A climate for sustainable wine production: Modelling the effects of weather variability and climate change on viticulture in England and Wales.

A thesis submitted to the School of Environmental Sciences of the University of East Anglia in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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Abstract

The spatial distribution of commercial viticulture is within narrow climatic niches characterised by growing season average temperatures of 13–21°C and meteorological structures conducive to *Vitis vinifera* L. grape maturation and sustainable grape yields. Climate change may significantly threaten viticulture in some established regions if in-situ adaptation is unviable or undesirable; it may also present opportunities elsewhere. This thesis explores past, present and future weather and climate risks in the emerging cool-climate viticulture regions of England and Wales. A recent (2004–2013) significant expansion (148%) in viticulture area and a shift to Chardonnay and Pinot noir cultivation for sparkling wine production has been accompanied by international recognition of high quality English wine. Warming growing seasons have been touted as the key growth enabler, however the geographic positioning of England and Wales exposes viticulture to threats from inter-annual weather variability.

This first quantitative and qualitative analysis of viticulture climate suitability in England and Wales considers grape-growers perspectives' on climate change and weather variability, complemented by an analysis of climate and weather data and their recent relationships with wine yields and sector growth. Employing spatial modelling tools and fuzzy logic this thesis also establishes the first mesoscale assessment of land suitability for viticulture in England and Wales. Furthermore, this study examines potential for agro-economic diversification and presents projected future (2021–2040 and 2041–2060) climate change impacts on wine production and quality in south-east England and the Champagne region of France.

Increasing bioclimatic index values superficially suggest enhanced cool-climate viticulture opportunities in England and Wales but critically mask shorter term meteorological phenomena and inter-annual weather variability that threaten productivity. These risks appear to have increased with the recent change to more 'sensitive' vine cultivars. Additionally, only 50% of vineyards were found to exist within modelled suitability parameters suggesting exposure to sub-optimal biophysical characteristics. However, significant opportunities for sector expansion into more suitable and meteorologically 'stable' areas were identified. An economic assessment of crop conversion potential indicates favourable returns for viticulture, and future climate change scenarios (2021–2040 and 2041–2060) indicate growing season warming in south-east England but a changing rainfall distribution that could threaten productivity. Champagne is projected to become drier during the critical maturation stages and the likely repetition of growing season conditions that have led to high quality Champagne vintages was found to be low.

Knowledge and tools developed herein are supporting the development of climate services to aid greater resilience of the English and Welsh viticulture sectors to weather and climate risks.

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First and foremost I thank my supervisory team who have been fantastic at supporting, guiding and mentoring me, and with whom I hope to continue working.

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English and Welsh wine producers were essential to completing this research. I thank all of those who provided data, participated in focus groups and completed questionnaires.

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Preface

This thesis was undertaken at a time of significant expansion in the English and Welsh wine production sector and within the context of increasing awareness about climate change threats to and opportunities for wine production. The author recognised a need for closer examination of relationships between weather, climate, climate change and viticulture in the new cool-climate viticulture regions of England and Wales. The sector, and those investing in it, have been exposed to a critical lack of data and analysis from which to draw considered conclusions about viticulture viability. The thesis aim was to make an original contribution to knowledge in the field of climate change and viticulture that would inform investment decisions, management activities and development opportunities. A core motivation was to establish the need for weather and climate services within the sector, with a view to knowledge conversion into commercial services. The multidisciplinary work presented in this thesis forms an initial but important contribution to that process.

During the course of research several outputs have been realised:

- Initial findings presented in Chapter 1, based on a literature review, were subsequently used to contribute to: Marangon, M., Nesbitt, A., and Milanowski, T., 2016. Global Climate Change and Wine Safety. In Begoña Bartolomé Sualdea and M. Victoria Moreno-Arribas, ed. *Wine Safety, Consumer Preference, and Human Health*. London. Springer International Publishing, pp. 97–116.
- Chapters 3 and 4 substantially represent a derived publication: Nesbitt, A., Kemp, B., Steele, C., Lovett, A., and Dorling, S. (2016). Impact of recent climate change and weather variability on the viability of UK viticulture – combining weather and climate records with producers ’ perspectives. *Australian Journal of Grape and Wine Research.* (Accepted for publication March 2016). Available in Appendix C.
- Results from Chapters 3 and 4 were orally presented at the ClimWine International Symposium (Sustainable grape and wine production in the context of climate change) in Bordeaux, France: 10–13 April 2016.
- Results from Chapters 5 will be presented orally at the International Cool Climate Wine Symposium in Brighton, England: 26–28 May 2016.

Further research in this field will enable development of a greater suite of tools to aid the integration of climate resilience into cool-climate viticulture and realise adaptive capacity in warm climate regions.

Chapter 1

Threats and opportunities for viticulture in changing climates, and the need for analysis

Wine grape cultivar establishment, wine ‘type’ and the productivity of a given region are largely determined by climate, to which grapevines are highly sensitive (Schultz & Jones 2010). Wine grape cultivars (predominantly *Vitis vinifera* L.) are suited to narrow latitudinal and climatic bands (Figure 1.1) and their climatic sensitivity exposes viticulture regions to threats and opportunities associated with climate change. It has been demonstrated that climate change could drive land-use conversion and agro-economic activity to profoundly alter the spatial structure of viticulture at regional and global scales (Fraga et al. 2013a; Hannah et al. 2013; Webb et al. 2013; Tóth & Végvári 2016).

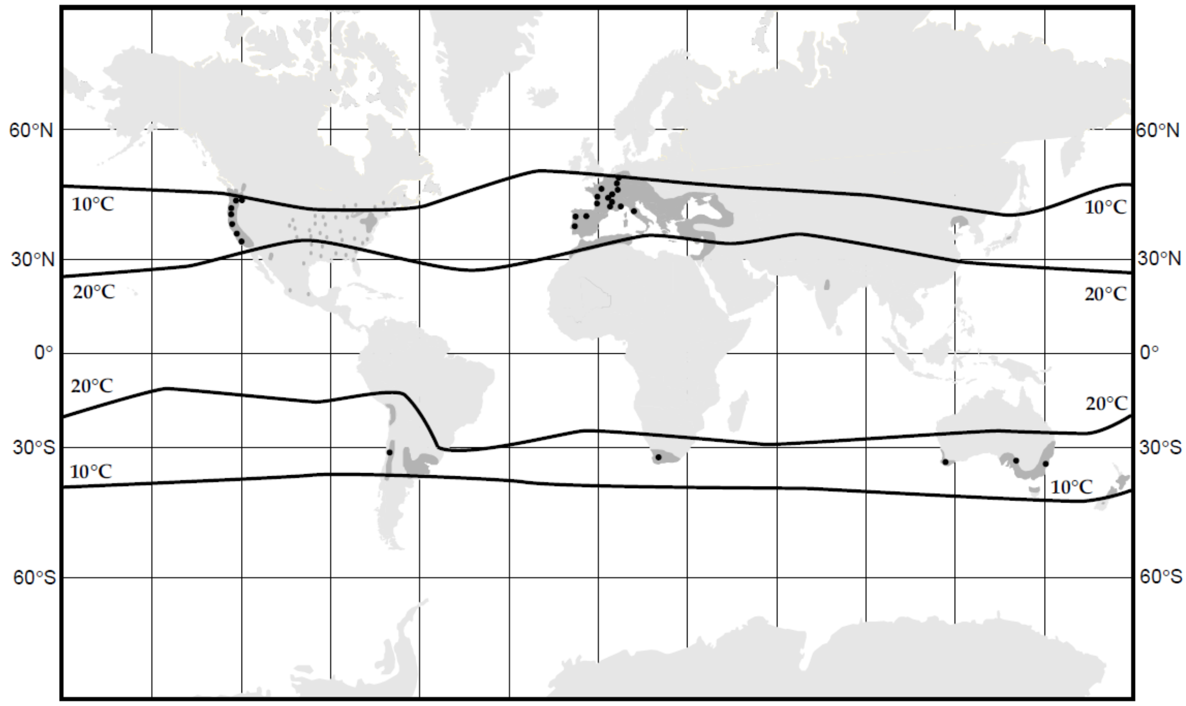


Figure 1.1: Key commercial viticulture regions worldwide.
Contours represent the mean annual 10°C and 20°C isotherms as a proxy for the latitudinal limits of the majority of the world’s grape growing areas. The solid dots represent the wine regions studied by Jones et al. (2004).

In hotter regions where warming climate conditions pose a threat to cultivar suitability or viticulture viability, both short (for example: sun-screen or irrigation) and longer-term (for example: cultivar change) adaptation measures may be considered as strategies to increase resilience. However, at the point at which in situ adaptation becomes unviable or undesirable, migration to cooler areas might present opportunities for more sustainable production. Whilst there is little sign of this occurring on a large scale in the short term, there is evidence of new emerging viticulture areas, outside of previously defined latitudinal norms, for example England (see Section 3.1), Denmark, and southern Sweden (Danskevingaarde 2015; Vinvagen 2016). The emergence of these areas could provide further evidence of changing regional climatic conditions, and of their exploitation from within areas historically deemed too cold for commercial viticulture.

To test these hypotheses, and understand the degree to which spatial change is viable now, both the biophysical, weather, and climatic suitability within potential 'new' areas of wine-grape production require investigation. Future climate change impacts on viticulture suitability, and associated spatial and temporal dimensions, require a modelling approach. Whilst several studies have examined potential effects of future climate change on the spatial structure of viticulture (Webb et al. 2013; Malheiro et al. 2010; Fraga, et al. 2013a; Hannah et al. 2013; Tóth & Végvári 2016), few have demonstrated the inherent uncertainties associated with climate change models and future climate scenarios. Furthermore, future climate change and viticulture impact studies predominantly relate solely to agronomic potential, i.e. the potential to grow wine grapes (Moriondo et al. 2013), but economic viability is critical, and this is largely driven by wine quality (Jones & Davis 2000a; Jones et al. 2005).

This thesis explores recent and future suitability for viticulture, from both agronomic and wine quality perspectives, for England and Wales, emerging viticulture regions at the cool-end of viticulture suitability that have received little viticulture – climate research attention, but which offer a new insight into regional climate change impacts.

Over the last decade England and Wales have seen a significant increase in viticulture (Section 3.1) but no analysis of their growing-season climate and weather, biophysical suitability, future potential, wine quality impacts, or producer perceptions of climate-change risks has been undertaken. This failure to elucidate, in particular climate related threats and opportunities for viticulture in England and Wales, presents a research gap indicative of existing investment risk. Without a considered analysis of viticulture potential in England and Wales, from a biophysical, climate and economic perspective, investment risk remains high and the potential to exploit land and climate suitability low. England and Wales therefore present both an interesting research driven case-study regarding viticulture suitability and climate change, and a chance to test hypotheses and tools that could inform producer and policy sectors to deliver a more sustainable production environment.

