	NA	NA	NA	NA	7	NA	NA	NA	NA	NA	7	7.0	Good
1974	NA	NA	NA	NA	NA	5	NA	NA	NA	NA	NA	5	5.0	Poor
1975	NA	NA	NA	NA	NA	8.5	NA	NA	NA	NA	NA	8.5	8.5	Excellent
1976	NA	NA	NA	NA	NA	7.5	NA	NA	NA	NA	NA	7.5	7.5	Good
1977	NA	NA	NA	NA	NA	5	NA	NA	NA	NA	NA	5	5.0	Poor
1978	NA	NA	NA	7	NA	9	NA	NA	NA	7	NA	9	8.0	Good
1979	NA	NA	NA	6	NA	7.5	NA	NA	NA	6	NA	7.5	6.8	Good
1980	NA	NA	3	6	NA	-	NA	NA	3	6	NA	-	4.5	Poor
1981	NA	NA	7	8	NA	-	NA	NA	7	8	NA	-	7.5	Good
1982	NA	NA	6	6	NA	-	NA	NA	6	6	NA	-	6.0	Good
1983	NA	NA	7	7	NA	-	NA	NA	7	7	NA	-	7.0	Good
1984	NA	NA	5	4	NA	-	NA	NA	5	4	NA	-	4.5	Poor
1985	NA	NA	9	7	NA	-	NA	NA	9	7	NA	-	8.0	Good
1986	NA	NA	6	7	NA	-	NA	NA	6	7	NA	-	6.5	Good

APPENDIX 2 - TABLE S1 (CONT.)

Biss, A., & Ellis, R. (2021). Modelling Chablis vintage quality in response to inter-annual variation in weather. *OENO One, 55*(3)
https://doi.org/10.20870/oeno-one.2021.55.3.4709

1987	NA	NA	6	5	NA	-	NA	NA	6	5	NA	-	5.5	Poor
1988	NA	NA	8	7	NA	-	NA	NA	8	7	NA	-	7.5	Good
1989	NA	NA	9	8	NA	-	NA	NA	9	8	NA	-	8.5	Excellent
1990	NA	NA	10	10	NA	-	NA	NA	10	10	NA	-	10.0	Excellent
1991	NA	NA	6	5	NA	-	NA	NA	6	5	NA	-	5.5	Poor
1992	NA	NA	7	8	NA	-	NA	NA	7	8	NA	-	7.5	Good
1993	NA	NA	8	6	NA	-	NA	NA	8	6	NA	-	7.0	Good
1994	NA	NA	6	6	NA	-	NA	NA	6	6	NA	-	6.0	Good
1995	NA	90	8	9	NA	-	NA	8	8	9	NA	-	8.3	Excellent
1996	NA	93	9	9	NA	-	NA	8.6	9	9	NA	-	8.9	Excellent
1997	NA	89	7	8	NA	-	NA	7.8	7	8	NA	-	7.6	Good
1998	NA	89	7	7	NA	-	NA	7.8	7	7	NA	-	7.3	Good
1999	NA	87	7	7	NA	-	NA	7.4	7	7	NA	-	7.1	Good
2000	NA	89	7	8	3	-	NA	7.8	7	8	6	-	7.2	Good
2001	NA	93	6	7	2.5	-	NA	8.6	6	7	5	-	6.7	Good
2002	NA	95	8	9	5	-	NA	9	8	9	10	-	9.0	Excellent
2003	NA	87	6	7	2	-	NA	7.4	6	7	4	-	6.1	Good
2004	NA	92	7	6	2.5	-	NA	8.4	7	6	5	-	6.6	Good
2005	4	95	9	9	5	-	8	9	9	9	10	-	9.0	Excellent
2006	3	91	7	7	3	-	6	8.2	7	7	6	-	6.8	Good
2007	4	91	8	8	2.5	-	8	8.2	8	8	5	-	7.4	Good
2008	4	91	7	8	4	-	8	8.2	7	8	8	-	7.8	Good
2009	3	95	6	7	4	-	6	9	6	7	8	-	7.2	Good
2010	5	96	8	10	5	-	10	9.2	8	10	10	-	9.4	Excellent
2011	3.5	94	7	7	2	-	7	8.8	7	7	4	-	6.8	Good
2012	4	95	8	9	4	-	8	9	8	9	8	-	8.4	Excellent
2013	4	90	7	7	3.5	-	8	8	7	7	7	-	7.4	Good
2014	4.5	95	9	10	5	-	9	9	9	10	10	-	9.4	Excellent
2015	4.5	94	7	7	3.5	-	9	8.8	7	7	7	-	7.8	Good
2016	NA	95	7	8	3.5	-	NA	9	7	8	7	-	7.8	Good
2017	NA	96	8	9	4	-	NA	9.2	8	9	8	-	8.6	Excellent
2018	NA	96	7	8	4	-	NA	9.2	7	8	8	-	8.1	Excellent

SUPPLEMENTARY DATA

Biss, A., & Ellis, R. (2021). Modelling Chablis vintage quality in response to inter-annual variation in weather. *OENO One, 55*(3)
https://doi.org/10.20870/oeno-one.2021.55.3.4709

TABLE S2. Predicted Chablis wine vintage scores (with 5-95 % prediction intervals) from Equation 1, with environmental data shown, for the period 2041 to 2070 for climate projections using the 5th, 50th and 95th percentiles of RCP 2.5, 4.5 and 8.5 scenarios (Drias, 2021) for the closest grid square to Chablis (47°48'27" N, 3°46'42" E). Two values are shown for the Cool Night Index, where *CNI2* is an alternative to *CNI* in which the increase in value from 1976-2005 to 2041-2070 was reduced to only 40% of the projected $Tmean_{Apr\text{-}Sep}$ rise. For reference, information for the periods 1976-2005 and 2009-2018 is also presented (actual mean vintage scores were 7.1 and 8.1, respectively).

	Weather Data				Chablis Vintage Model	
Year and Scenario	$Tmean_{Apr\text{-}Sep}$ (°C)	*CNI* (°C)	*CNI2* (°C)	$P_{Jun\text{-}Sep}$ (mm)	Calculated Score	Calculated Score *CNI2*
1976–2005	15.8	9.4	n/a	233.6	7.7	n/a
2009–2018	16.8	9.8	n/a	236.0	7.8	n/a
Projections for 2041–2070						
RCP 2.6						
5th Percentile	16.1	10.4	9.58	193.5	7.8 (5.8 – 10.1)	8.2 (6.1 – 10.4)
Median	17.0	10.8	9.91	222.6	7.4 (5.3 – 9.6)	7.7 (5.7 – 10.0)
95th Percentile	17.6	11.2	10.17	270.1	6.1 (4.0 – 8.5)	6.6 (4.4 – 8.9)
RCP 4.5						
5th Percentile	16.5	10.1	9.70	175.0	8.2 (6.1 – 10.4)	8.3 (6.3 – 10.6)
Median	17.7	11.5	10.20	220.1	6.3 (4.1 – 8.6)	6.8 (4.6 – 9.1)
95th Percentile	18.7	12.2	10.61	283.4	3.1 (0.3 – 6.1)	3.8 (1.0 – 6.6)
RCP 8.5						
5th Percentile	17.1	11.2	9.96	156.8	7.6 (5.5 – 9.9)	8.1 (6.0 – 10.3)
Median	18.2	12.0	10.41	210.7	5.1 (2.7 – 7.6)	5.7 (3.4 – 8.2)
95th Percentile	19.2	13.1	10.80	281.3	1.1 (-2.2 – 4.5)	2.1 (-1.1 – 5.4)

SUPPLEMENTARY DATA
Biss, A. J., & Ellis, R. H. (2022). Weather potential for high-quality still wine from Chardonnay viticulture in different regions of the UK with climate change. *OENO One*, *56*(4), 201–220. https://doi.org/10.20870/oeno-one.2022.56.4.5458

Supplementary data

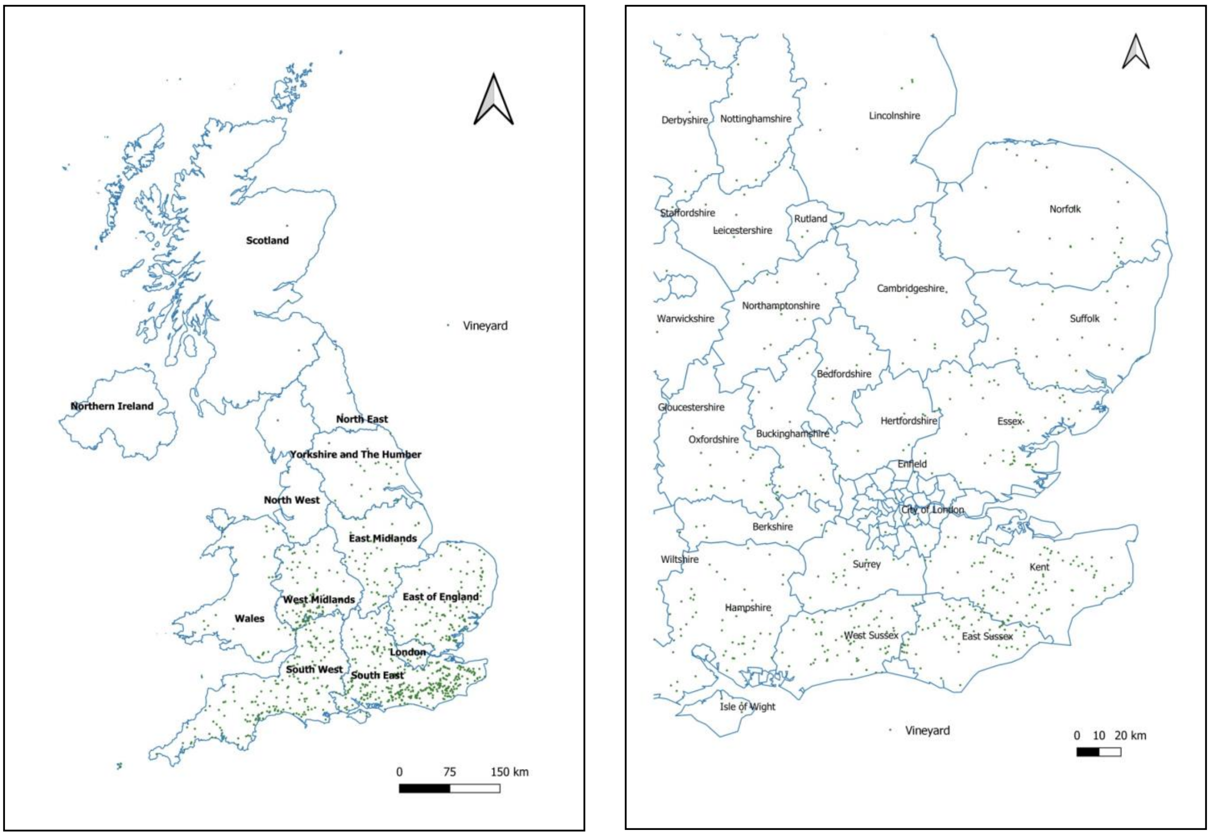


Figure S1. Location of vineyards in relation to administrative regions of the UK (left panel) and the counties of East of England, East Midlands and South East England (right panel, with Greater London's Enfield and City of London also marked). Location of vineyards as of 11 November 2020

APPENDIX 3 - TABLES S1 TO S4

SUPPLEMENTARY DATA
Biss, A. J., & Ellis, R. H. (2022). Weather potential for high-quality still wine from Chardonnay viticulture in different regions of the UK with climate change. *OENO One*, *56*(4), 201–220. https://doi.org/10.20870/oeno-one.2022.56.4.5458

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Table S1. UKCP18 probabilistic projections for mean summer temperature in England and Wales, in 2040-2059, with different emissions scenarios. Source: UKCP18 Key Results, Met Office (n.d.[b]).

Region	Time Horizon (relative to 1981-2000)	Emissions Scenario	Change in Mean Summer Temperature (°C)				
			5th percentile change	10th percentile change	50th percentile change	90th percentile change	95th percentile change
England and Wales	2040-2059	RCP2.6	0.5	0.8	1.8	2.8	3.1
England and Wales	2040-2059	RCP4.5	0.3	0.6	1.7	2.9	3.2
England and Wales	2040-2059	RCP6.0	0.3	0.5	1.6	2.7	3
England and Wales	2040-2059	RCP8.5	0.7	1	2.3	3.6	4

Table S2. Change in mean climate indices ($Tmean_{Apr\text{-}Sep}$, *CNI* and $P_{Jun\text{-}Sep}$) from 1981-2000 to 2010-19, derived from HadUK-Grid data and summarized by UK administrative region. Also provided is the ratio of change in *CNI* to that in $Tmean_{Apr\text{-}Sep}$.