This chapter commences with an exploration of the symbiotic relationships between weather, climate and viticulture that inform suitability. Climate change and associated spatial and temporal dynamics are subsequently introduced as potential drivers for alterations in the distribution of viticulture, globally. Then a brief synopsis of the recent growth in English and Welsh viticulture is presented to illustrate the impetus for this work. In Section 2 of this chapter the inter-disciplinary research that has been undertaken to date, as a means of identifying past and future climate change impacts on viticulture, is critiqued, and the context and focus of this area of study is discussed and defined. Finally, Section 3 establishes the aims and delimitations of this study.

1.1. Weather, climate and viticulture: drivers behind spatial and cultivar distribution

Vitis vinifera L., the predominant commercial wine grape species, is very sensitive to climate conditions and this sensitivity has been elegantly illustrated through its use as a proxy indicator of past climates, in particular through use of harvest dates for spring and summer temperature re-construction (Krieger et al. 2011; Daux et al. 2012; Yiou et al. 2012). These works demonstrate how only relatively small changes in climate conditions affect changes in wine grape phenology, harvest dates and cultivar suitability.

Wine grapes are predominantly grown in narrow latitudinal bands (30–50°N and 30–40°S; shown in Figure 1.1) and in specific climatic conditions, characterised by a lack of extreme heat and extreme cold (White et al. 2006; Schultz & Jones 2010). Within these parameters viticultural management, grapevine cultivar, clone and rootstock selection, and wine 'type' vary in response to local and mesoscale meteorological phenomena, soil 'types', established cultural practices, and market demands. Weather and climate, at local and mesoscales, are considered key determinants of both cultivar and viticulture suitability (Schultz & Jones 2010). Atmospheric phenomena at these scales have dimensions of the order of a few hundred metres to almost 1000 km and a timescale of hours to weeks, as demonstrated in Figure 1.2. They form part of a continuum of atmospheric features lying between the synoptic and microscales.

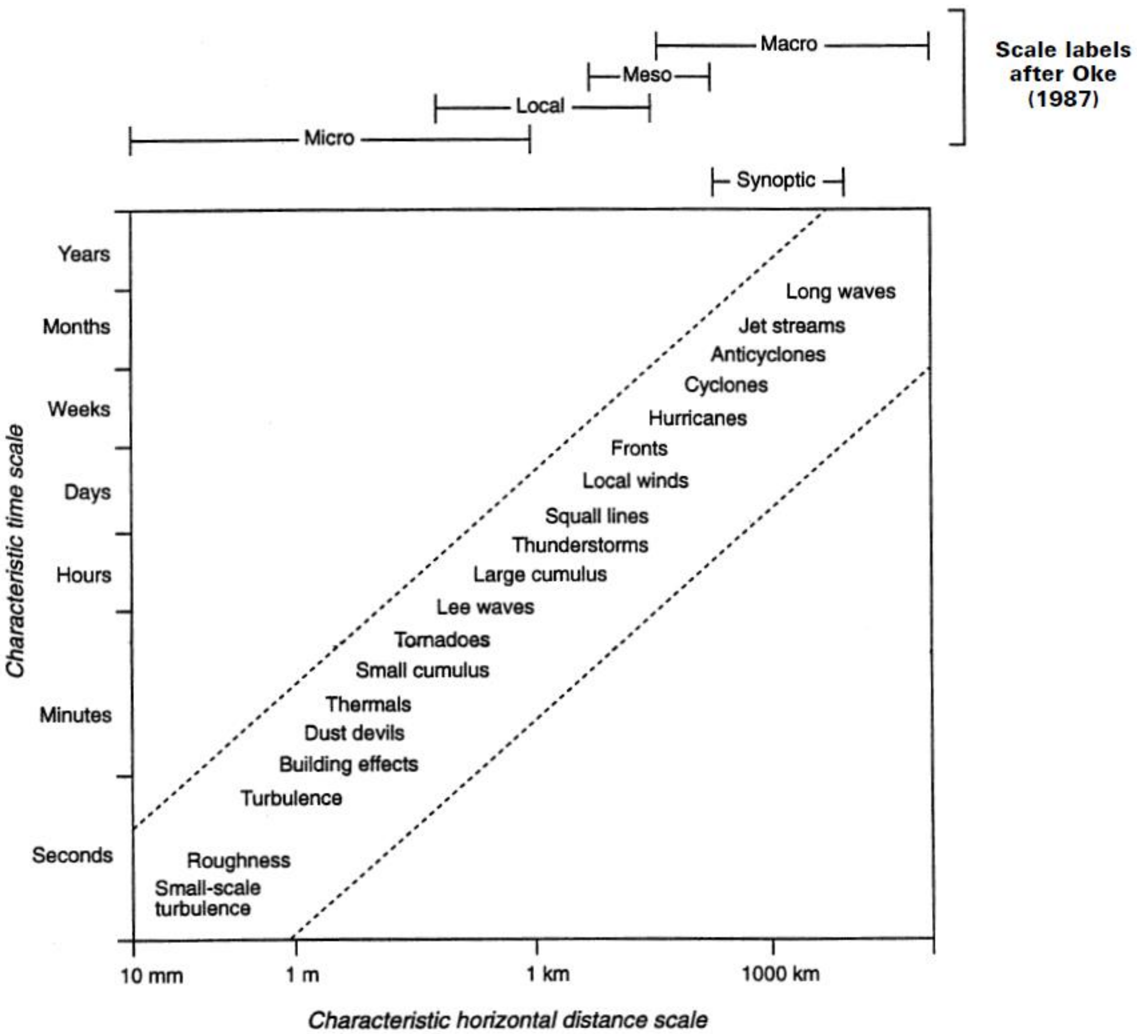


Figure 1.2: Characteristic time and space scales associated with atmospheric phenomena. Adopted from Sturman et al. (1999). Origional source: Sturman & Trapper (1996), after Oke (1987).

The spatial distribution of mesoscale atmospheric phenomena depends largely on whether they originate as disturbances that result from instabilities within synoptic weather systems, or as the result of the interaction of such systems with the earth's surface. In the first case, they can occur anywhere, while in the latter they tend to have a geographical distribution determined by the varying character of the underlying surface (Sturman et al. 1999). This thesis focusses primarily on the effects of surface-induced mesoscale and local atmospheric processes as these ultimately drive viticulture suitability locally (Fraga et al. 2012; Moriondo et al. 2013; Santos et al. 2012a) and deliver a global patchwork of wine grape cultivars and wine 'types' that bring complexity and value to the wine market. While micro-climatic variations play an important role in wine grape growth and quality (Jones 2005), the assumption in this work is that the mesoclimate data employed presents a mean of the microclimates of a given area. Therefore, growing season mesoclimate should match well with regional wine quality and quantity for a given vintage.

It is the coupling between spatial and temporal dimensions of weather and climate (Jones & Davis 2000) that signify that global climate change will have regional affects, which are not uniform in space or time (Intergovernmental Panel on Climate Change 2013a). Changes to regional weather patterns and/or climatic conditions could impact viticulture locally, alter 'traditional' market segmentation, and affect the socio-economic contributions of viticulture and wine production (Jones & Storchmann 2001). It is not surprising therefore that over the last two decades there has been a marked increase in research focussed on climate change and viticulture. Related to climate change, a range of studies cover the relationships between temperature and vine phenology (Bindi et al. 1996; Webb et al. 2008; Keller 2010; Tomasi et al. 2011; Neethling et al. 2012); projected temperature change in viticultural regions (Webb et al. 2008; Jones & Goodrich 2008; Tomasi et al. 2011; Fraga et al. 2012; Hannah et al. 2013); potential viticultural migration (Kenny & Harrison 1992; Hannah et al. 2013; Fraga et al. 2013a) impacts on wine grape quality parameters, yields, and wine quality (Jones et al. 2005; Keller 2010; Mira de Orduña 2010; Tomasi et al. 2011; Neethling et al. 2012); and, the potential for viticultural adaptation to climate change (Belliveau et al. 2006; Nicholas 2008; Diffenbaugh et al. 2011; Pickering et al. 2015). Interest has particularly been centred on Australia (Webb et al. 2008; Hall & Jones 2008), Western USA (Jones & Goodrich 2008; Jones et al. 2010), Bordeaux and the Loire Valley (Jones & Davis 2000a; Neethling et al. 2012), Spain (Ramos et al. 2008), Portugal (Santos et al. 2012a; Fraga et al. 2014a), Germany (Urhausen et al. 2011), and Italy (Tomasi et al. 2011). Most of these works are subjected to review in the later sections of this Chapter (Section 1.2) to inform the direction and hypotheses central to this thesis. Critically though, whilst authors such as Xu et al. (2012), Neethling et al. (2012), and Sturman & Quénol (2013) have looked closely at localised changes (for Burgundy (France), the Loire Valley (France), and New Zealand respectively) the majority of work to date examines synoptic or macro-scale assessments of climate change impacts on 'established' viticulture regions of the world. Only two studies, Jackson & Cherry (1988) and Kenny & Harrison (1992), have considered the potential implications of climate change for viticulture in England, and only Mosedale et al. (2015) have examined the micro-scale effects of one weather phenomenon (spring air frost) on English viticulture. Work has not been undertaken to investigate the broader relationships between weather, climate, and climate change and viticulture suitability across England and Wales. This 'gap' leaves those involved in English and Welsh viticulture exposed to uncertainties about risks and opportunities presented by recent and future weather and climates. Furthermore, without considered spatial and temporal suitability evaluations they remain unable to maximise spatial or cultivar potential.

This section begins with a synopsis of the relationships between weather, climate and viticulture in terms of phenology, berry quality traits, and spatial distribution to inform subsequent work. Sections 1.1.2 and 1.1.3 introduce the subject of climate change and its potential impact on the spatial distribution of viticulture. Section 1.1.4 highlights recent changes in English and Welsh viticulture which is subsequently adopted as a case study of climate change impacts for the remainder of this thesis.

1.1.1. Weather, climate and viticulture: an intrinsic relationship

Grape cultivars and wine 'types' in any given region are, in general, a result of the underlying climate, and variations in this climate commonly result in changes to vintage quality and wine quantity (Jones et al. 2005). Vintage variation is not a new concept in wine production, in-fact it is one of the vagaries of wine that feeds into its marketing and its value. However, where the magnitude of climate change and/or range of climate variability is beyond an acceptable 'norm' decisions around adaptive capacity and viticultural viability are required. These decisions are made more critical and more challenging by the long life-span of *Vitis vinifera* L. which is generally planted with a >35 year outlook (Ashenfelter & Storchmann 2014). Whilst historic climate data (>30-years) may have traditionally been deemed sufficient to adequately inform spatial and cultivar establishment decisions for vineyards, existing producers in some regions and those looking to invest in viticulture are likely to now extract value from climate change information (Section 1.2.1). The symbiotic nature of the relationships between weather, climate and viticulture therefore become central to understanding and modelling spatial and temporal suitability under present and future climate conditions.

Climate plays a predominant role in grapevine growth, as vine physiology and phenology are determined primarily by specific environmental conditions (van-Leeuwen et al. 2004; Santos et al. 2010). *Vitis vinifera* L. cultivars are characterised by an annual growth cycle, as depicted in Figure 1.3. For the northern hemisphere this begins with bud-break in March/April, continues with flowering in May/June, berry growth and colouring in July/August, maturation in September/October, and culminates with leaf fall in autumn, followed by winter dormancy (Gladstones 1992). Bud-break and its timing consistency is tied to winter chilling (which promotes bud dormancy initiating carbohydrate reserves for the following season (Field et al. 2009), and is determined by the cessation of winter dormancy (mediated by the accumulated exposure to low temperatures) and warm springs (Moncur et al. 1989; Keller 2010). Flowering time meanwhile correlates with maximum temperatures in the preceding month (Calo et al. 1996); diurnal temperature range helps determine acidity levels and the concentration of aromatic and colour compounds (Kliewer & Torres 1972); and, veraison (the point at which berry colour changes, representing the transition from berry growth to berry ripening) and harvest events are determined by average temperatures or heat accumulation over the growing season (Jones et al. 2005). Whilst mean growing season temperature highly influences grapevine physiology and fruit metabolism/composition, intra-seasonal conditions relating to temperature variability, precipitation, solar radiation and wind can affect phenological development, grape quality and quantity.

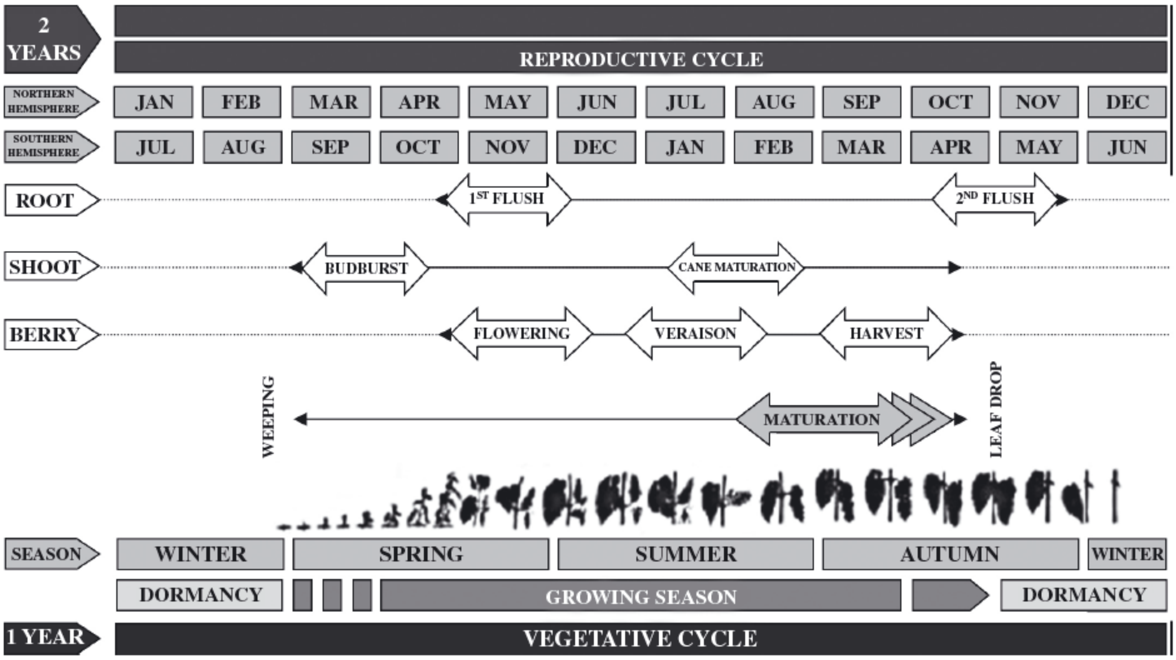


Figure 1.3: Vegetative and reproductive cycles and vine phenological stages. From Fraga et al. (2012)

Temperature

Of all meteorological variables temperature is considered the key factor in viticulture viability and wine quality (Jones et al. 2005). In general viticulture is deemed suitable within areas that have a growing season (April–October: Northern Hemisphere) average temperature (GST) of 12–22^{o}C (Jones 2007), (see Table 2.1 for GST equation), but high quality commercial production is mainly found within regions that experience a GST of 13–21^{o}C (Jones 2006). Temperature is a major cause of regional variation in *Vitis vinifera* L. cultivars, grape quality traits and wine 'types'. For example, berry sugar accumulation is directly affected by temperature, either via an increase in photosynthetic efficiency during the ripening season, especially in cool climates, or by indirect sugar concentration due to berry dehydration, particularly in warm climates (Keller 2010). Greater sugar accumulation presents higher potential alcohol in wines, and affects wine 'type' and style. Although cultivar specific, higher temperatures during the growing season generally result in juice with higher pH and lower total acidity (Keller 2010), again affecting wine style and organoleptic quality. Temperature also plays a role in modulating the final content of other compounds in grape berries that are essential in determining grape quality, such as phenolics, flavour compounds and proteins (Kliewer & Torres 1972; Gladstones 1992). In general higher temperatures lead to riper grapes in which fruity flavours tend to be predominant, rather than the green flavours associated with methoxypyrazine found in cooler-climates (Harris et al. 2012).

Desired wine style and organoleptic qualities are therefore instrumental in selecting cultivars suited to thermal conditions in which optimal balance and full physiological and/or industrial maturity can be achieved.

Temperature variability

It is the average growing season thermal characteristics that are generally applied to determine cultivar suitability, whilst climate variability within and between seasons commonly influences the quantity and quality of grapes produced (Ashenfelter & Storchmann 2014). Inter-annual variability also plays an important role in modulating the value and availability of premium quality wines, as 'vintage' quality is commonly associated with growing season weather conditions. Whilst a colder than average growing season in a cool-climate can result in unripe and low-quality fruit the opposite can be true in hotter viticulture climates. Accordingly, under climate change conditions, warming temperatures may increase the number of good vintages in cool-climate wine producing regions and decrease the number of good vintages in hot climate growing regions.

However, notwithstanding this hypothesis, historic relationships between weather conditions within a growing season and subsequent wine quality has surprisingly received little research attention. This thesis takes the opportunity to evaluate historic growing season monthly mean temperature and rainfall volumes for England and the Champagne region of France, as both are dominated by the same cultivars (Chardonnay and Pinot noir), to inform modelling work regarding likely repetition of these conditions in the future.

Extreme temperatures

Although some *Vitis vinifera* L. cultivars can tolerate minimum winter (dormant period) temperatures of as low as -20°C (Davenport et al. 2008), spring air frosts that injure developing shoots and buds, and frosts after budburst that reduce yield, are among the most common detrimental effects of minimum temperature extremes on wine grapevines. Spring air frosts in particular pose a significant economic risk to vineyards as, due to the perennial nature of grape vines, they can lead to crop loss in both the present and following year of production (Trought et al. 1999). Cool-climate wine producing regions (those with a GST of 13–15°C (Figure 1.4) are particularly exposed to the risk of late frost events when the advancement of budburst occurs in response to increased spring air temperatures (Molitor et al. 2014a;

Mosedale et al. 2015). A range of methods to protect vines from cold air accumulation and frost are available, but their employment and success rate has not been evaluated.

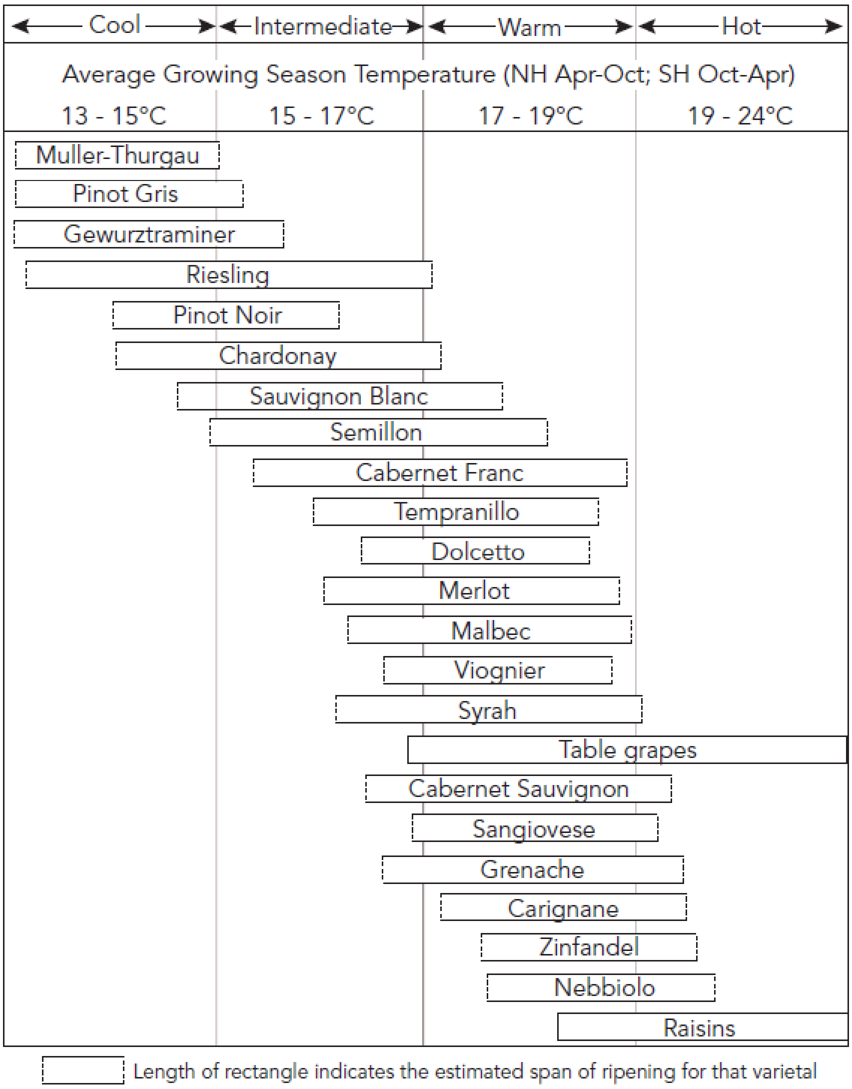


Figure 1.4: Grapevine Climate/Maturity Groupings (adopted from Jones (2006))

Extreme maximum temperatures in summer can cause substantial heat damage by inhibiting photosynthesis and causing sunburn (Moutinho-Pereira et al. 2007). Since red wines more than whites depend on skin-derived components such as pigments and tannins, reds are more affected than whites because the skin is the part of the berry that is most sensitive to heat damage (Gladstones 1992). Wine grapevines that experience severe heat stress can exhibit significant decline in productivity, due to stomatal and mesophyll limitations in photosynthesis, as well as injuries under other physiological processes (Moutinho-Pereira et al. 2004). Although this thesis focusses on the cooler end of viticulture suitability, extreme heat remains a potential push factor for migration, and a potential risk to cool-climate suitable cultivars.