UK Region	Change (1981-2000 to 2010-19)			
	$Tmean_{Apr\text{-}Sep}$ (°C)	*CNI* (°C)	$P_{Jun\text{-}Sep}$ (%)	$\Delta CNI / \Delta Tmean_{Apr\text{-}Sep}$ (%)
England				
East Midlands	0.72	0.30	7.7	42.2
East of England	0.70	0.06	2.0	8.6
London	0.64	0.06	4.3	9.3
North East England	0.68	0.71	20.4	105.1
North West England	0.50	0.52	21.9	104.2
South East England	0.59	0.10	3.8	16.9
South West England	0.53	0.37	6.4	70.7
West Midlands	0.57	0.24	5.7	42.3
Yorkshire and Humber	0.67	0.47	12.8	69.8
Northern Ireland	0.48	0.55	11.5	113.6
Scotland	0.49	0.74	10.0	150.6
Wales	0.48	0.37	9.3	78.3

Table S3. Climate indices for the 30 UK counties with the largest areas of planted vineyards. Indices are weighted within each county based on vineyard size. See Table S4 for individual vineyard scores and climate indices. <see Excel> 1.

Table S4. Vintage scores provided by the Model for 819 UK vineyards. Vineyard name, size, address and location from Skelton (2020b). <see Excel> 2.

1. https://oeno-one.eu/article/view/5458/25197

2. https://oeno-one.eu/article/view/5458/25198

APPENDIX 4

Minerality in wine: textual analysis of Chablis Premier Cru tasting notes

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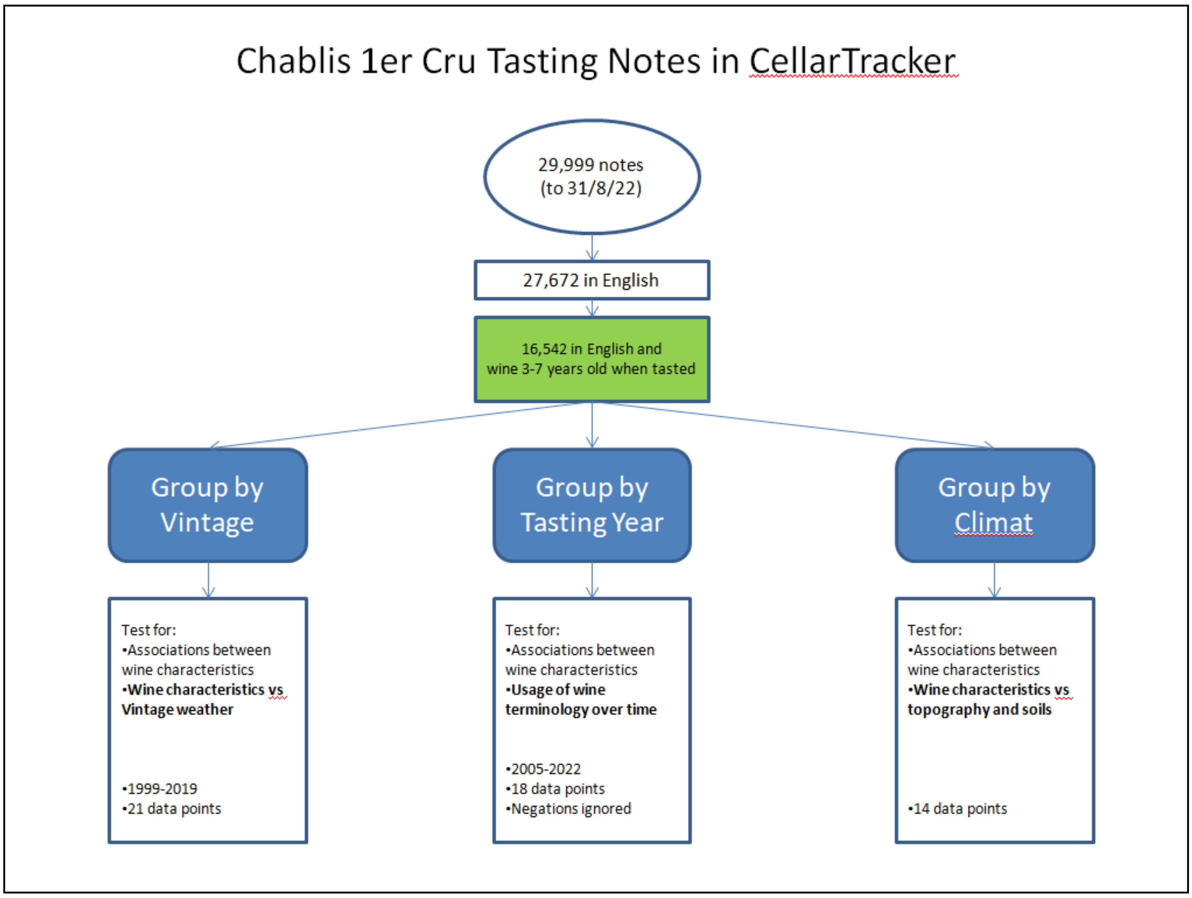
Supplementary Materials

Supplementary Table S1. The 17 principal Chablis Premier Cru Climats and their land area (m^2). From Biss [30].

Principal Climat	**Area (m^2)**
Beauroy	639,721
Berdiot	19,643
Chaume de Talvat	108,694
Côte de Jouan	93,634
Côte de Léchet	529,063
Côte de Vaubarousse	14,405
Fourchaume	1,380,278
Les Beauregards	200,363
Les Fourneaux	356,856
Mont de Milieu	462,275
Montée de Tonnerre	431,501
Montmains	1,226,405
Vaillons	1,359,980
Vau de Vey	401,381
Vau Ligneau	313,640
Vaucoupin	523,170
Vosgros	233,102

APPENDIX 4 - FIGURE S1

Supplementary Figure S1. Mean age of Chablis Premier Cru wine recorded each year in CellarTracker tasting notes of all wines (red line, range 3.8 to 7.3), wines aged between 3 and 7 years (black line, range 4.3 to 4.8, except for 2005), wines aged between 3 and 10 years (blue line, range 4.7 to 5.8), or wines aged between 5 and 10 years (green line, range 5.9 to 7.4). Linear regression analysis revealed significant trends ($p < 0.05$) for all periods except for wines restricted to between 3 and 7 years (black line, $p = 0.21$).



Supplementary Figure S2. Schematic diagram to show how the Chablis Premier Cru tasting notes from CellarTracker were organised into separate sub-databases for analyses.

APPENDIX 4 - TABLE S2

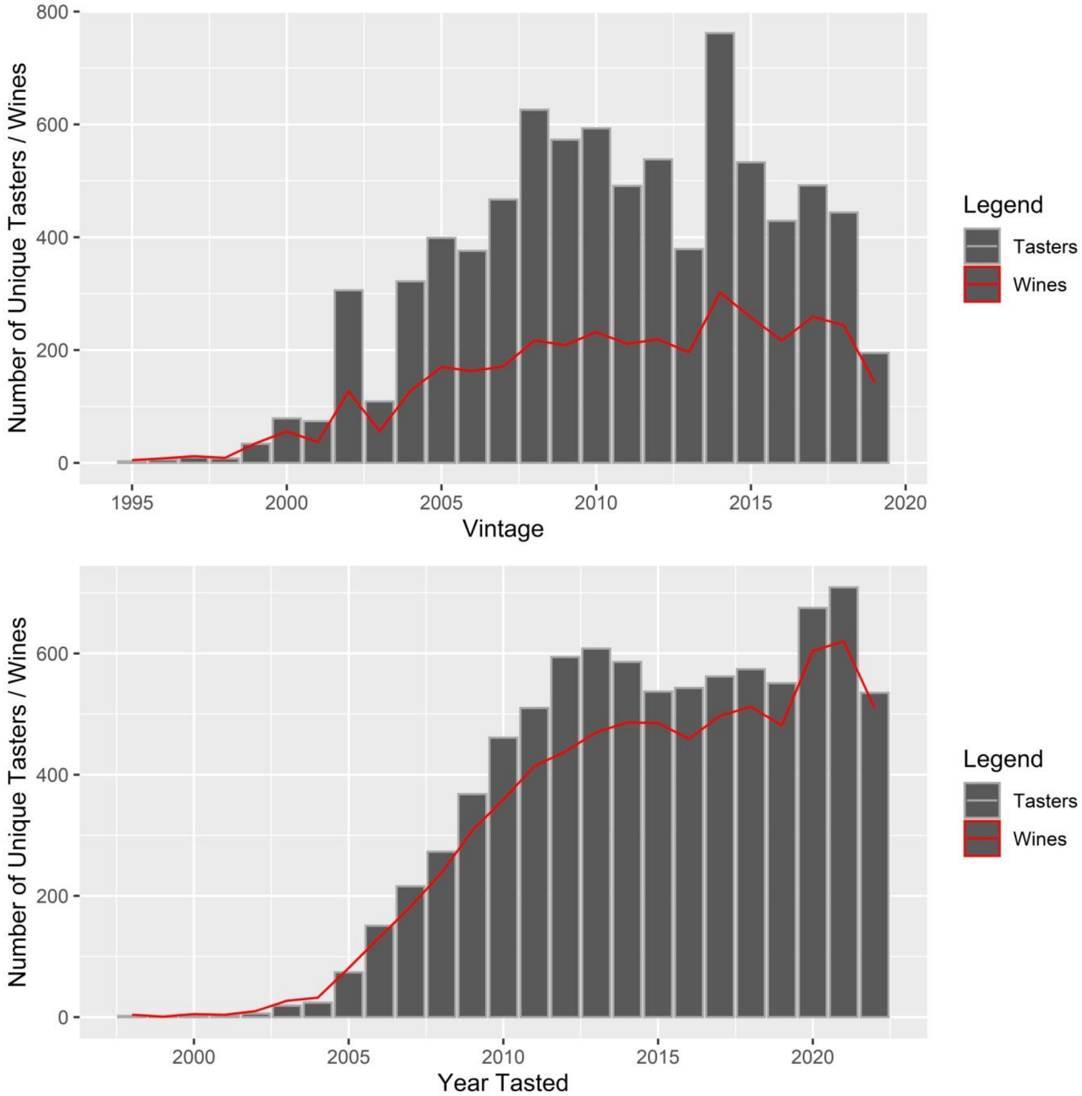
Supplementary Table S2. Descriptive statistics for the CellarTracker Premier Cru tasting notes analysed. All wines were between 3 and 7 years of age when tasted.