Precipitation

Wine grape quality and quantity are affected by water availability and precipitation (Moutinho-Pereira et al. 2007; Makra et al. 2009). Water stress at budburst and shoot/inflorescence development can lead to poor shoot growth, poor flower cluster and berry set development (Hardie et al. 1976), ultimately leading to lower yields. Conversely, high humidity during early development stages can overstimulate vegetative growth, leading to dense canopies and a higher likelihood of disease pressures. Water stress at flowering results in low leaf area, limiting photosynthesis, increasing flower abortion, and causing cluster abscission (Jones & Davis 2000a). During flowering and maturation, moderately dry and stable atmospheric conditions are considered favourable for high-quality wines (Jones & Davis 2000a; Nemani et al. 2001; Ramos et al. 2008). When vines are irrigated water supply can be adjusted to meet the vines needs, but in large viticultural areas such as those in Europe irrigation is not yet practiced.

At the other end of the precipitation scale both extreme precipitation and hail can have devastating effects on the current season's crop, and on the following years' harvest. They can cause severe plant defoliation before adequate reserves have been accumulated, thus negatively impacting development the following spring, and leading to a decrease in bud fruitfulness and production (Iland et al. 2011). High precipitation volumes at flowering can disrupt the process and affect fruit set, again leading to lower yields (Jones & Davis 2000a).

Radiation

Sunlight and solar radiation energy play a particularly beneficial role during berry ripening and maturation where sugar and phenolic contents are favoured by sunshine (Gladstones 1992). Berry temperature has been found to increase linearly with exposure to incident light (Smart & Sinclair 1976; Bergqvist et al. 2001) which contributes positively to increased phenolic concentrations, particularly tannins (Downey et al. 2006; Kemp et al. 2011). Solar radiation at the earth's surface, insolation, also provides energy through photosynthetic processes for grapevine growth. Whilst the exact quantification of sunshine magnitude and phenolic concentrations remains undetermined for a range of cultivars it is the case that links between sunshine and temperature indicate that areas with greater solar radiation exposure are likely to be more favourable to *Vitis vinifera* L. cultivation.

Wind

Wind can negatively affect yield and quality. Windy conditions can disrupt flowering, lower vineyard temperatures (Jones & Davis 2000a) and impact vine canopy structures causing shading and reduced photosynthesis. Conversely breezes are regarded as beneficial in providing air movement and reducing disease instance (Skelton 2014).

Climate

The nature, temporal occurrence and patterns of weather are critical to wine grape production, quality and quantity. The integration of a given set of meteorological conditions, typically a 30-year period (World Meteorological Organization 2016), into a climate norm allows for a descriptor of the mean and inter-annual variability of growing-season conditions for a given location. Given the previously identified importance of intra-seasonal weather conditions it is therefore perhaps surprising that climatic suitability for viticulture is commonly defined through thermal based bioclimatic indices that categorise cultivar suitability through an averaging of growing season temperatures (for example: Kenny & Harrison (1992) – Europe; Tonietto & Carbonneau (2004) – Europe; Duchêne & Schneider (2005) – Alsace; Hall & Jones (2010) – Australia; or Anderson et al. (2012) – New Zealand). These metrics, discussed further in Section 1.2.2, place numerical or descriptive envelopes around summed or averaged daily or monthly growing-season temperatures to express suitability ranges. However, the thermally averaged or summed nature of bioclimatic indices results in only crude indicators of suitability which do not allow for an assessment of intra-annual variability, or critical hourly or daily time-scale events such as frosts, which are known to threaten productivity. Furthermore, where restricted to thermal phenomena they exclude other meteorological events that can affect suitability, at both regional and local scales. Additionally, their aggregated nature masks 'seasonality' that is important in defining the structure of meteorological conditions that contribute to both cultivar suitability, wine quality and wine style. Ultimately they are empirically based indicators that assume a strong relationship between observed cultivar occurrence and suitability. As such they are open to evaluation and critique as they are not absolute in their 'classification' of what does or does not constitute 'suitable' growing conditions.

This synopsis of the relationships between weather, climate and viticulture illustrates both the complexity and the importance of selecting and evaluating meteorological and climate data to ascertain viticulture suitability at a given spatial and temporal scale. Further, it informs the selection and analysis of weather and climate data in this work, to better understand localised impacts on viticulture in England and Wales, and to help model spatial suitability and risk both now and under future climate change scenarios.

1.1.2. Climate change

The temperature of the earth is essentially controlled by the balance between radiational heat energy from the sun and radiational heat loss from the ground. Where heat energy is released into the earth's atmosphere, greenhouse gases (GHG), such as carbon dioxide (CO_2) naturally trap or absorb some of it and radiate it back towards earth, increasing the earth's temperature. This positive 'greenhouse effect' raises the average temperature of the planet from about -18°C to a more habitable 15°C (Dessler &

Parson 2010). Historically the earth has experienced changes in its climate, which over the last million years has been driven predominantly by fluctuations in the earth's orbit, resulting in a cyclical progression of ice ages and inter-glacial periods (Dessler & Pasron 2010). The last ice age ended about 18,000 years ago. However, since the industrial revolution at the end of the 18^{th} and early 19^{th} centuries, GHG concentrations have increased in the atmosphere and these have enhanced the greenhouse effect and resulted in changes to the earth's climate. The attribution of the increase in GHGs is primarily anthropogenic, that is to say through deforestation and burning of fossil fuels such as coal and gasoline that contain carbon, by mankind (Intergovernmental Panel on Climate Change 2013a). Methane (CH_4) that is released from industry and agriculture, Nitrous Oxide (N_2O) mainly from agriculture, and low-atmosphere ozone (O_3), a by-product of smog as well as other industrial chemicals related to air conditioning and refrigeration, together account for about 80% as much greenhouse warming as CO_2 (Dessler & Parson 2010).

In 2013 The Intergovernmental Panel on Climate Change (IPCC) concluded that globally averaged combined land and ocean surface temperature data showed a warming of 0.85°C over the period 1880–2012, assuming a linear trend (Intergovernmental Panel on Climate Change 2013a). The UK has seen warming occur faster than the global average: at 0.23°C and 0.28°C per decade in winter and summer respectively, since 1960 (Met Office 2014a). Records also show that post–1910 the eight warmest years in the UK have all occurred since 2002 (Met Office 2015b). Furthermore, and perhaps more importantly, a range of computer models aligned to future socio-economic scenarios and Representative Concentration Pathways (RCPs) indicate that changes in climate are projected to continue unless significant mitigation occurs (van Vuuren et al. 2011). Anthropogenic GHG emissions are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy, and the RCPs which are used for making projections based on these factors, describe different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5. RCP2.6 is representative of a scenario that aims to keep global warming likely below 2°C above pre-industrial temperatures (Intergovernmental Panel on Climate Change 2014). Depending on economic and political actions regarding energy, resource use and climate change mitigation in the near future, mean projections for change in globally averaged temperatures at the end of the century range from 1–4°C, above a 1986–2005 baseline. These projections and the associated model uncertainties in them are shown in Figure 1.5, and are further illustrated in Figure 1.6a.

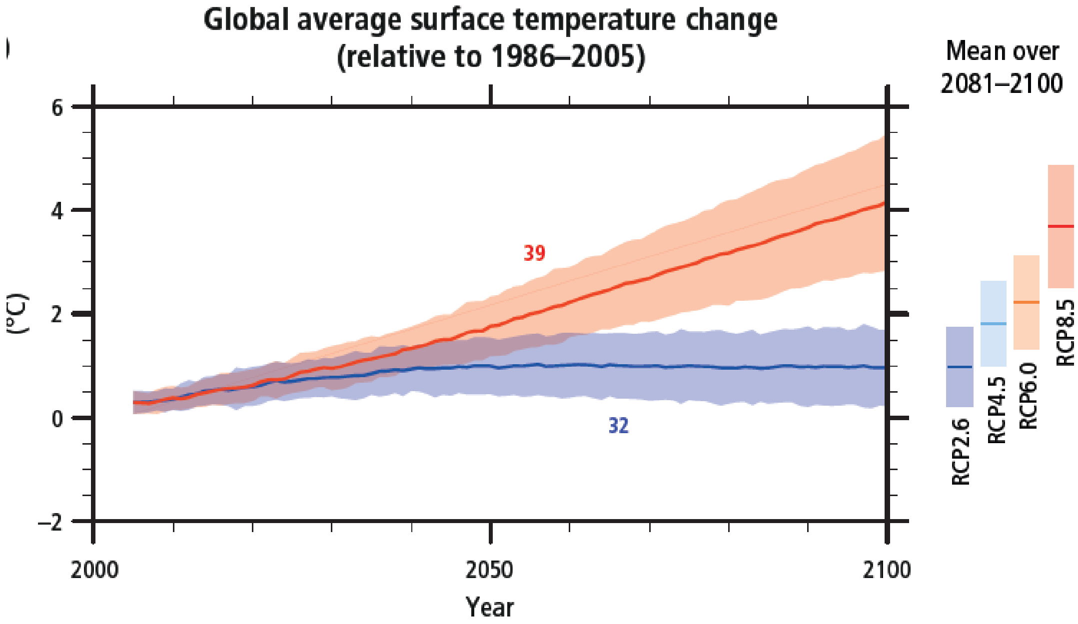


Figure 1.5: Global average surface temperature change from 2006 to 2100 as determined by multi-model simulations. All changes are relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as coloured vertical bars at the right hand side of each panel. The number of Coupled Model Intercomparison Project Phase 5 (CMIP5) models used to calculate the multi-model mean is indicated. Reproduced with kind permission from the IPCC (2014)

Temperature changes are likely to affect agro-economic activity temporally and spatially, in both the UK and globally. Through this work both recent and future potential impacts on viticulture suitability in England and Wales are examined in relation to temperature. However, as summarised in Section 1.1.1 temperature is not the only atmospheric parameter that affects viticulture viability or suitability. Amongst other variables precipitation and water availability are also critical. Changes in precipitation are not projected to be spatially uniform under climate change scenarios, the high latitudes and the equatorial Pacific are likely to experience an increase in annual mean precipitation under the RCP8.5 scenario due to the increased specific humidity of the warmer troposphere as well as increased transport of water vapour from the tropics (Intergovernmental Panel on Climate Change 2014). In many mid-latitude and subtropical dry regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase under the RCP8.5 scenario (Figure 1.6b). Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent (Intergovernmental Panel on Climate Change 2014).

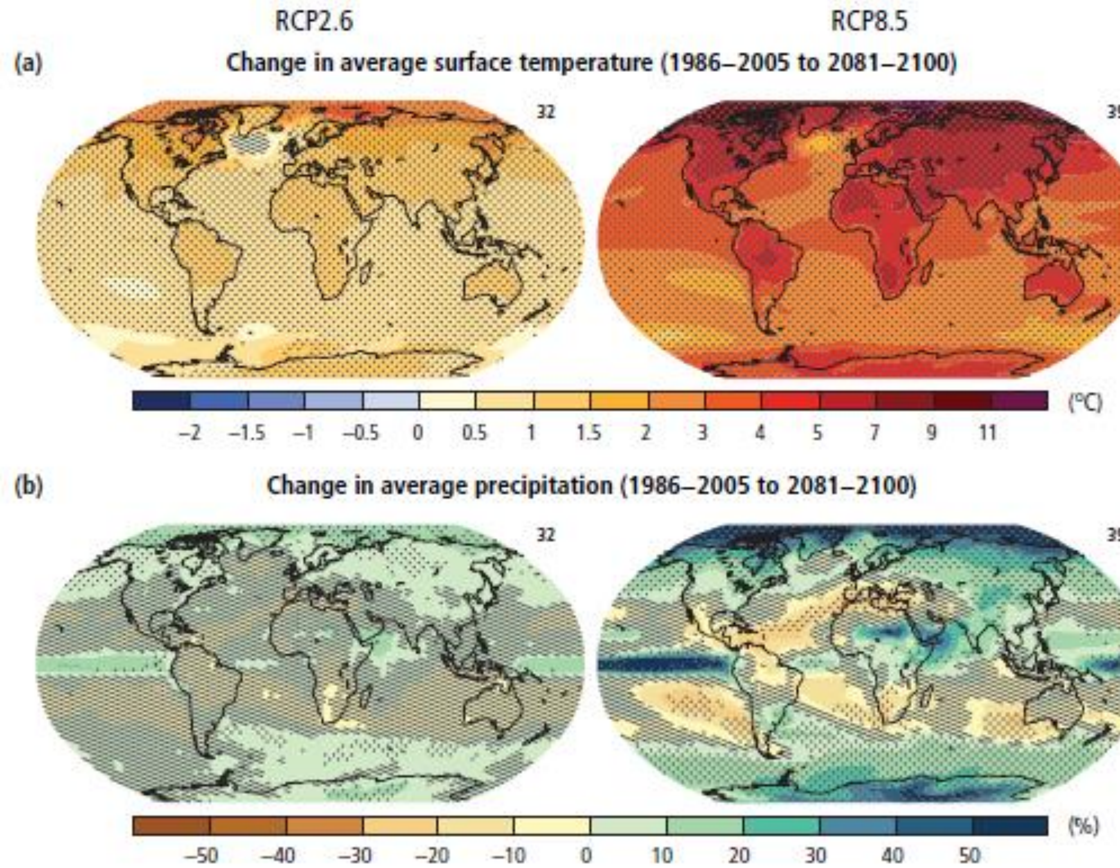


Figure 1.6: Change in average surface temperature (°C) (a) and change in average precipitation (%) (b) based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios. The number of models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (i.e., dots) shows regions where the projected change is large compared to natural internal variability and where at least 90% of models agree on the sign of change. Hatching (i.e., diagonal lines) shows regions where the projected change is less than one standard deviation of the natural internal variability. Reproduced with kind permission from the IPCC (2014)

Climate change, at global and regional scales, will largely determine the future of viticulture suitability, both spatially and temporally. The narrow climatic envelopes in which wine grape cultivars have been observed to perform best (Jones 2006) put *Vitis vinifera* L. at a greater potential risk from climatic variations and change than crops with a broader geographic range. However, climate change has not been evidenced as a linear year-on-year continuum of temperature or precipitation alteration and as such the nonlinearity of changing climates is an important consideration in assessing viticultural vulnerability that has not received much attention in viticulture climate research (Section 1.2). In practice it is the number of good or bad seasons over a given period that is likely to have a greater bearing on viticulture viability, than the average of conditions or projected change over a ≥30 year period (Kenny & Harrison 1992). In this thesis therefore both intra- and inter-annual variability of temperature and precipitation are given greater attention as it is hypothesised that, notwithstanding changes to thermal or precipitation averages, these factors are equally valuable in decision making regarding spatial suitability for a 30–40 year lifespan of a wine grape vine.

As well as variability across mean temperature and precipitation the probability of extreme events occurring under climate change conditions increases where the average of temperatures or rainfall rises (Beniston et al. 2007). In particular this is likely to affect the number of extreme hot days that in some areas could negatively affect viticulture, especially where extreme heat coincides with critical periods such as maturation and harvest. Schultz (2000) and Jones et al. (2005) both found that in some southern Europe wine producing regions future anticipated changes in inter-annual variability and extremes may increase the variability of yields, with detrimental effects on the whole winemaking sector, and on wine quality. Conversely extreme freeze events in spring may reduce but importantly, under warming conditions, grapevine phenology has been seen to advance (Webb et al. 2011), giving rise to greater risks from earlier frosts. This has recently been demonstrated as a risk in England by Mosedale et al. (2015). Whilst extreme heat could cause problems for wine producers in England and Wales it is the latter subject of frost risk that is given greater attention in this thesis, mainly because, as evidenced in Chapters 3 and 4, spring frost in particular has been shown to affect wine yields.

1.1.3. The spatial distribution of viticulture: a global change perspective

The spatial and cultivar distribution of longer established wine producing regions of the world, often termed the 'old-world', is largely attributed to centuries of experience, adaptation and 'trial and error' (Jones 2012). However, here it should be noted that there is actually little evidence of 'validation' or research to indicate that cultivars are planted in 'optimal' areas and it may be that political, cultural or historic dynamics have as much to do with cultivar positioning as climatic optimisation. Nevertheless, whilst for the most part these, and newer ('new-world') vineyard areas, are positioned in narrow latitudinal and climatic bands (Figure 1.1), recent research suggests that under future climate change scenarios higher latitude regions may have increasing viticultural suitability (Stock et al. 2005; Jones 2007; Hall & Jones 2008; Schultz & Jones 2010). In the Southern Hemisphere there is not much room for poleward migration due to limited land mass. In the Northern Hemisphere future warmer climates may be beneficial for many existing regions in central and western Europe, such as Alsace, Champagne, Bordeaux, Bourgogne, Loire Valley, Mosel, and Rheingau (Stock et al. 2005; Malheiro et al. 2010; Neethling et al. 2012), and for new regions touted as potentially having increased future suitability, including England and Wales (Kenny & Harrison 1992; Fraga et al. 2013a).

Small degrees of migratory shifts in viticulture could be said to be evidenced through vineyards beyond the 30–50^{o} latitude bands in small pockets of North America, Northern Europe, Canada and New Zealand. These areas tend to be predisposed to weather and climate risks, such as frosts or cool growing-season temperatures (Powell 2014) and expansion into them, or further poleward areas, requires either the spatial identification of climatic 'niches' embedded into an otherwise 'cool-climate' environment, or changing climate conditions that will progressively accommodate the commercial production of *Vitis vinifera* L. In this thesis both of these options are explored.

1.1.4. The growing English and Welsh wine production industry: a climate change indicator?

Two emerging and rapidly expanding wine producing regions, previously referred to, are loosely defined as England and Wales. They are distinct politically and as wine producing areas, each with individual options for Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) schemes (United Kingdon Vineyards Association 2015). Established wine producing regions exist in the Champagne region of France and the Rhine and Mosel regions of Germany, which until recently have marked the northern limits of commercial European viticulture. However a recent increase in wine production in England and Wales has resulted in England and Wales becoming two of the most northerly established commercial viticultural regions in Europe (see Section 3.1). Others include Eastern Denmark and Southern Sweden (Danskevingaarde 2015; Vinvagen 2016).

Evidence points to the existence of vineyards in southern England during the Medieval Warm Period (~1000 – 1200 AD) (Gladstones 1992; Selley 2004), and to their potential existence in Roman Britain (Selley 2004). Their presence is mainly attributed to suitable climatic conditions, in particular to accompanying air temperature (Gladstones 1992; Selley 2004); indeed during a period of lower temperature, the Little Ice Age, (1300–1850; Dessler & Parson 2010), vineyard numbers in the UK declined. The subsequent revival of English and Welsh viticulture began in the early 1950s and growth in the sector accelerated from the mid-1990s. Despite recent sector expansion (see Section 3.1) there has been no research into growth drivers, and surprisingly little analysis or commentary on the scale and distribution of English and Welsh viticulture. Section 3.1 of this thesis presents results from investigations and analysis of recent sector growth, from which this study can be placed in context.

The relationship between this growth industry, climate change and other contributory factors has not been examined until now. Indeed the suitability of England and Wales for viticulture has not been explored by the research community from a climatic or biophysical perspective. Critically the *prima facie* opportunities presented by warming climatic conditions have not been studied for the growing season, and the threats and opportunities presented by climate change for viticulture in England and Wales have not been elucidated. Without research into these areas, assumptions regarding the potential for poleward migration of viticulture cannot be tested, and the relative degree of suitability for viticulture in biophysically suitable 'new' areas cannot be established. England and Wales therefore provide an opportunity to evaluate viticulture adaptation potential, when represented as migration, and to investigate risks for a 'new' viticulture region from weather, climate and climate change.

1.2. Climate change impacts on viticulture: producers' perspectives, modelling recent and future change, mapping spatial suitability, and gaps in the literature

Questions about the impact of climate change on viticulture and wine production are typically answered through empirical investigations into the effects of recent climate change on grapevine phenology, yield, berry and wine quality; and, extrapolation of these relationships under modelled future conditions. However, the perceptions of climate-change risk held by wine producers, and the interaction between their views on impact and those of observed or modelled threats and opportunities have received little research attention. Section 1.2.1 explores the work that has been undertaken in this area, as a means of informing the engagement with producers undertaken as part of this thesis, detailed in Chapters 2 and 3. Present and future climate – cultivar suitability assessments have predominantly been undertaken through the employment of one or more bioclimatic indices, the nature and value of which are examined further in Section 1.2.2 and in Chapters 4 and 5. Where these have been employed to spatially map risks or opportunities for viticulture, under present or future conditions, the outcomes offer varying degrees of information relevant to suitability assessments and risk analysis. In Section 1.2.3 existing spatial suitability research is critiqued to inform methodological processes outlined in Chapter 2, and applied in Chapter 5, where a suitability model for England and Wales is presented. Section 1.2.4 of this chapter is devoted to an analysis of observed climate change impacts on viticultural regions.

This summary of findings both provides the impetus for this work and allows for climate change projections, presented in Chapter 6, to be aligned with viticulture impacts. A critique of future climate change and viticulture research to-date (Section 1.2.5) informs the methods adopted in this thesis to model climate change.

1.2.1. Producers' perspectives of climate change

Research regarding potential changes to the spatial or cultivar distribution of viticulture under climate change scenarios rarely takes into account opportunities for buffering provided through climate change adaptation, or wine producers' perspectives on climate change impacts and risk. The former, adaptation potential, is partly determined by the latter as threats, opportunities and capacity for adaptation are likely to be determined by producers understanding, experiences and perception of risk. Threats to and opportunities for viticulture associated with climate change can be presented through observed changes and modelled processes which illustrate impact. However, the perception of climate-change effects on agro-economic activity are not often independent of human operators or the degree to which their business is resilient to events or change. In other words assumptions of weather and climate risks made independently of the producer may be very different to those of the producers themselves. Only by understanding producer's perceptions of climate change threats and opportunities can risk be more fully determined, and adaptive capacity illuminated.