Vintage	Notes	Year Tasted	Notes	Principal PC Climat	Bank	Notes
1995	5	1998	4	Beauregard	Left	90
1996	9	1999	1	Beauroy	Left	361
1997	20	2000	5	Côte de Léchet	Left	871
1998	10	2001	4	Côtes de Jouan	Left	37
1999	50	2002	11	Fourchaume	Right	2546
2000	135	2003	30	Generic	N/A	582
2001	104	2004	35	Generic Left Bank	Left	1
2002	678	2005	118	Generic Right Bank	Right	5
2003	165	2006	241	Les Fourneaux	Right	244
2004	655	2007	384	Mont de Milieu	Right	973
2005	826	2008	519	Montée de Tonnerre	Right	2739
2006	712	2009	729	Montmains	Left	3865
2007	983	2010	843	Vaillons	Left	3228
2008	1387	2011	1024	Vau de Vey	Left	322
2009	1051	2012	1109	Vaucoupin	Right	395
2010	1346	2013	1179	Vauligneau	Left	91
2011	1041	2014	1143	Vosgros	Left	192
2012	1108	2015	1129			
2013	702	2016	1007			
2014	2028	2017	1181		**Wine Age**	**Notes**
2015	915	2018	1124		3	5088
2016	725	2019	1071		4	3828
2017	927	2020	1322		5	2997
2018	706	2021	1436		6	2567
2019	254	2022	893		7	2062

	Users	Notes
Unique Users	3960	16,542
Users with 100+ Notes	14	2082
Users with 10-99 Notes	324	6677
Users with 5-9 Notes	415	2717
Users with 1-4 Notes	3207	5066

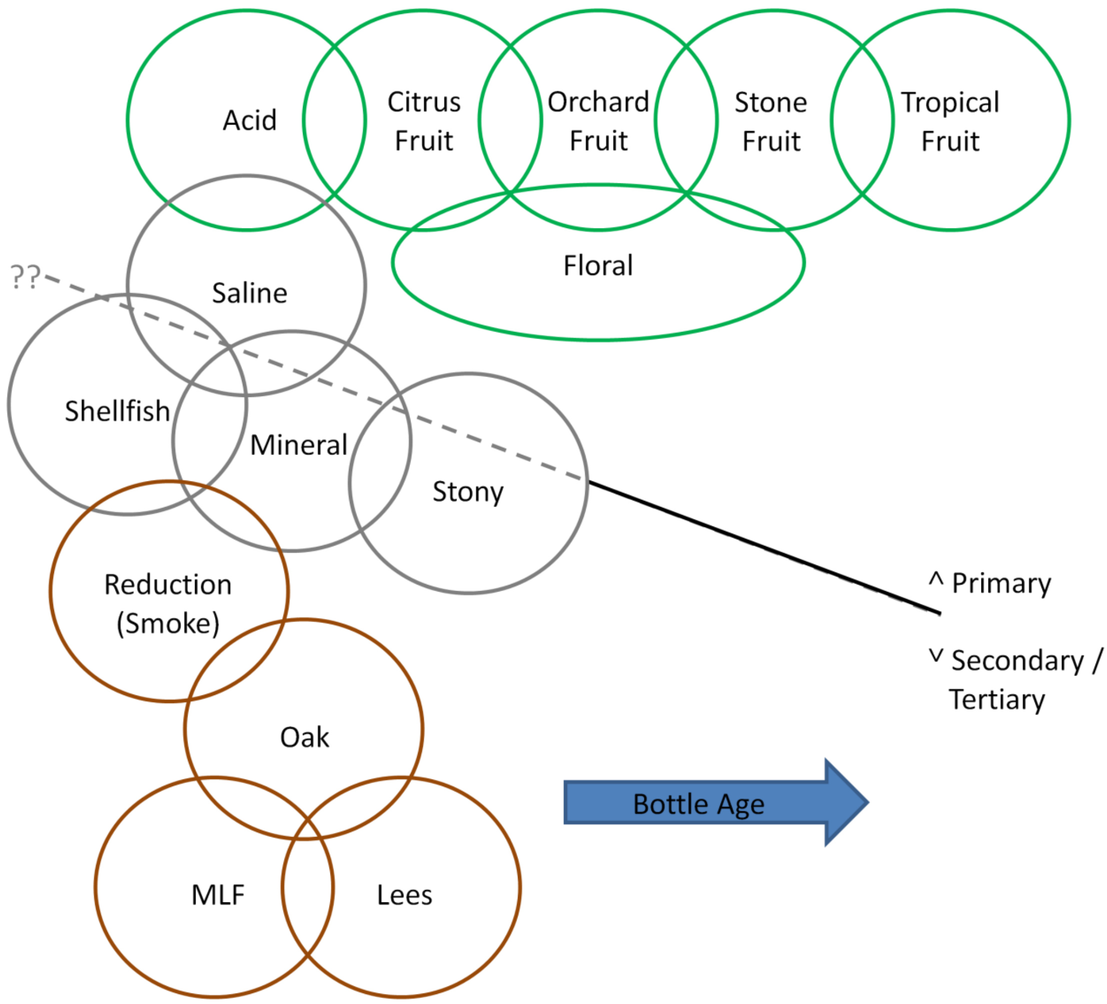
	Wines	Notes
Unique Wines	3684	16,542
Wines with 100+ Notes	1	105
Wines with 10-99 Notes	402	8086
Wines with 5-9 Notes	536	3491
Wines with 1-4 Notes	2745	4860

APPENDIX 4 - FIGURE S3



Supplementary Figure S3. Number of distinct tasters (grey bar) and wines (red line) per Vintage (top pane) and Year Tasted (bottom pane) for Chablis Premier Cru tasting notes from CellarTracker. All wines were between 3 and 7 years of age when tasted.

APPENDIX 4 - FIGURE S4



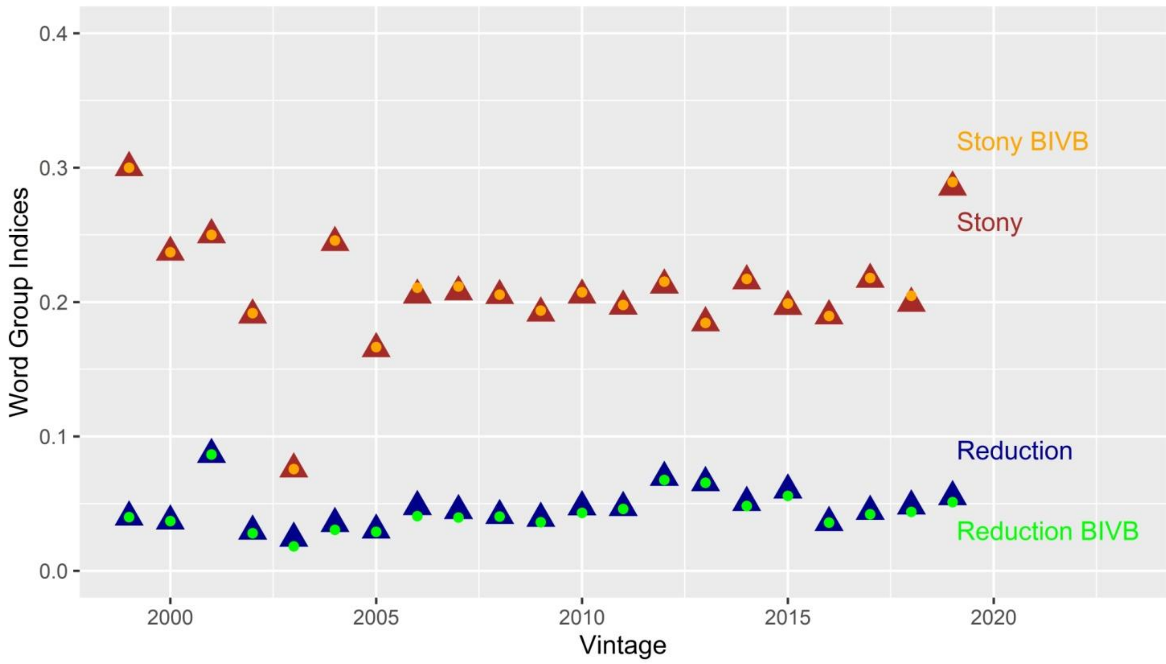
Supplementary Figure S4. Word groupings selected by the authors for text analysis of Chablis Premier Cru wine notes (see Materials and Methods). Overlapping areas represent either a) uncertainty in origin of aroma/flavour, e.g. smoky notes may come from oak ageing, reductive processes, or may relate to minerality, or b) similarity/relatedness of aroma or taste sensation, e.g. peach vs peach blossom (stone fruit vs floral). The dividing line represents flavours and aromas from primary sources (i.e. the grapes) and those from secondary (vinification) and tertiary (ageing) sources; the grey dashed line represents uncertainty regarding the origin (primary vs secondary/tertiary) of some aromas and flavours in groups which overlap it. The figure takes no account of possible masking effects between groupings or whether groups can be present in a wine simultaneously. For example, floral aromas/flavours may be found simultaneously with tropical fruit aromas/flavours, and exposure to lees *may* mask mineral aromas/flavours. Placement of circles is based on the authors' schematic understanding of closeness/relatedness of word groups from the literature rather than any statistical study. Circles and overlapping areas are not drawn to any scale.

APPENDIX 4 - TABLE S3

Supplementary Table S3. Component words and bigrams of descriptive word groups used for textual analysis of CellarTracker Premier Cru tasting notes.

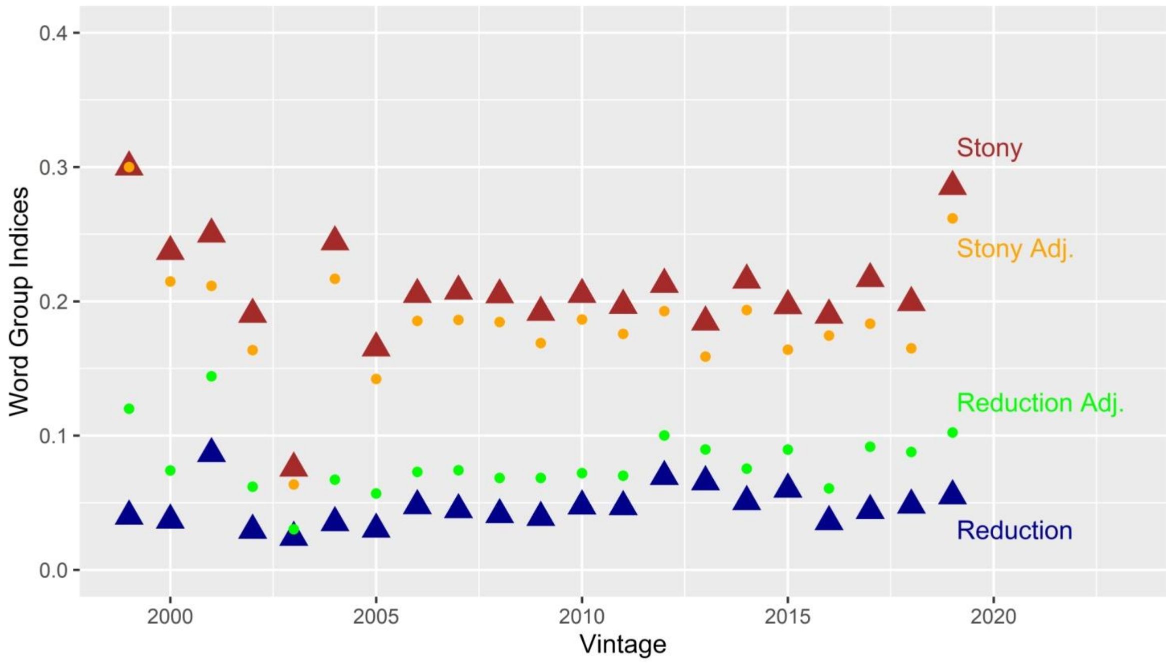
Word Group	Component Words	Component Bigrams
Acidity	acid, acidey, acidic, acidity, acids, acidy	
Citrus Fruit	citric, citrous, citrus, citrusey, citrusfruit, citruslike, citrussey, citrussy, citrusy, grapefruit, grapefruitey, grapefruits, grapefruity, lemon, lemoney, lemons, lemony, lime, limes, limey, limy	
Floral	acacia, blossom, blossomey, blossoms, blossomy, camomile, chamomile, elderflower, elderflowers, floral, floraley, floralley, florally, florals, floraly, flower, flowerey, flower-like, flowers, flowery, geranium, geraniums, hawthorn, hawthorns, honeysuckle, honeysuckles, jasmine, jasmines, lavender, rose, rosehip, rosehips, roses, violet, violets	
Lees	almond, almonds, biscuit, biscuits, bread, breadiness, breadish, bready, breadyness, brioche, cereal, croissant, croissants, dough, doughy, lees, leesy, maize, marzipan, oat, oats, oaty, pastries, pastry, rye, shortbread, walnut, walnuts, wheat, wheaty, yeast, yeastiness, yeastish, yeasty, yeastyness	
Malolactic Fermentation (MLF)	beeswax, butter, buttercream, buttercreams, buttercrème, buttercrèmes, butterish, butterishness, butterscotch, buttery, cream, creaminess, creamy, creamyness, creme, crème, curd, diacetyl, lactic, malo, malolactic, mlf, silk, silkish, silkishness, silky, smooth, smoothness, velvet, velvetish, velvetishness, velvety, wax, waxey, waxy, yoghurt, yoghurtey, yoghurty	
Minerality	mineral, minerality, minerall, minerallity, mineralls, minerally, minerals, mineraly	
Oak	caramel, caramelly, caramely, coconut, coconuts, oak, oakey, oakier, oakiness, oakish, oakishness, oakness, oaky, oakyness, oakyshness, toast, toastie, toastiness, toasty, toastyness, toffee, toffees, vanilla, wood, woodiness, woody, woodyness	
Orchard Fruit	apple, appleish, apple-ish, apples, appley, applish, gooseberries, gooseberry, pear, pearey, pearish, pears, peary	orchard fruit, orchard fruits

Reduction (Smoke)	cabbage, cabbagey, cabbagy, corn, egg, eggey, eggs, eggy, fusil, gunflint, gun-flint, gunflintey, gun-flintey, gunflinty, gun-flinty, gunmetal, gun-metal, gunpowder, lapsang, matchstick, match-stick, matchsticks, match-sticks, reduced, reduction, reductive, rubber, rubbery, skunk, skunky, smoke, smokey, smoky, sulfide, sulfides, sulfur, sulfurous, sulphide, sulphides, sulphur, sulphurous	bad drain, bad drains, gun flint, rotten drain, rotten drains, stinky drain, stinky drains, struck match, struck matches, match stick, match sticks
Saline	brine, brines, briney, brineyness, brinish, brinishness, briny, brinyness, iodeine, iodene, iodine, oceanic, oceans, oceanspray, ocean-spray, saline, salinity, salt, salted, saltiness, saltwater, salty, seabreeze, seasalt, seashore, seaside, seaspray, seawater, seaweed	ocean / sea: air, aroma, aromas, breeze, breezes, feeling, flavor, flavors, flavour, flavours, foam, mist, shore, side, spray, water, weed; tidal pool, tidal pools
Shellfish	oyster, oystershell, oystershells, seashell, seashells , shell, shelley, shellfishey, shellfishness, shellfishy, shelliness, shellish, shells, shelly, shellyness	oyster shell, oyster shells, shell fish
Stone Fruit	apricot, apricotey, apricotish, apricots, apricoty, nectarine, nectarines, nectariney, nectarinish, nectariny, peach, peaches, peachey, peachish, peachy	stone fruit, stone fruits, stoney fruit, stoney fruits, stony fruit, stony fruits
Stony	chalk, chalkey, chalkiness, chalkish, chalky, chalkyness, flint, flintey, flinty, granite, graphite, gravel, graveley, graveliness, gravelish, gravell, gravelley, gravelliness, gravelly, gravellyness, gravels, gravely, gravelyness, gypsum, lead-like, limestone, limestones, limestoney, limestony, marl, marley, marliness, marly, marlyness, pebble, pebbles, pebbley, pebbliness, pebbly, pebblyish, pebblyness, pencil, rock, rockey, rockiness, rockish, rocks, rocky, rockyness, shale, slate, slate-like, slatey, stone, stones, stoney, stony	wet stone, wet stones
Tropical Fruit	banana, bananas, candied, cantaloupe, fig, figs, guava, guavas, honeydew, jackfruit, jackfruits, kiwi, kiwis, lychee, lychees, mango, mangoes, mangoish, mango-ish, mangoness, mangos, melon, melons, melony, papaya, papayas, passionfruit, passion-fruit, passionfruits, pawpaw, pawpaws, pineapple, pineapples, pineappley, starfruit, starfruits, tropical, tropical-fruit, tropical-fruits	jack fruit, jack fruits, passion fruit, passion fruits, star fruit, star fruits



Supplementary Figure S5. Plot of stony and reduction word groups used to describe Chablis Premier Cru wine in CellarTracker tasting notes against Vintage before (circles) and after (triangles) the gunflint words were re-assigned from the stony word group (as per BIVB [40]) to the reduction word group. The words reassigned were "gunflint","gunflinty","fusil","gun-flint","gun-flinty","gunflintey","gun-flintey","gunpowder","gunmetal", and "gun-metal". Re-assignment of these words made little difference to the absolute values or trends.

APPENDIX 4 - FIGURE S6



Supplementary Figure S6. Plot of stony and reduction word groups used to describe Chablis Premier Cru wine in CellarTracker tasting notes against Vintage before (triangles) and after (circles) the flint words were temporarily re-assigned from the stony word group to the reduction word group. The words temporarily reassigned were “flint”, “flintey”, and “flinty”. Despite the differences shown, the relationships between these two word groups and the other variables under study were mostly unchanged by re-assignment in terms of which were significant and which were not, except for three: i) The linear regression between reduction and Tasting Year (Table S4) and ii) the Spearman’s rank correlation between reduction and UCS30 soil type (Table S5), were both no longer significant with Bonferroni correction; iii) The Spearman’s rank correlation between reduction and slope gradient became significant ($p < 0.05$) but not with Bonferroni correction (Table S5). Note the flint words were left in the stony word group for all analyses presented in the paper.

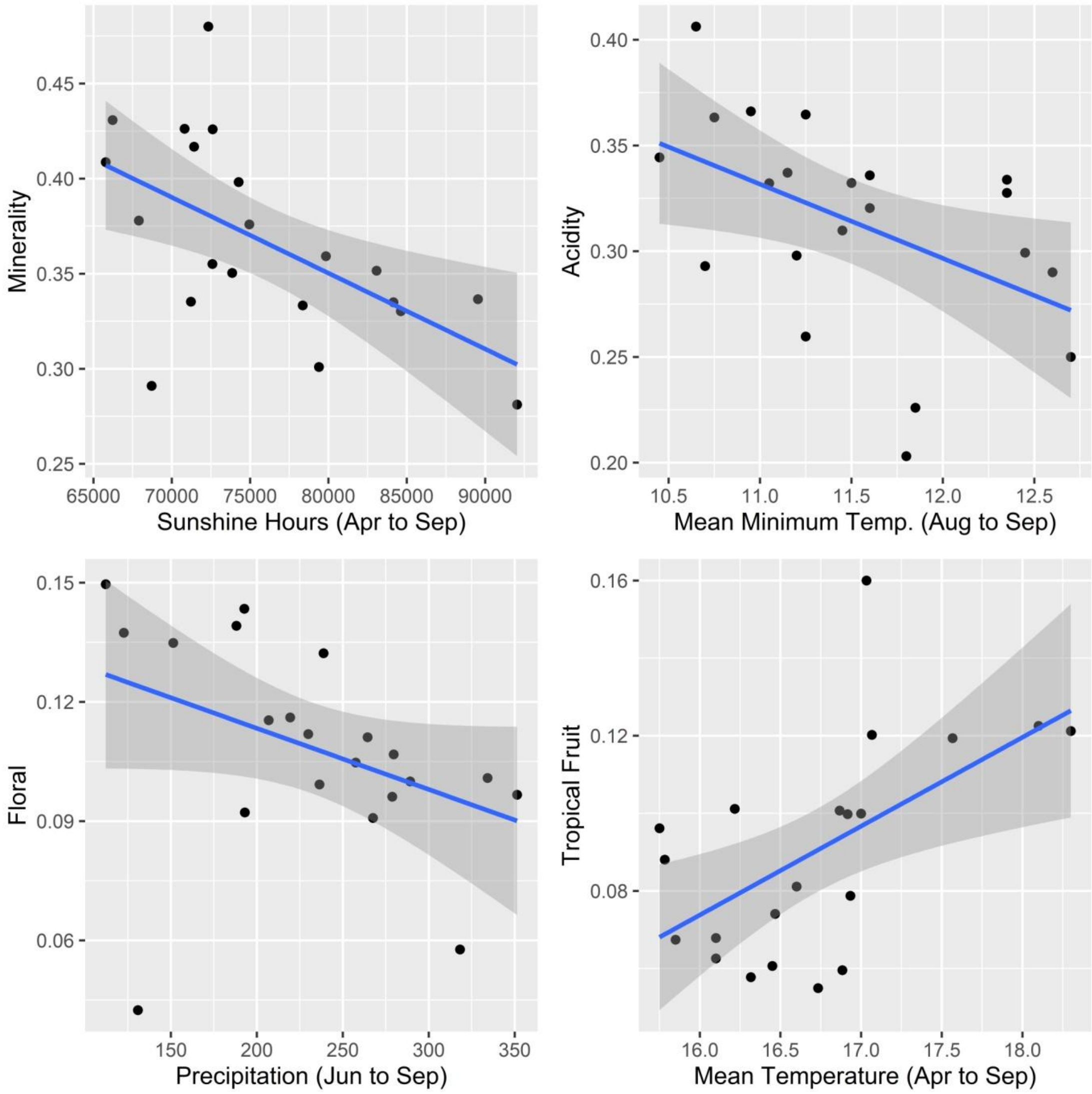
Supplementary Table S4. Median, interquartile range (IQR), and linear trend in the reduction and stony word groups used to describe Chablis Premier Cru wine in CellarTracker tasting notes against a) Vintage (1999 to 2019) and b) Tasting Year (2005 to 2022), before and after ("Adj.") flint words were temporarily re-assigned from the stony word group to the reduction word group. The word group indices range in value from 0 (zero presence) to 1 (found in 100% of all tasting notes); thus a slope of 0.01 is effectively a 1% increase per year of the word group in absolute terms. Note the linear regression between reduction and Tasting Year would no longer be significant with Bonferroni correction ($p > 0.0036$, i.e. 0.05 / 14, in bold). All wines were between 3 and 7 years of age when tasted.

	Median	**IQR**	**Slope**	**SE**	**R^2**	***p***
a) Vintage (1999 to 2019)						
Reduction	0.04	0.01	0.0006	0.0005	0.07	0.260
Reduction Adj.	0.07	0.02	0.0002	0.0009	0.00	0.858
Stony	0.21	0.03	-0.0001	0.0016	0.00	0.940
Stony Adj.	0.18	0.03	-0.0006	0.0017	0.01	0.744
b) Tasting Year (2005 to 2022)						
Reduction	0.05	0.02	0.0018	0.0004	0.57	**0.000**
Reduction Adj.	0.08	0.02	0.0013	0.0005	0.31	**0.016**
Stony	0.20	0.02	0.0001	0.0007	0.00	0.851
Stony Adj.	0.18	0.02	0.0003	0.0006	0.01	0.632

Supplementary Table S5. Significant Spearman's rank correlation coefficients ($p < 0.10$) between reduction and stony word groups and other variables under study, before ("Presented in Paper") and after ("Adjusted for Flint Words") flint words were temporarily re-assigned from the stony word group to the reduction word group. Significant differences are marked in bold. Only the relationship between reduction and USC30 soil type as presented in the paper, however, was significant with Bonferroni correction ($p < 0.0045$, i.e. 0.05 / 11). All wines were Chablis Premier Cru and between 3 and 7 years of age when tasted. Tasting notes were recorded in CellarTracker.

	Presented in Paper		**Adjusted for Flint Words**	
	r_s	p	r_s	p
Reduction vs UCS30 Soil Type	**0.87**	**0.001**	**0.63**	**0.017**
Reduction vs Slope Gradient	**-0.33**	**0.253**	**-0.54**	**0.048**
Stony vs Relative Elevation	0.59	0.029	0.60	0.025
Stony vs Slope Gradient	-0.56	0.038	-0.55	0.044

APPENDIX 4 - FIGURE S7



Supplementary Figure S7. Selected significant Spearman's rank correlation scatterplots ($p < 0.05$) between word groups used to describe Chablis Premier Cru wine in the CellarTracker database and certain vintage weather variables: Minerality vs Sunshine Hours from 1 April to 30 September (top left); Acidity vs Mean Minimum Temperature (°C) in August and September (top right); Floral vs Precipitation (mm) from 1 June to 30 September (bottom left); Tropical Fruit vs Mean Temperature (°C) from 1 April to 30 September (bottom right). All wines were between 3 and 7 years of age when tasted.

APPENDIX 5

Appendices for Chapter 5. Identification of suitable sites for high-quality still wine from Chardonnay viticulture in England: an assessment of topography and soils

APPENDIX 5A

Appendix 5A. Comments regarding the quality of English still Chardonnay wine. Taken from answers to Q6, Appendix 5G, and from personal communication in response to the email survey request.

Positive

“I hope we see more still English Chardonnay in the coming years and suspect it could be excellent in decent years.”

“English still wines offer vibrant acidity - an increasingly valued commodity in light of global warming.”

“English still Chardonnay is so exciting. The best still wine we currently do. The wines have naturally refreshing acidity (which many regions struggle with now) as well as increasingly assured winemaking. The issue is the price.”

“Chardonnay really is becoming the strong point of English still white wine production. We feel it has a more glorious future than Bacchus.”

“English Chardonnay's have improved a great deal over the past few years as the cool climate suits the style of wine. I also like the fact that while some producers use oak, most are fruit-driven.”

“Thanks, but I haven't had enough exposure to English still wines to contribute anything useful. Certainly the last decade has shown that England can indeed produce Chardonnay and Pinot Noir of impressive quality - but at a price.”

“This is interesting… it’s a fascinating topic and there is so much progress to be made, I’m glad that there is serious research into it.”