Where the limited research in this direction has been conducted questionnaires or interviews have commonly been undertaken with a sample of growers to better understand their perceptions of risk and their response mechanisms. Belliveau et al. (2006) – Okanagan Valley, Nicholas (2008) – California, Battaglini et al. (2009) – France, Germany and Italy, Lereboullet et al. (2013) – Roussillion region of France and McLaren Vale in Australia, and Pickering et al. (2015) – Ontario, all present research into risk perception and adaptation capacity in this way. All found that the majority of those who responded to surveys viewed climate change or warming as a potential stress to production, although in Ontario Pickering et al. (2015) found that more respondents believed climate change would have positive impacts for the region than negative. Interestingly Nicholas (2008) found that producers in California were accustomed to responding to different weather events and climate variability and that in fact there was a disconnect between their focus on day-to-day or season-to-season weather conditions and the research focus on future potential impacts of climate change. This disconnect was also established by Battaglini et al. (2008) in their survey of wine producers' perceptions of climate change. Here 80% of the 255 producers who responded indicated that they viewed threats associated with climate change as having increased over 'the last 10–20 years', but crucially the authors note that the information collected by their survey could not determine the extent to which a particular weather event – as opposed to longer term trends – impacted these perceptions (Battaglini et al. 2008). Perceived climate change threats to production were related to increasing pest and disease pressures, excessive rain, more frequent periods of drought, and higher weather extremes. Yet as with Belliveau et al. (2006) climate-change risks identified by Battaglini et al. (2008) were largely restricted to specific weather events that had historically caused yield and quality reductions, rather than the average of thermal conditions that had been correlated by producers to higher quality production.

With regards to climate change adaptation Battaglini et al. (2008) and Pickering et al. (2013) found that there was a demand for information on adaptation strategies, but interestingly Battaglini et al. (2008) found a slight majority (52%) of respondents indicated that they would not change cultivars in response to climate change. Meanwhile in Germany over 50% of growers indicated that they are already planning and would continue to plan to use new cultivars as a response to climate change, an outcome that may provide a small insight into perceived spatial threat variance, or socio-political dimensions to cultivars that the study did not investigate.

These few studies demonstrate how rarely stakeholder engagement has occurred in viticulture-climate research but reveal the benefits of incorporating producer's perspectives to more fully understand risks and producer focus at a local vineyard scale, and to facilitate planning for change and adaptation throughout the lifespan of *Vitis vinifera* L. (Lereboullet et al. 2013). This thesis draws on these findings through a first survey of English and Welsh wine producers to better understand their perceptions of weather, climate and climate change risks upon which subsequent research is based (see Sections 2.2.1 and 3.2). Additionally findings from these works, particularly that producers' focus is more explicitly on the 'here and now' of production with tacit acknowledgement for a need for future planning, have guided this thesis to focus on past, present, and future conditions. Recent and present conditions are presumably core drivers behind the expansion of viticulture in England and Wales, and where this research translates into tools to help producers identify climatically suitable production areas, it is this focus that underpins applications.

Climate change adaptation is not explicitly taken into account in the approach adopted through this thesis, and although it is recognised that strategies exist to mitigate heat in vineyards, where it is the case that there is insufficient heat during the growing season, outdoor viticulture potential can be severely compromised. It is this 'bottom' end of suitability which is more likely to affect 'cool-climate' viticulture in England and Wales, and therefore with which this work is concerned.

1.2.2. Bioclimatic indices as tools for climate suitability and climate change impact modelling

Assessing temporal and spatial suitability for viticulture, viticulture zoning, and comparing viticulture regions is commonly aided by the application of bioclimatic indices (Kenny & Harrison 1992; Tonietto & Carbonneau 2004; Duchêne & Schneider 2005; Hall & Jones 2010; Anderson et al. 2012). These are utilised as indicators of commercial viticulture and cultivar suitability (Hall & Jones 2010). However, the applicability of bioclimatic indices to model suitability in the England or Wales has not previously been evaluated. Furthermore, their strengths and weaknesses require discussion to inform their potential deployment.

All bioclimatic index equations that are subsequently employed in this thesis can be found in Chapter 2, Table 2.1.

Bioclimatic indices, as applied to viticulture, were instigated through the work of Amerine & Winkler (1944) who constructed a simple summation of Growing Degree Days (GDD) to help categorise Californian viticulture regions by cultivar and thermal accumulation over the growing season. GDD is calculated as a summation of the daily mean (T*max* + T*min* / 2) temperature above a base of 10°C, for the period April–October (Northern Hemisphere). The 10°C base temperature is the minimum threshold considered necessary for grapevines to initiate their growing cycle (Amerine & Winkler 1944) but its ability to adequately distinguish cultivar suitability has been questioned. In 1989 Moncur et al. analysed rates of bud-break and leaf appearance of cuttings from 10 dormant cultivars grown in temperature controlled environments. These were used to estimate base temperature for each cultivar. Bud-break ranged from temperatures of 0.4–4.6°C (mean 3.5°C) and leaf appearance from 5–8°C (mean 7.1°C), indicating the 10°C base of GDD is somewhat arbitrary and does not accurately define the thermal conditions in which cultivars initiate growth. This conclusion has been further supported by research into two *Vitis vinifera* L. cultivars: Riesling and Müller-Thurgau, grown in 13 northern European vineyards. Here (Nendel 2010) discovered that average parameters for predicting bud-break were less accurate than using site-specific temperature measurements, where thresholds for bud-break ranged between 5.1–6.9°C. These findings do not affect the use of GDDs as a comparator of thermal accumulation during the growing-season between viticulture areas, or for the purpose of zoning, but they do bring into question their reliability for establishing cultivar suitability.

The GDD index was modified by Gladstones (1992) to include, a) an upper limit of 19°C above which he suggests no physiological activity occurs, b) a correction factor for latitude to account for variances in solar radiation, and c) a diurnal temperature range (DTR) adjustment (upward if the DTR is >13°C and downward if <10°C). The resulting index was termed the Biologically Effective Degree Days (BEDD) index. This slightly more complex index was developed for and employed in Australian viticulture regions (Gladstones 1992) and provides a tool that potentially more accurately delineates between cultivar and spatial suitability, yet retains the limitations associated with a base of 10°C.

In both the case of GDD and BEDD daily temperature data is required to perform the calculations.

Before Gladstones work Huglin (1978) developed the Huglin Index (HI), see Table 2.1, sometimes referred to as the Heliothermal Index, which is similar to the BEDD index but accounts for maximum temperatures during the growing season as these could be considered to be better predictors of plant growth, because this is the time during which photosynthesis occurs (Hall & Jones 2010). Unlike the degree day indices the HI is calculated using only April–September (Northern Hemisphere) or October–March (Southern Hemisphere) as Huglin asserted that because vine growth is so limited during the last month before harvest (October or April) its temperature is not a contributory factor to maturation. Jones et al. (2010) noted that comparisons between the HI calculated for April–October and April–September are highly correlated ($r > 0.95$) for many regions, indicating that the exclusion of the last growing season month does not materially affect the bioclimatic classifications. The HI accounts for both day-length/latitude, and mean and maximum temperatures, both which have a strong influence on grape development and quality (Jones & Davis 2000a). Indeed the relatively long day-lengths at higher latitudes contribute to higher levels of insolation during the growing period which partially compensate for lower average temperatures, and in doing so lead to a northward extension of the viticultural suitability (Malheiro et al. 2010). High HI values indicate suitable areas for grapevine cultivars with late maturation, whilst low values are more likely to indicate appropriateness for early maturing cultivars. By way of illustration, Jones et al. (2005) found a high positive correlation between HI and later season phenological events (véraison and harvest).

Other less commonly applied bioclimatic indices for viticulture were developed by Jackson & Cherry (1988) and Kenny & Harrison (1992) who used a Latitude Temperature Index (LTI) (a calculation of Mean Temperature of the Warmest Month (MTWM) x latitude – 60, although later adjusted by Kenny & Shao (1992) to 75); Tonietto & Carbonneau (2004) who advocated the Cool Night Index (CI), calculated as the minimum air temperature in the month preceding harvest, and who used the Dryness Index (DI), developed to estimate potential soil water availability during the growing season. The MTWM alone has also been advocated as a reliable indicator of viticulture suitability (Smart & Dry 1980) as has Mean Temperature of the Coldest Month (MTCM) which again arbitrarily distinguishes cultivar suitability (Jackson & Cherry 1988). Jackson & Cherry (1988) assessed GDD (with different base temperatures), MTWM, MTCM, and the LTI in Australia and New Zealand as they were of the opinion that index values generated for Europe or the US were not adequate in evaluating the ripening potential of districts in New Zealand or Southern Australia. They concluded that LTI and GDD (with a higher base temperature) gave stronger correlations, and GDDs with higher bases are better at distinguishing between 'cool-climate' cultivars (for example: Gewürztraminer, Madelaine Angevine, Reichensteiner, Müller-Thurgau, Pinot gris, Pinot noir, Pinot meunier, Chardonnay, Bacchus, and Riesling), whilst lower bases separated groupings with cultivars such as Cabernet Sauvignon, Cabernet Franc, Merlot, Malbec, Sauvignon blanc, Semillon, Grenache, Shiraz, and Zinfandel, found in warmer regions. Of interest they noted that some of these varietals found in warmer conditions can often be grown in colder regions but seldom reach the same quality. Their work was the first piece of research that assessed the viticulture climate in the UK, regarded as a 'cool-climate' region with a LTI of <380, and suitable for growing Gewurztraminer, Madelaine Angevine, Reichensteiner, Perle, Schönburger, Triomphe d'Alsace and Müller-Thurgau. However, meteorological data for the UK was limited to station data from Kew and Plymouth, not necessarily representative of viticultural production areas. Following on from their work, Kenny & Shao (1992) also compared GDD and LTI, and found that GDD produces a shift south in suitable area of cultivation that would indicate the Champagne region was the most northerly suitable region for viticulture. However, they also noted that grapes were being grown in the UK and concluded that the adjusted LTI gave a more realistic northern limit for viticulture suitability.

More recently Jones (2005) developed one of the most widely used bioclimatic indices, the Growing Season Average Temperature (GST). This simple algorithm calculates average daily mean temperatures summed for the growing season (Northern Hemisphere: April–October). GST is easier to calculate than GDD but is functionally identical (Anderson et al. 2012). Jones (2005) classified cultivar suitability based on observed instances of establishment in several wine producing regions of the world, i.e. the classifications attributed to GST are based on empirical observation. The cultivar climatic-envelopes for these observed instances can be seen in Figure 1.4.