Negative

“I have not tasted English chardonnay for many years, Mr Biss, so I cannot complete your survey. All I can tell you is that the idea of a complete chardonnay from anywhere in the UK is as fanciful and possibly as ridiculous a notion as growing tea in the Arctic. Great English wine is largely a fantasy, compared with the wines from elsewhere in Europe (not to speak of the rest of the world), and not, apart from a few toothsome exceptional specimens, to be taken seriously. We are not a wine producer of any distinction or relevance on the world stage.”

“I haven't answered your questionnaire because I haven't bought any English Chardonnay. I don't drink much white wine and I think there are more exciting white varieties grown in England than Chardonnay.”

“I go by the motto 'death before chardonnay'.”

“I don’t drink Chardonnay wine.”

Appendix 5B. Comparison of QGIS computed gradient data for a parcel of land using LIDAR 1m and LIDAR 10m resolution elevation data.

Appendix 5C. Land included/excluded from the analysis (Figure 5.3), based on soil class.

Data	Source	Included (ID and Name)	Excluded (ID and Name)
Soil	National Soil Resources Institute	3. Shallow lime-rich soils over chalk or limestone	1. Saltmarsh soils
	NATMAPSOILSCAPES	5. Freely draining lime-rich loamy soils	2. Shallow very acid peaty soils over rock
	LandIS, Cranfield University	6. Freely draining slightly acid loamy soils	4. Sand dune soils
	(01/05/2001)	7. Freely draining slightly acid but base rich soils	12. Freely draining floodplain soils
		10. Freely draining slightly acid sandy soils	15. Naturally wet very acid sandy and loamy soils
		11. Freely draining sandy Breckland soils	16. Very acid loamy upland soils with a wet peaty surface
		13. Freely draining acid loamy soils over rock	19. Slowly permeable wet very acid upland soils with a peaty surface
		14. Freely draining very acid sandy and loamy soils	20. Loamy and clayey floodplain soils with naturally high groundwater
			21. Loamy and clayey soils of coastal flats with naturally high groundwater
		Also, if slope gradient > 2% (otherwise excluded):	22. Loamy soils with naturally high groundwater
		8. Slightly acid loamy and clayey soils with impeded drainage	23. Loamy and sandy soils with naturally high groundwater and a peaty surface
		9. Lime-rich loamy and clayey soils with impeded drainage	24. Restored soils mostly from quarry and opencast spoil
		17. Slowly permeable seasonally wet acid loamy and clayey soils	25. Blanket bog peat soils
		18. Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils	26. Raised bog peat soils
			27. Fen peat soils

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Appendix 5D. Land included/excluded from the analysis (Figure 5.3), based on type of land cover.

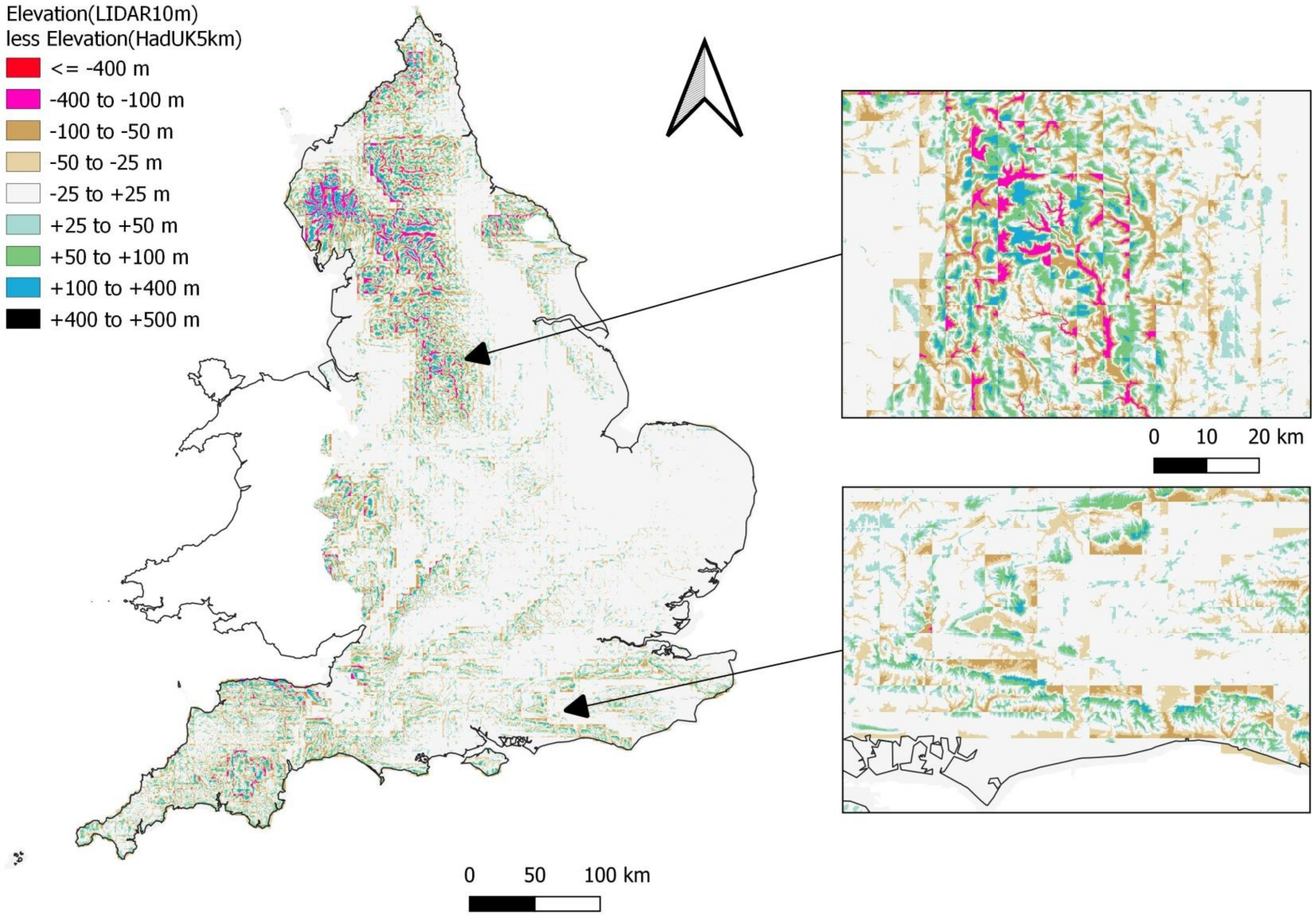
Data	Source	Included (ID and Name)	Excluded (ID and Name)
Land Cover	Land Cover Map 2023	3. Arable and Horticulture	1. Broadleaved Woodland
	Centre for Ecology and Hydrology	4. Improved Grassland	2. Coniferous Woodland
	10m classified pixels	5. Neutral Grassland	8. Fen, Marsh and Swamp
		6. Calcareous Grassland	9. Heather
		7. Acid Grassland	10. Heather Grassland
			11. Bog
			12. Inland Rock
			13. Saltwater
			14. Freshwater
			15. Supralittoral Rock
			16. Supralittoral Sediment
			17. Littoral Rock
			18. Littoral Sediment
			19. Saltmarsh
			20. Urban
			21. Suburban

Appendix 5E. Land excluded from the analysis (Figure 5.3), based on designated protection and flood risk.

Data	Source	Excluded
Designated Areas	Natural England (defra.com) - updated 6/6/24	Country Parks[1]
	Natural England (defra.com) - updated 18/6/24	Local Nature Reserves (LNR)
	Natural England (defra.com) - updated 6/6/24	Millenium Greens[1]
	Natural England (defra.com) - updated 18/6/24	National Nature Reserves (NNR)
	Natural England (defra.com) - updated 23/1/24	Ramsars (Wetland)[1]
	Natural England (defra.com) - updated 23/7/24	Sites of Special Scientific Interest (SSSI)
	Natural England (defra.com) - updated 16/4/24	Special Areas of Conservation (SAC)
	Natural England (defra.com) - updated 16/4/24	Special Protection Areas (SPA)
	Historic England - updated 8/8/24	Building Preservation Notices
	Historic England - updated 8/8/24	Listed Buildings
	Historic England - updated 8/8/24	Registered Battlefields
	Historic England - updated 8/8/24	Scheduled Monuments
	Historic England - updated 8/8/24	World Heritage Sights
Flood Risk	Environment Agency 2023	Flood Zone 2
		Flood Zone 3

[1]Note this study excludes for consideration Country Parks (Natural England) instead of Registered Parks and Gardens (Historic England) (Nesbitt et. al., 2018). Country Parks are public green spaces, often owned by the local authority, situated at the edge of urban areas for the public to enjoy access to the outdoors. Conversely, many Registered Parks and Gardens are privately owned and not protected by a separate planning regime. Thus, although some Registered Parks and Gardens may be public parks or cemeteries and therefore unavailable for viticulture, many of these areas could potentially be considered for viticulture by their private landowners subject to normal planning permission. This study also added to the Exclusion list Millenium Greens and Ramsars (wetland areas) from the Natural England database. These differences with Nesbitt et al.'s methodology (2018) are small, however.

Appendix 5F. Elevation differences between LIDAR 10 x10 m cells and mean elevation of associated Had-UK 5 x 5 km grid cells used for climate projections.



Appendix 5G. Survey of wine experts (on Qualtrix XM platform)
The survey form provided to wine experts used to evaluate findings. The survey was completed by 35 wine journalists, writers, bloggers and merchants.

Start of Block: Default Question Block

English still Chardonnay wine

We are researching the influence of various environmental factors on the eventual quality of English still Chardonnay wine and would appreciate your help.

We would like to ask you, as a wine expert, a few questions about the current quality of English still Chardonnay wine, to understand where the best wines are coming from. Your answers will be used to test the validity of a model that seeks to identify prospective sites in England for premium-quality Chardonnay viticulture.

Please note:

- You were selected for this questionnaire from attending the Vineyard & Winery Show (Kent, 20 November 2024) and/or because you are well-known for your expertise in English wine.
- Your answers will remain confidential. The data will be analysed and presented in anonymous form only, in order to demonstrate consensus views.
- Individual responses will be deleted once the associated chapter of the study is complete, which will be no later than 31 March 2025.
- Respondents have the right to withdraw at any time prior to 31 December 2024 by contacting either of the contacts below.
- An individual's decision to answer the questions will be taken as acknowledgement that they have had the terms of their participation adequately explained and that they consent to them.

Contact details:
Alex Biss: alex.biss@pgr.reading.ac.uk
Richard Ellis: r.h.ellis@reading.ac.uk

Page Break

Q1 Please pick up to 5 of your favourite producers for single-variety non-sparkling Chardonnay wine, based on quality only. Do not take into account price and, where possible, base your assessment over several years, rather than just one vintage.

- ☐ Balfour Winery (Hush Heath), Kent (1)
- ☐ Bolney Wine Estate, West Sussex (2)
- ☐ Burn Valley Vineyard, Norfolk (3)
- ☐ Burnt House Vineyard, Suffolk (4)
- ☐ Cary Wine Estate, Kent (5)
- ☐ Chapel Down Wines - Kit's Coty Vineyard, Kent (6)
- ☐ Danbury Ridge Wine Estates, Essex (7)
- ☐ Denbies Wine Estate, Surrey (8)
- ☐ Furleigh Estate, Dorset (9)
- ☐ Greyfriars Vineyard, Surrey (10)
- ☐ Gusbourne Vineyard, Kent (11)
- ☐ Hattingley Valley Vineyard, Hampshire (12)
- ☐ Heppington Vineyard, Kent (13)
- ☐ Lympstone Manor Vineyard, Devon (14)
- ☐ Martin's Lane Vineyard, Essex (Used for Lyme Bay Winery Chardonnay) (15)
- ☐ Maud Heath Vineyard, Wiltshire (16)
- ☐ Missing Gate Vineyard, Essex (Used for Gutter & Stars, Star69) (17)

- ☐ Oastbrook Estate Vineyard, East Sussex (18)
- ☐ Oxney Organic Estate, East Sussex (19)
- ☐ Riverview Vineyard, Essex (20)
- ☐ Simpson's Wine Estate - The Roman Road, Kent (21)
- ☐ Springfields Vineyard (Balfour), East Sussex (22)
- ☐ Whitewolfe Vineyard, Kent (23)
- ☐ Yotes Court Vineyard, Kent (24)

Q2 If you had to pick just one favourite, which would it be?

____

Q3 How familiar are you with the wines listed in Q1? (Choose the rating that best fits)

- ○ Limited familiarity (1)
- ○ Familiar with a handful only (2)
- ○ Familiar with around half (3)
- ○ I know most of the wines (4)
- ○ I know all the wines well (5)

Q4 Which of these wines do you consider the most like Chablis?

____

Page Break

Q5 Are there any producers or wines not listed in Q1 that you would consider among your favourites?

____

Q6 Any additional comments?

____

Page Break

Q7 Thank you for your help. If you would like to be sent the findings from this research, please provide your email address.

____

End of Block: Default Question Block

Appendix 5G: Note regarding Question 5

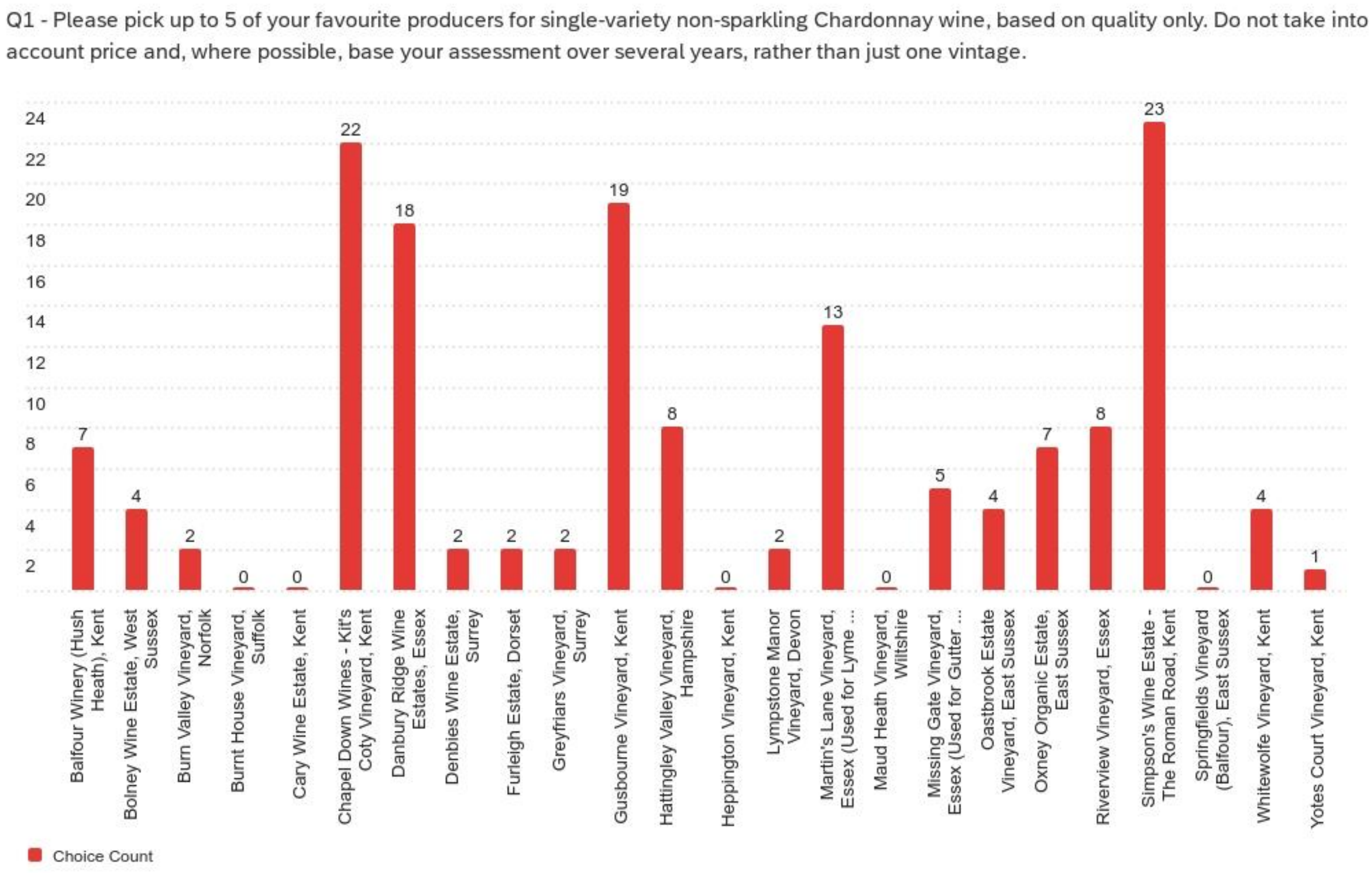
Several producers were mentioned in the experts' answers to Q5 that were not listed in Q1. Some of these, i) had only recently released their first still Chardonnay wine (e.g. Sugrue), ii) only produced still Chardonnay wine in exceptional vintages such as 2018 (e.g. New Hall), iii) did not produce wines made 100% from Chardonnay (e.g. Artelium), and/or iv) sourced their wines from undeclared vineyards or vineyards that changed from year-to-year (e.g. Blackbook and Flint Vineyard); these producers were excluded from the analysis. Some producers were mistakenly omitted from the study, however. These comprised: Althorne Estate (Essex); Bride Valley Vineyard (Dorset); Henners Vineyard (East Sussex); Hidden Spring Vineyard (East Sussex); Nine Oaks Vineyard (Kent); and Stopham Vineyard (West Sussex).

Appendix 5H. Robustness of proof-of-concept results

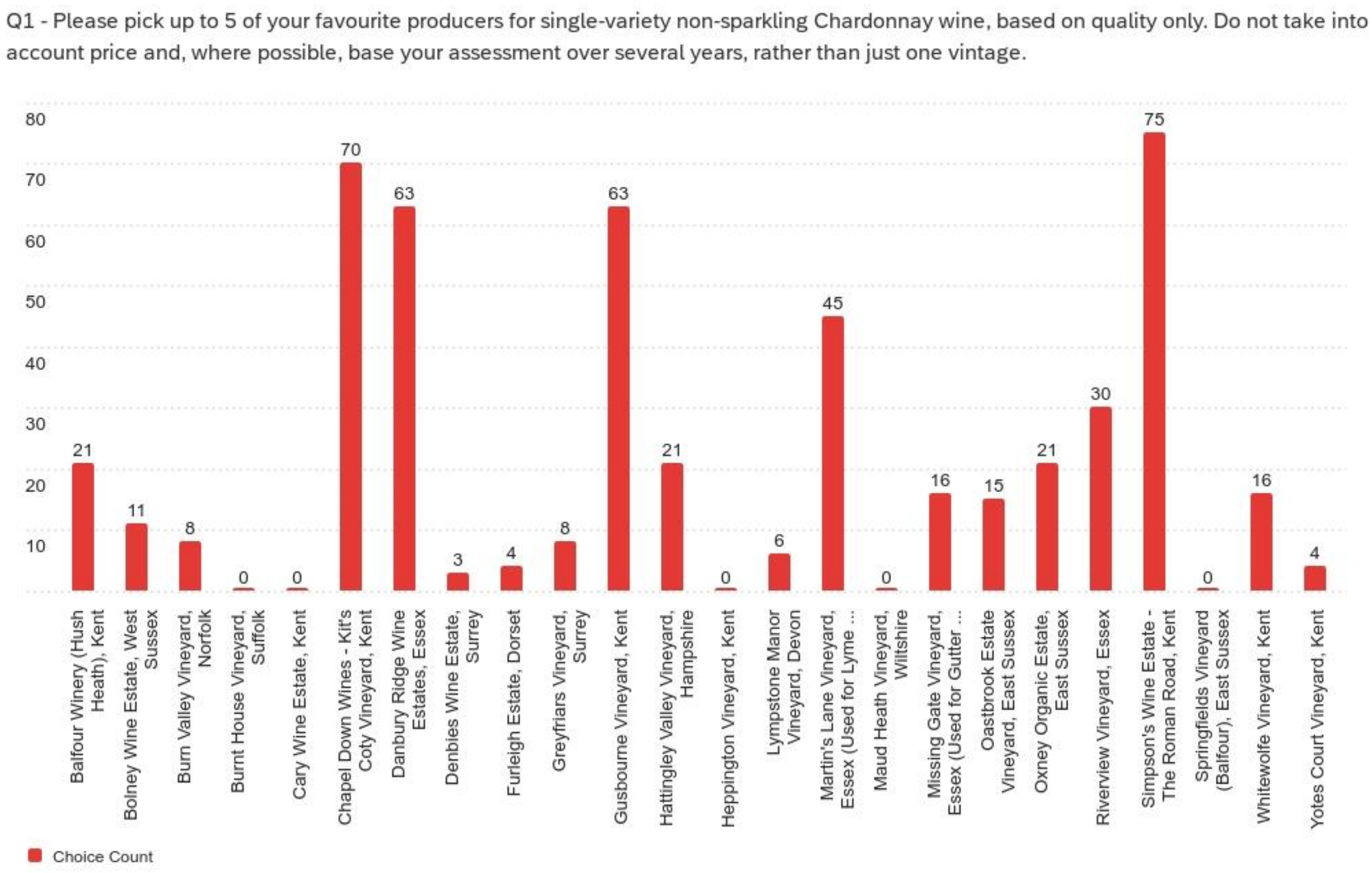
Comparison of i) different methods for analysing responses from Q1 of the Survey (Appendix 5G), and ii) different weightings for calculating relative land suitability of English vineyards currently being used to produce still Chardonnay wine (in terms of the relative influence of climate versus topography & soils). Note the monotonic relationship with different land quality weightings and the peak at 60 (Climate) to 40 (Topography & Soils). Note also the Weighted method for totalling survey responses (see Section 2.8) provides slightly increased correlation coefficients and increased significance compared to the other two methods. The Weighted method was deemed intuitively better than the other two methods, even prior to this analysis, given it accounts for wine experts' differing levels of familiarity with the list of wines assessed (Q3, Appendix 5G). The presentation in Figure 5.6 used the 60:40 Climate:Topography and Soils weighting for the x-axis and the Weighted responses (incorporating familiarity) from the survey results for the y-axis.

	Relative Land Quality Weighting (Climate:Topography & Soils)										
Method for Assessing Survey Responses	**0:100**	**20:80**	**30:70**	**40:60**	**50:50**	**55:45**	**60:40**	**65:35**	**70:30**	**80:20**	**100:0**
A. Simple Total											
Spearman's rank r_s	0.05	0.15	0.18	0.26	0.33	0.38	**0.43**	0.40	0.38	0.37	0.33
P	*0.813*	*0.482*	*0.391*	*0.217*	*0.118*	*0.071*	***0.036***	*0.053*	*0.066*	*0.072*	*0.112*
B. Excluding "Limited Familiarity" Response											
Spearman's rank r_s	0.05	0.15	0.19	0.27	0.34	0.39	**0.44**	0.41	0.39	0.39	0.35
P	*0.825*	*0.482*	*0.381*	*0.203*	*0.103*	*0.060*	***0.030***	*0.047*	*0.059*	*0.062*	*0.097*
C. Weighted											
Spearman's rank r_s	0.05	0.16	0.20	0.29	0.37	0.41	**0.47**	0.44	0.42	0.42	0.37
P	*0.820*	*0.461*	*0.338*	*0.163*	*0.078*	*0.045*	***0.020***	*0.032*	*0.043*	*0.041*	*0.072*

Appendix 5I. Results from survey of wine experts (Q1, Appendix 5G). Unweighted.