There have been recent attempts to develop indices that provide uniform climatic descriptors of grape-growing regions worldwide. These, such as the Multi-Criteria Classification (MCC) indices developed by Tonietto & Carbonneau (2004), which combines the HI, CI and DI to distinguish 36 different climatic types, provide broad areas of climate classifications incorporating minimum, maximum, and mean air temperature, mean wind speed, solar radiation, sunshine hours and potential evapotranspiration. Although the MCC advances the complexity of thermal-based indices, it is limited by difficulties in obtaining homogenous suitable time series of required data from which to calculate results. It has been used by Blanco-Ward et al. (2007) and Jones et al. (2009) but has not been adopted further. Malheiro et al. (2010) also developed a composite index (CompI) based on the limiting thresholds of three bioclimatic indices: HI (≥ 1200°C), DI (≥ 100 mm), and a Hydrothermic index (HyI: ≥ 5100) which evaluates the potential risk of grapevine exposure to diseases such as downy mildew by integrating precipitation in its definition. It was later amended by Fraga et al. (2012) but again subsequent uptake has been limited.

The value of bioclimatic indices as metrics for cultivar and spatial suitability has been subject to limited critique. The indices discussed above have all been applied in different regions, for different timescales, using different spatial resolutions, and driven by both observed and modelled climate data. Often they are not calculated from high-resolution data and are not applied at scales which resolve the range of climatic processes likely to influence sub-regional climate-agriculture relationships (Jackson & Cherry 1988; White et al. 2006). Furthermore bioclimatic indices are commonly calculated using climate station data from a limited number of stations which seldom depict the spatial variation of climate found within winegrowing regions (Jones et al. 2009). Data interpolation has been used (Moriondo et al. 2011; Jones & Alves 2012) but these use certain assumptions and generate biased predictions. Even when employed using spatially representative and accurate data bioclimatic indices are limited in their evaluation of cultivar suitability as their classification envelopes are restricted to observed occurrence of cultivar establishment within such bands. Under both present and future climate conditions the physiological adaptation potential of grapevine cultivars is not represented through bioclimatic indices (Jones & Storchmann 2001; Webb et al. 2008; Tomasi et al. 2011). Additionally, where conclusions about climate change and viticulture are drawn from bioclimatic indices they do not allow for an illustration of the capacity of viticulture to be adapted to climate changes through vineyard management techniques (Webb et al. 2008).

The lack of homogeneity in data and use of bioclimatic indices makes comparing research results difficult and raises questions about the suitability of their application in both spatial and climate change suitability modelling. They are in essence crude measures of suitability that may mask or overstate true viticulture potential in a specific location. As such, in this work the employment of bioclimatic indices is limited to GST, GDD and the HI, applied in Chapters 3, 4 and 5, with the sole aim of representing spatial and temporal variability of growing season average thermal conditions, as done by Hall & Jones (2010) in Australia. Where they are applied to models of viticulture potential they are used as analogues, and with the assumption that larger bioclimatic values present increased opportunity, where the bottom end of ‘cool-climate’ is being explored.

Other indices such as the Cool Night Index that provides an estimate of ripening stage (Tonietto & Carbonneau 2004), the Latitude Temperature Index (Kenny & Shao 1992), Biologically Effective Degree Days (Gladstones 1992), and multi-parameter or multi-index methods are not employed in this work because their comparative values are limited by less globally available data (Jones et al. 2010).

1.2.3. Mapping viticulture suitability

Bioclimatic indices are often employed as one means of evaluating climatic suitability where the spatial suitability of land for viticulture, under present or future climate conditions, requires analysis. Other variables that help determine spatial suitability include biophysical factors, namely topography, soil and land use, and meteorological and climate phenomena covering precipitation, temperature, temperature extremes, temperature variability, solar radiation, and wind exposure. These two latter meteorological variables are likely to have a physiological effect on grape vines but are rarely considered in climatic suitability evaluations (Jones & Davis 2000a).

Viticulture – climate studies to-date (see Section 1.2.5), which have concentrated on the impact of future climate change on the spatial distribution of viticulture, have examined primarily the potential for viticulture dispersion in relation only to climate. That is to say they have examined where may be climatically suitable under a range of future conditions. Yet doing so only presents part of the picture. Viticulture is not only reliant on suitable climatic conditions, but also on establishment in appropriate biophysical locations. Elevation, aspect, slope, land cover, and soil characteristics are important factors when considering suitability and all require alignment before spatial suitability can be determined. In other words just because somewhere is climatically 'suitable' for viticulture does not automatically indicate it is appropriate for commercial viticulture. In this thesis efforts have been made to address this critical issue by combining both climatic and biophysical data into a viticulture suitability map for England and Wales. To do so the suitability parameters of biophysical and climatic variables need to be known. These are summarised here with parameters employed in mapping viticulture suitability in England and Wales presented in Chapter 2, along with the datasets employed and methods of integrating them into a suitability model.

Soil

Soil texture, its porosity and permeability, has a major impact on vine nutrient and water availability, which in turn influences vine growth (van-Leeuwen et al. 2004; Field et al. 2009). As such it has been chosen as a suitability indicator in several studies (Leeuwen et al. 2004; Field et al. 2009; Fraga et al. 2014), including this one. Very small particles that make up clay soils lead to poor drainage but facilitate good water holding capacity and can favour vine root development, whereas sandy soils are coarse and well drained with low water retention capacity (De Andrés-De Prado et al. 2007). Loamy soils have relatively even proportions between particles and are typically well drained with sufficient nutrient retention for viticulture. The ability of a soil to drain is a major attribute required for viticulture in all climates (Lanyon et al. 2004), well drained soils generally warm up quicker (temperature affects the size and function of the root system) and induce lower levels of humidity, reducing the risk of mildews and other disease pressures (Lanyon et al. 2004; Davenport & Stevens 2006). Furthermore, well drained soils are also likely to support better accessibility to machinery. On the other hand, too little water availability can lead to excessive vine water deficit stress that negatively affects growth, and can lead to soil cracking and wind erosion that negatively affect soil structure. Soil pH is one of the most important determinants of soil fertility through its influence on the solubility of metal ions e.g. nitrogen, calcium, magnesium, iron, manganese, copper and zinc, its effect on the supply of nutrient cations and anions, and its influence on microbes present in soil (Riches et al. 2013). Grape cultivars and rootstocks vary in their tolerance to very acid soils (Himelrick 1991) but in general vines do not perform well when soil pH is <5.0–5.5 due to stunted shoot and root growth attributable to increased concentrations of exchangeable aluminium (Lanyon et al. 2004). With soils >8.0 pH, availability of metal ions is reduced (Lanyon et al. 2004). These high soil pH values are also associated with boron toxicity and elevated concentrations of very fine carbonates that can cause severe lime-induced chlorosis (iron deficiency) (Lanyon et al. 2004). It is generally accepted that soil pH should be between 5.5–8.0 for optimum vine growth and soil microbial composition (Cass & Maschmedt 1998; Lanyon et al. 2004; Jones et al. 2004; Riches et al. 2013). The cycling of soil organic matter is important because of its association with nutrients (Nitrogen, Phosphorus and Sulphur) and the beneficial contributions that it makes to soil chemical, physical and biological properties (Lanyon et al. 2004). However, threshold values for organic matter content are very limited and it is difficult to generalise what organic matter levels are adequate for viticultural soils (White 2010). In grapevines, nutrient and water uptake occur mostly within the 0.5–1.0m soil profile and compact and shallow soils can limit root growth by obstructing access to oxygen, water and nutrients (Jackson & Lombard 1993).

Elevation

Elevation suitability for viticulture is restricted by decreasing temperatures at higher altitudes and a greater potential for wind exposure where surrounding terrain does not afford shelter (Gladstones 1992). Cooler temperatures can reduce vine growth and retard maturation (Jones & Hellman 2002). Cooler temperatures can also increase air frost risk where adequate cold air drainage is not available. In marginal climates such as England and Wales decreasing temperatures and wind exposure at higher elevations could significantly affect production (see Section 2.4.4).

Aspect

At higher latitudes (in the Northern Hemisphere) south facing slopes have greater direct solar radiation gain potential (Coombe & Dry 2004; Jackson 2014) due to their reduced angle of incidence (the angle between the sun's beam and an imaginary line perpendicular to the slope), particularly during the ripening period when the sun is higher in the sky, and are deemed favourable for vineyards (Skelton

2014). They are also conducive to reducing the lag phase during which a site heats up and dries out after a cold night (Jackson 2014).

Slope

The angle of slope also affects the quantity of diffuse radiation but ideal slopes for viticulture are considered to be 5–15% and within this range angle was considered unlikely to have any significant effect on diffuse radiation capture (Jones 2004). The potential for mechanical vineyard-management activity becomes limited on slopes above 10% (Jackson 2014) and erosion risk increases, below 1% there is an increased risk of cold air accumulation and potential frost damage.

Landcover

Existing landcover of potential vineyards can provide an indication of viticulture suitability, i.e. if the land is already used for arable production or horticulture there is an indication that it could possess suitable attributes. Alternatively if the land was dedicated to urban development or encompassed water features it is unlikely to represent such opportunity. In this thesis an attempt was made to delimit potential biophysically suitable areas to those already classified as arable, horticulture or grassland (see Section 2.4.4).

Defining and integrating these different variables into a modelled approach to assessing suitability is a challenging process dependent upon appropriate data availability and modelling expertise. The potential value of such an approach is that it delivers an accessible suitability model for interpretation and applications in investment, risk, and policy. Perhaps surprisingly, very limited effort has been directed to such work regarding viticulture, globally, and none has been undertaken to help identify present and future opportunities and risks across England and Wales.

Geographic Information Systems (GIS) have been used to map combined biophysical and climatic suitability for viticulture in Romania (Irimia et al. 2011) and Oregon (Jones et al. 2006). In both these cases the suitability assessments were undertaken using a Boolean logic approach, i.e. logical true/false, rule-based approaches that use a series of logical operators and, in some cases weighting factors to discriminate data value and define 'suitability'. However, the intersection operator 'and' can be very restrictive (risk averse) when overlaying multiple datasets because if a single criterion fails to meet its threshold an area is excluded. Conversely with the union operator 'or' there is the risk that an entire area could be chosen as long as a single criterion meets its threshold (Romano et al. 2015). In reality environmental factors that contribute to suitability for viticulture are not discrete but individually and collectively give a range of suitability without 'crisp' boundaries.

Through this work viticulture-suitability modelling is advanced using a wide range of data (Table 2.2) and the application of Fuzzy Logic as a means of demonstrating the range of suitability in England and Wales. Decisions regarding biophysical and climatic suitability in England and Wales cannot be based on regression-based predictions as these require quantitative relationships between variables, and these have not been objectively established. Reliance on expert opinion for the same means can lead to disagreement and subjectivity around critical characteristics, their relative degrees of importance and the weightings that should be applied to them. Compounding these challenges is the imprecision characterising natural resource data (Braimoh et al. 2004) and the need for multi-criteria decision analysis to be integrated into a modelled approach to suitability. To help address these issues the interrogation of spatially representative data can be undertaken using Fuzzy Logic. In a fuzzy set the concept of membership is not definitive because all members have degrees of association between 0 and 1 (Malczewski 2004). Whilst the advent of computerised GIS enables the digital representation of information and permits the representation, manipulation, and display of geographical phenomena, owing to the characteristics of the mapping methodology and uncertainty regarding suitability parameters of the phenomenon being mapped, it is often difficult to be absolutely certain of what is where, and how suitable it is. In set theory the membership of an element in a particular set is defined by a characteristic function. Non-fuzzy classification uses characteristic functions that result in a location being classified as either a member of a set or not. However, percent slope for example, can be calculated in ArcGIS from a Digital Terrain Model, using a characteristic function that says that all locations where the percent slope is between 5 and 10% will be classified as suitable. But, at which value of percent slope specifically does a location go from being suitable to not suitable? The applied characteristic function (or rule) implies that locations with a percent slope of 10.01 are classed as not suitable while locations with 9.99 are. Additionally the rule suggests that there is equal suitability for a slope of 5% as there is for a location with a slope of 10%. This assumption may not reflect reality. This is the fundamental proposition upon which fuzzy set theory is based. In other words, the characteristic function indexes the degree to which a location is a member of a set with larger values denoting higher degrees of set membership. Such a function is referred to as a membership function. The set defined by such a membership function is a fuzzy set.