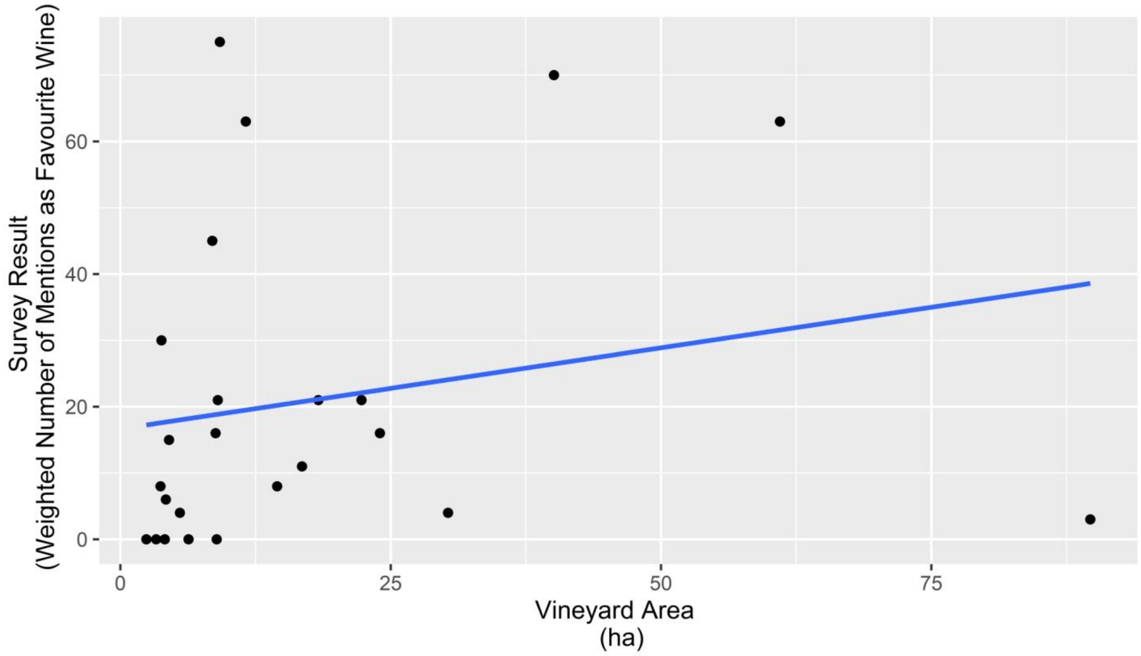


Appendix 5J. Results from survey of wine experts (Q1, Appendix 5G). Weighted by their familiarity with the list of wines, from "Limited familiarity" = 1 to "I know all the wines well" = 5 (Q3, Appendix 5G).

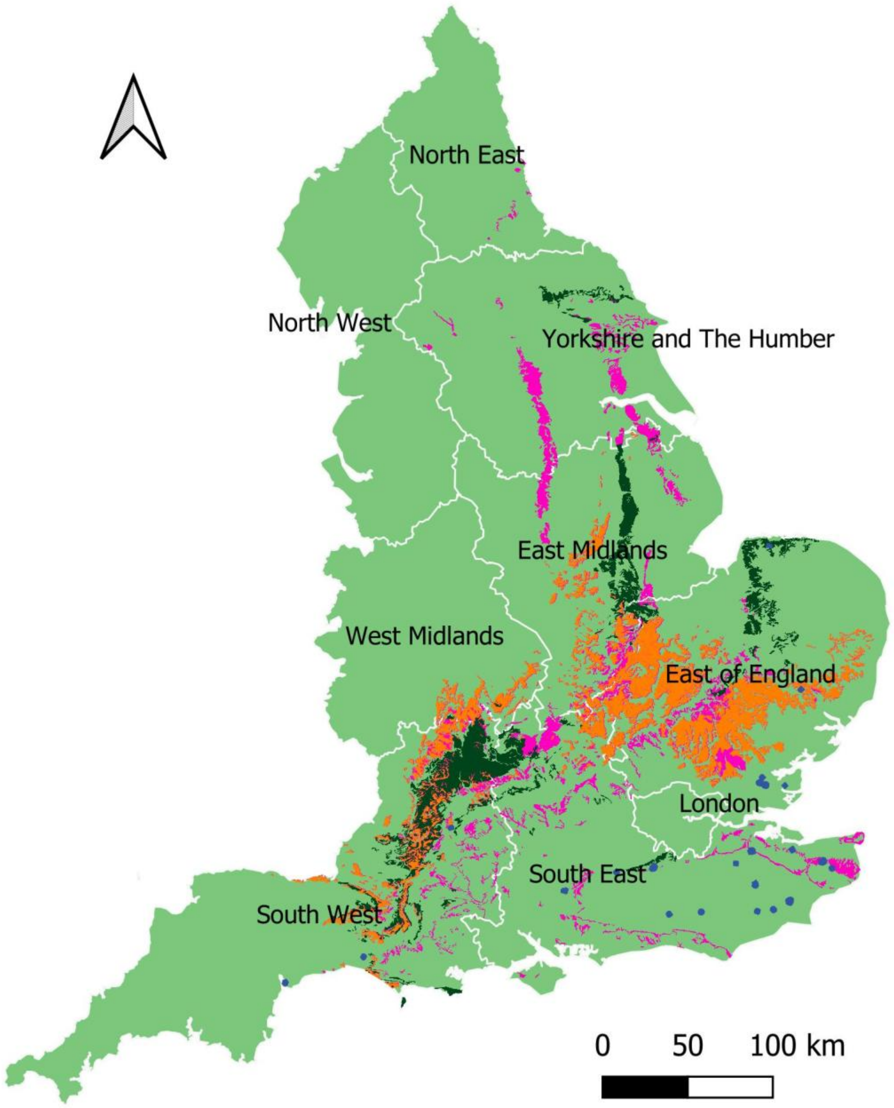


Appendix 5K. Robustness of proof-of-concept results
The weighted number of mentions as a favourite wine in the Survey (Q1, Appendix 6F) are unlikely to be related to the amount of that wine on the market (i.e. more familiarity does not necessarily increase mentions).

Despite a significant Spearman's rank correlation (r_s = 0.42, P = 0.040), visual inspection of the plot below suggests there is no relationship between size of vineyard area of producers in England currently producing still Chardonnay wine (as a proxy for the amount of still Chardonnay wine produced) and the weighted number of mentions as a favourite wine (Q1, Appendix 6F) . The Spearman's rank relationship is heavily dependent on two outliers.



Appendix 5L. Identification of areas in England with broadly similar soils to the Kimmeridigian soils in Chablis, France, in terms of calcareous and clay content, and without seasonal or permanent waterlogging. This comprises three soil subgroups: calcareous pelosols (in orange), non-gleyic brown calcareous earths (in pink), and brown rendzinas (in dark green). Blue symbols denote vineyards that are currently producing still Chardonnay wine. Data from LandIS National Soil Map (2018) (see Appendix 5M).



Appendix 5M. Soils included (excluded) for their similarity (lack of similarity) to Kimmeridgian soils in Chablis. Three soil subgroups were selected (out of 67) because of their material calcareous and clay content. All other soils were excluded because of their lack of clay or calcareous content, or because of poor drainage (gley, stagnogley, etc.).

Data	Source	Included (ID and Name)	Excluded (ID and Name)
Soil	The National Soil Map and	3.4.3 Brown rendzinas	1. Terrestrial raw soils
	Soil Classification	4.1.1 Typical calcareous pelosols	2. Raw gley soils
	National Soil Resources Institute	5.1.1 Typical brown calcareous earths	3. Lithomorphic soils (except 3.4.3)
	LandIS, Cranfield University	5.1.4 Colluvial brown calcareous earths	4. Pelosols (except 4.1.1)
	(02/07/2018)		5. Brown soils (except 5.1.1 and 5.1.4)
			6. Podzolic soils
			7. Surface-water gley soils
			8. Ground-water gley soils
			9. Man made soils
			10. Peat soils

Appendix 5N. Area of Ceremonial County land classified as Premier or Grand Cru quality, with Kimmeridgian-type soils (Appendix 5L), and with vintage score ≥ 6 for 2040-59 (RCP 4.5 50th percentile). Ordered by total land area that has been categorised as Premier or Grand Cru (ha).

			2040-59 (RCP 4.5 50th percentile) (GST +1.3 to +1.6 °C from 1981-2000) Area of land (ha) with vintage score ≥ 6	
County	Region	Total County Area (ha)	Total Premier & Grand (ha)	% of County Land[1]
Suffolk	East of England	385,344	13,363	3.5
Somerset	South West England	425,585	10,254	2.4
Cambridgeshire	East of England	339,745	9,904	2.9
Buckinghamshire	South East England	187,357	7,827	4.2
Kent	South East England	390,829	7,804	2.0
Essex	East of England	394,734	7,768	2.0
Bedfordshire	East of England	123,543	6,976	5.6
Oxfordshire	South East England	260,595	6,274	2.4
Gloucestershire	South West England	324,117	5,608	1.7
Hertfordshire	East of England	164,306	5,413	3.3
Dorset	South West England	269,484	4,526	1.7
Northamptonshire	East Midlands	236,699	4,496	1.9
Wiltshire	South West England	348,543	2,802	0.8
Worcestershire	West Midlands	174,051	2,698	1.5
Norfolk	East of England	550,919	2,337	0.4
Hampshire	South East England	385,436	2,301	0.6
West Sussex	South East England	202,362	2,155	1.1
Warwickshire	West Midlands	197,753	1,886	1.0
Surrey	South East England	167,007	1,530	0.9
Lincolnshire	East Midlands	718,201	1,502	0.2
Rutland	East Midlands	39,375	1,183	3.0
Berkshire	South East England	126,390	807	0.6
East Sussex	South East England	181,055	735	0.4
Nottinghamshire	East Midlands	216,151	546	0.3
Leicestershire	East Midlands	215,713	351	0.2
Isle of Wight	South East England	39,493	186	0.5
County of Bristol	South West England	23,534	45	0.2
South Yorkshire	Yorkshire and Humber	155,211	17	0.0
Greater London	London	159,470	3	0.0
Total		**7,402,999**	**111,295**	**1.5**

[1]Premier and Grand cru suitability as % of all land in County.

APPENDIX 6A

Land Parcel A, XXX, East Sussex
15 February 2025

Overall Quality: Excellent

Summary

Land Parcel A has **excellent** potential to produce premium quality Chardonnay grapes for still and sparkling wine both now and into mid-century.

1. Climate Scores (out of 10)

Current Climate (2010-19)	5.8
Lower Projection for Mid-Century (2040-59)	5.8
Median Projection for Mid-Century (2040-59)	7.2
Upper Projection for Mid-Century (2040-59)	8.8

2. Land Classification

Percentage of Land Parcel A classified as Basic, Premier Cru and Grand Cru potential quality

Unclassified	2.2%
Basic	9.3%
Premier Cru	1.4%
Grand Cru	87.1%

3. Combined Score and Benchmark to Existing Producers

Comparison of Land Parcel A with the vineyards of existing producers in England

Score	89 (Excellent)

Poor	Below Average	Average	Good	Excellent
~~0 - 20~~	~~20 - 40~~	~~40 - 60~~	~~60 - 80~~	80 - 100

Key and Further Information

1. Climate Scores

Climate scores are measured on a 0 to 10 scale, with the following interpretation:

0 - 4	=	Poor
4 - 5	=	OK for sparkling wine, Poor for still wine
5 - 6	=	Good for sparkling wine, OK for still wine
6 - 8	=	Good to Very Good
8 - 10	=	Excellent

1.1 Current Climate (2010-19): **5.8. Good for sparkling wine, OK for still wine**

The current climate score is particularly promising as it falls within the upper quartile of climate scores for existing vineyards in Essex, Kent and Sussex (Figure 1). This indicates that premium sparkling wine can already be produced reliably, with still wine achievable in favourable years. A vineyard established today would not need to rely on future warming to achieve premium quality sparkling wine. Additionally, the current climate serves as a conservative baseline for mid-century projections.

1.2 Prediction for Mid-Century (2040-59)

Lower Projection:	**5.8. Good for sparkling wine, OK for still wine**
Median Projection[1]:	**7.2. Good to Very Good**
Upper Projection[2]:	**8.8. Excellent**

By mid-century (median projection), reliable production of both premium quality sparkling and still wine would be achievable, with a potential shift towards still wine under the upper projection. The lower projection for mid-century would resemble current climate conditions (see section 1.1 above). Overall, the scores align with the upper quartile of climate scores for existing vineyards in Essex, Kent and Sussex (Figure 1), indicating that Land Parcel A is well-situated for viticulture.

[1] The median projection assumes an increase of 1.1°C in the average April to September temperature (from 2010-19).
[2] The upper projection assumes an increase of 2.3°C in the average April to September temperature (from 2010-19).

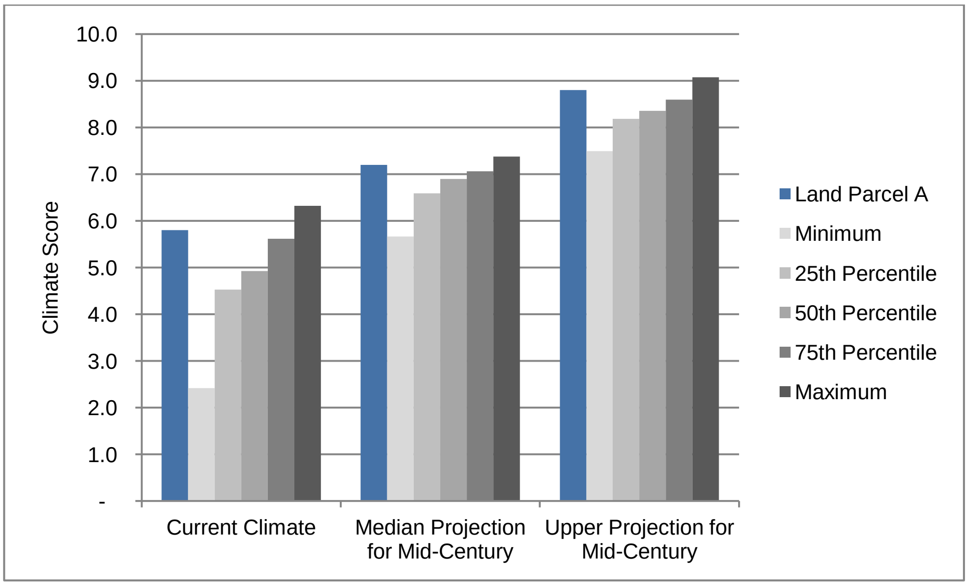


Figure 1. Comparison of climate scores for Land Parcel A (blue bars) against the range in climate scores for 273 established vineyards in England's counties currently most favourable for viticulture - Essex, Kent and Sussex (East and West), (grey bars).

2. Land Classification

2.1 Topography

Land Parcel A has been classified into three quality categories based on topography. These are, in increasing quality: Basic (very gentle slopes); Premier Cru (gentle, moderate or strong slopes facing East to South-East); and Grand Cru (gentle, moderate or strong slopes facing South to West).

The percentage of Land Parcel A classified as Basic, Premier Cru and Grand Cru quality is as follows:

Unclassified (Substandard)	2.2%
Basic	9.3%
Premier Cru	1.4%
Grand Cru	**87.1%**

Figure 2 illustrates the distribution of land classification across Land Parcel A. Better land classification is especially important when climate scores are marginal (< 6), as it increases solar radiation and warmth while also improving drainage. Land Parcel A is excellent in this regard, with a large majority of its land qualifying as Grand Cru quality.

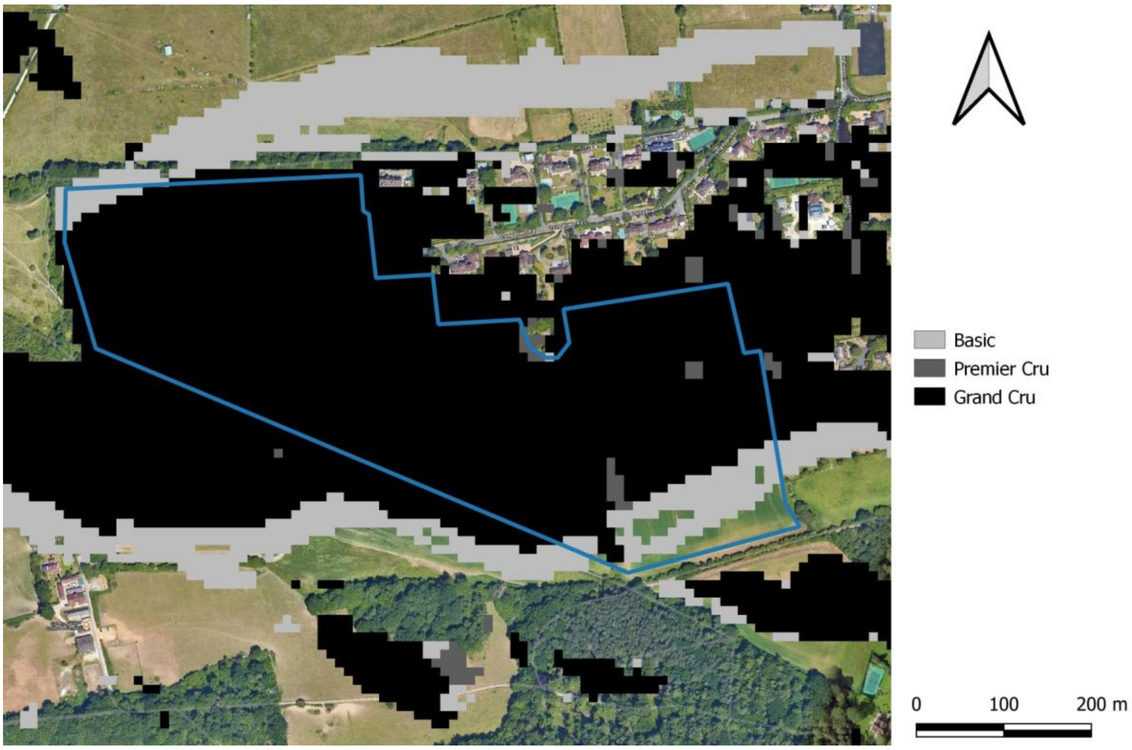


Figure 2. Land classification based on an analysis of topography and soils.
Note: i) Land with slope gradient ≤ 2% and > 30% are unclassified. They are usually too flat for efficient drainage of rainwater and cold air (factors important to vine health and frost risk) or considered too steep for safe operation of machinery. ii) Land at the top and bottom of hills is usually sub-optimal for viticulture. By only identifying slopes with gradient greater than 2%, these problematic "summit" and "toeslope" areas are effectively excluded.

2.2 Soils

Land Parcel A soils have been identified as **freely draining, shallow lime-rich soils over chalk or limestone** and are generally suitable for viticulture. Note, however, these soils are vulnerable to leaching of nitrate and pesticides to groundwater and attract stricter fertiliser limits (Cranfield University, n.d.). A detailed soil survey is advised.

3. Combined Score and Benchmark to Existing Producers

By integrating climate scores and land classification, and comparing Land Parcel A to the vineyards of 24 producers in England that currently make *both* sparkling and still Chardonnay wine, Land Parcel A receives a relative land quality score[3] of **89**.

The relative land quality score is measured on a 0 to 100 scale, with the following interpretation:

Poor	Below Average	Average	Good	Excellent
~~0 – 20~~	~~20 - 40~~	~~40 - 60~~	~~60 - 80~~	80 - 100

Land Parcel A's high score places it in the top quintile of existing producers (Figure 3), indicating excellent potential for producing premium quality still and sparkling wine, both now and over the next three to four decades.

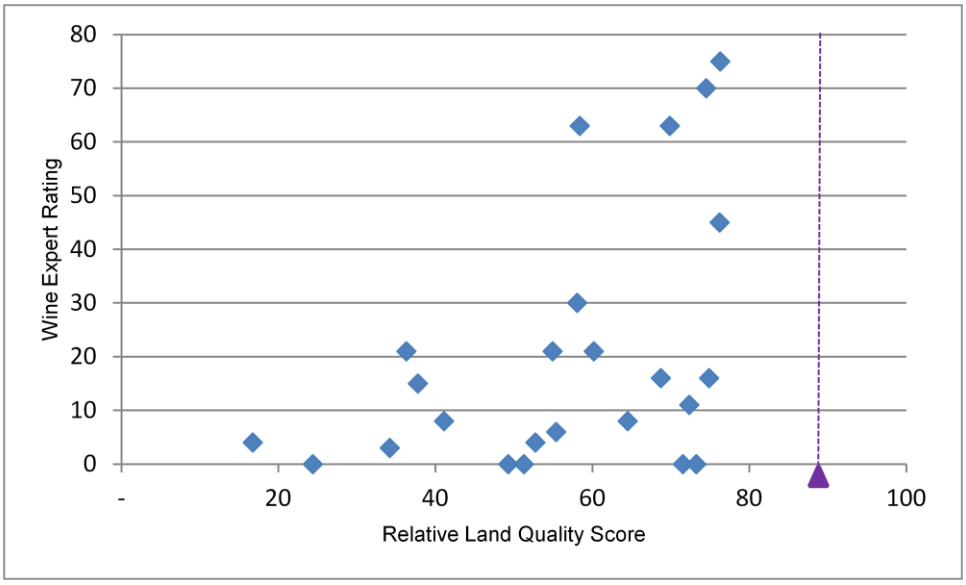


Figure 3. Relative land quality scores for i) Land Parcel A (purple arrow and dashed vertical line) and ii) the vineyards of 24 producers in England known currently for production of both sparkling and still Chardonnay wine, plotted against the number of times they were cited as a favourite still Chardonnay wine producer by wine experts in a survey (Biss, 2025). Note the higher the land quality score the greater the *potential* for making premium quality wine.

[3] The relative land quality score (ranging from 0 to 100) combines the current climate score and land classification, weighted 60% climate and 40% land classification (see Biss, 2025).

Assumptions

The model was designed with the production of premium still Chardonnay wine in mind, using the Chablis region of France as an analogue. Chardonnay, Pinot Noir, and Pinot Meunier share broadly similar climate requirements (see Jones, 2006). Therefore, this model can serve as a first-approximation for all three varieties. However, production of sparkling wine can tolerate a slightly cooler climate compared to still Chardonnay wine, which is why many English sparkling wine producers have performed well in the current climate. As such, as a rule of thumb, it is suggested looking for mean vintage scores ≥ 4.0-5.0 for sparkling wine and ≥ 5.0-6.0 for still wine (depending on land classification). To maintain flexibility, consider planting Chardonnay and Pinot Noir clones that can be used for both still and sparkling wine. It may then be possible to use weather and crop conditions for the May to July period to help plan whether, or in which proportion, to produce still or sparkling wine (Biss and Ellis, 2021).

Note current and projected climate scores are based on mean temperature from April to September, precipitation from June to September and the Cool Night Index (mean minimum temperature for September) (Biss and Ellis, 2021). These factors encompass the key stages of the growing season, from early development through to ripening, and are important for achieving good fruit that can be used to produce balanced wines. They account for:

- Growing season warmth, key to sugar and secondary metabolite accumulation in berries
- Flowering and fruit set, which are crucial for yield and even berry development, and
- Night time temperatures in September, which play a vital role in maintaining berry acidity

Disclaimers and Caveats

The LandIS SoilScapes database is used for this report. This provides a good general idea of drainage conditions. The soils in your plot are likely, however, to be considerably more spatially varied in terms of their structure, texture, pH, available macro- and micro-nutrients, drainage, and water holding capacity, and possibly even contaminants. It is advisable to seek professional advice on what soil amelioration and preparation may be needed.

The model was designed to capture wine quality, not yield. However, the two are often well correlated especially in cooler wine regions like England, except for when extreme damage to crops occurs through frost and/or hail. These risks are particularly high in the weeks after budburst when buds are delicate, typically from April to May. Note:

- The potential damage from hail or other extreme events was not accounted for in the model.
- Some consideration was given to frost risk. Only slopes with gradient greater than 2% were included for land classification, thus excluding problematic Summit and Toeslope areas where cold air drainage is impeded. Other barriers, however, such as hedges, woods, etc., may serve as barriers to cold air drainage, and/or dips in the land may create cold air pooling. Any site would need to be fully investigated to decide on frost risk and mitigation measures.

Climate projections are taken from the UK Met Office (UKCP18), using the intermediate Representative Concentration Pathway (RCP) 4.5. The two other main RCPs (2.6 and 6.0) give broadly similar results to RCP 4.5 for 2040-59, given the warming effects of these different emissions scenarios do not deviate significantly until the latter half of the 21st Century. RCP 8.5, often called "business as usual", would result in median projections similar to the upper end of the RCP 4.5 projections presented here.

Note however that the change in climate is unlikely to follow a straight trajectory. There remains a risk of multi-year cold and/or wet spells. Of greater risk is the potential significant decline or collapse of the Atlantic Meridional Overturning Circulation (AMOC). This could lead to considerably cooler temperatures in Europe. Overall, this can be viewed as a very low probability, high risk event that would likely end viticulture in the UK. There is considerable ongoing research and debate regarding the extent to which AMOC is slowing, if and by when it might reach a tipping point and collapse, and what the effects might be. For the moment, it remains of academic interest.

Interannual variability in weather is of much greater and immediate concern however, and takes on especial importance when climate is marginal for growing grapevines, as is currently the case in England and Wales. For example, the climate score for 2010–2019 hides significant vintage variation in the UK: 2012 was poor almost everywhere and 2018 was generally excellent for most of Southern, Eastern, South-Eastern and Central England, with the other eight years somewhere in-between.

Next Steps

If you are considering planting a vineyard on this site, we recommend consulting a professional. This should include a detailed site inspection, soil analysis, and discussions on vineyard design, frost risk mitigation, and the selection of grape variety, clone, and rootstock. Please let us know if you would like consultant recommendations.

References and Further Reading

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