Fuzzy Logic has been used in land suitability assessments for crops such as maize (Braimoh et al. 2004) and to aid in spatial planning for optimal positioning of technologies such as photovoltaic cells (Charabi & Gastli 2011), but there is no evidence of it having been used in viticulture suitability assessments. Several land evaluation approaches exist, qualitative approaches, parametric or process-based models, but land evaluation procedures focus increasingly on the use of quantitative procedures to enhance the qualitative interpretation of land resource surveys (Braimoh et al. 2004). Where suitability parameters for viticulture are defined and delimited, fuzzy logic therefore presents a valuable tool for integrating data and modelling risk, and is applied in this work.

1.2.4. Observed climate change in viticulture regions

Analysis by Jones et al. (2005) of 27 'high-quality' wine regions worldwide using a 1950–1999 gridded monthly mean temperature data set, from the Global Historical Climatology Network (v2) and station records of monthly and annual mean air temperature, showed that average winter and summer temperatures had increased by 1.26 and 1.38°C respectively, with a greater increase for regions in the northern hemisphere. However, the warming they observed was not uniform across the regions with greater magnitudes in the western U.S. and Europe, than in Chile, South Africa, and Australia. The greatest warming they found was in the Iberian Peninsula, Southern France, and parts of Washington and California, where temperatures had increased >2.5°C. Of the 27 regions they examined 18 also showed an increase in inter-annual growing season temperature variability, with evidence in some regions that night temperatures have increased more than day temperatures, possibly impacting grape quality and phenolic character (Jones 2006). Temperature increase correlated strongly with advanced phenological stages of vine and grape development, and Jones et al. (2005) concluded that grapevine phenology had shown an average of 5–10 days advancement per 1°C of warming. Duchêne & Schneider (2005), Seguin & de Cortazar (2005) and Tomasi et al. (2011) also evidenced recent (30–50 year) increased temperatures leading to earlier and shorter periods between bud-break and harvest for a range of cultivars in Alsace, Bordeaux and Italy respectively. Duchêne & Schneider (2005) found days with mean temperature above 10°C in the Alsace region have increased by more than one day per year during the period 1972–2002. They also found budburst and flowering events occurred about two weeks earlier in 2003 compared to 1965, and that the period between flowering and veraison shrunk by 8 days with veraison occurring almost 23 days earlier. Tomasi et al. (2011) found bud-break was on average 2.9 days earlier and veraison 3.2 days earlier per 1°C increase in temperature; and, flowering, veraison and harvest dates had advanced by 13-19 days over the 1964–2009 period. In Australia Webb et al. (2011) assessed historical trends (25 – 115 years in length) in wine grape maturity dates from vineyards located in geographically diverse viticulture growing regions. A trend to earlier maturity was observed that was statistically significant for 35 of 44 vineyard blocks, for the period 1993–2009. Where earlier maturation and harvest occur the potential for higher alcohol content increases, as does the risks of warmer fruit and potential microbial spoilage (Marangon et al. 2016). Higher alcohol levels may not meet market requirements.

As well as findings concerning average annual and growing season trends in viticulture regions, in warmer areas such as the Douro (Portugal) and California (USA) higher numbers of acute heat stress events and a reduction in cold spells have been observed (Nemani et al. 2001; Jones et al. 2005; Sturman & Quénol 2013). Significantly, Sturman & Quénol (2013) examined recent trends in air temperature in New Zealand vineyard areas since 1941 and found, in Marlborough and other vineyards areas in eastern New Zealand, an increase in temperature range, with both rising maximum temperatures, as found elsewhere, and declining minimum temperatures, not observed in other studies of major vineyard areas. They concluded that these observed changes were closely linked to larger-scale changes in atmospheric circulation via the Southern Annular Mode and Southern Oscillation. Their results show that the impact of global warming can have significant regional variations, particularly over areas of complex terrain such as New Zealand.

These observed changes serve to indicate the impact of recent climate change on established viticulture regions, and the potential risks of further change. Yet, whilst most research to date is concerned with existing and warmer production regions, this thesis is focussed on potential opportunities and risks in new emerging regions, based on both recent change and future scenarios.

1.2.5. Future climate projections for viticulture and wine quality

Climate change predictions and projections for the 21st century may have significant impacts on viticulture and wine quality. Changes in temperature and precipitation patterns may modify spatial suitability (Malheiro et al. 2010), future phenological timings (Webb et al. 2008), and affect both pest and disease pressures, and the chemical composition of grape berries.

There have been numerous studies into projected climate change on viticulture within existing viticulture regions. Early projections of the impact of climate change on viticulture suggested that in Europe growing seasons should lengthen and that precipitation would increase in the north and decrease in the south (Lough et al. 1983). This research also found strong relationships between wine quality (vintage ratings) and climate, indicating that vintage quality, especially in Bordeaux and Champagne, should improve under the simulated future climates. Spatial modelling has indicated potential geographical shifts and/or expansion of viticultural regions with parts of southern Europe becoming too hot to produce high-quality wines and northern regions becoming viable once again (Kenny & Harrison 1992; Fraga et al. 2013a). Other studies of the impacts of climate change on grape growing and wine production reveal greater pest and disease pressure due to milder winters, changes in sea level potentially altering the coastal zone influences on viticultural climates, and the effect that increases in CO_2 might have on grape quality and the texture of oak wood which is used for making wine barrels (Schultz 2000; Tate 2001).

The common approach in these studies has been to use one or more bioclimatic indices to illustrate change in climate as either a linear trend or as a comparator between one to three time periods. Future conditions have been presented from results derived commonly from just one or two climate models and one or two greenhouse gas emission scenarios. Both the spatial and temporal scales of studies vary, as do the bioclimatic indices applied and the meteorological data source, across studies.

The single model and scenario approach to 'modelling' climate change projections for viticulture can be demonstrated through Jones et al. (2005), referred to previously, who employed the Hadley Centre global climate model (HadCM3) and a Special Report on Emissions Scenario (SRES) A2 emissions scenario (Different future SRES scenarios included: rapid economic growth (A1B); regionally oriented economic development (A2); and global environmental sustainability (B1) (Intergovernmental Panel on Climate Change 2007)) for 27 of the world's 'top' wine producing regions. They used the model to compare 1950–1999 and 2000–2049 periods. Using this approach, Jones et al. (2005) showed projected temperature changes and that many wine producing regions may already be at or near their optimum growing season temperatures for high quality wine production, suggesting further temperature increases could be detrimental. Similar findings were made by White et al. (2006), in their focus on the Western United States (US). Using one regional climate model (RegCM3) (~25 km resolution) forced by one SRES scenario A2 they concluded that by the late 21st century premium wine grape production areas in the Western US could decrease by up to 81%. They also concluded that changes in the frequency of extreme temperatures may have greater impact than changes in mean climate. Critically, in neither case was the relationship between climatic conditions and wine 'quality' considered.

Using three emissions scenarios and the CSIRO MK3.0 GCM for 2030, 2050 and 2070, Hall & Jones (2008) compared projected future conditions in Australia with 1971–2000 daily mean temperatures extracted from 238 meteorological stations and interpolated over winegrape growing areas. They found an average projected temperature increase, across all three emissions scenarios, of 0.9^{o}C by 2030, 1.6^{o}C by 2050 and 2.3^{o}C by 2070, and concluded that by 2070 there could be large parts of Australia inappropriate for viticulture. In 2012 Jones et al. also used three SRES scenarios (B2, A1B and B2), to drive the HadCM3 climate model to project future climate possibilities within the Douro region of Portugal, for 2020, 2050 and 2080, from a 1950–2000 climate period derived from the 'WorldClim' global database developed by Hijmans et al. (2005). The WorldClim database was created through weather station data interpolated using a thin-plate smoothing spline algorithm implemented in the ANUSPLIN package, using latitude, longitude, and elevation as independent variables. The station data is interpolated to a 30 arc second spatial resolution; which is equivalent to about 0.86 km^2 at the equator and less elsewhere, but is close to 1 km in a mid-latitude area. The resulting high-resolution gridded data set provides monthly maximum temperatures, minimum temperatures, and precipitation for 1950–2000, representing the highest resolution available at the global scale for spatial climate analyses. Projected temperature changes ranged from 0.5–1.4°C by 2020, 1.4–3.3°C by 2050 and 2.1–5.1°C by 2080 which would classify 54% of existing viticultural areas into the 'Very Hot' classification, designated by Jones (2005) (Figure 1.4). Jones et al. (2012) projected a decrease in precipitation during the growing season of 10–42% by 2080 and projected less rainfall and greater variability in the occurrence of heat waves or intense rainfalls.

The key limitations to these works, further addressed in Section 1.2.6, stem from the methods of deriving a projection from 1–3 emissions scenarios, but for only a single climate model. Doing so prevents any bias or uncertainty associated with the model from being represented. It is also now the case that the emissions scenarios used in these works has been replaced with more up-to-date Representative Concentration Pathways (RCPs) (van Vuuren 2011). When combined with the fact that these works did not assess producers' perceptions of climate change impacts or the adaptive capacity of the wine production process to mitigate heat or rainfall risks, they have only limited value as climate impact assessments.

Within the last five years there has been four pieces of research concerning climate change and viticulture that have adopted a multi-model ensemble approach to consider multiple projections for the potential distribution of viticulture under climate change scenarios.

Santos et al. (2012a) used a multi-model (16 simulations from transient model experiments) Global Climate Model/Regional Climate Model (RCM)) ensemble to examine the Douro region of Portugal to assess potential impacts of future climate change. Yet in this case they only applied the A1B scenario (now replaced). They used model output statistics to fit the RCM data to observational data, thus calibrating their model. Their model ensemble demonstrated that springtime warming may lead to earlier budburst under a future warmer climate, which may affect wine quality. The authors in this study recognised the novelty in viticulture – climate modelling that applying large multi-model GCM/RCM ensemble with calibrated data delivered.

Webb et al. (2013) compared current and future climate among key global wine producing regions using an ensemble of 23 climate models, using a process known as pattern scaling (see Section 1.2.7) . Along with Fraga et al. (2013a) for Portugal and subsequently for Europe (Fraga et al. 2013b), the work by

Webb et al. (2013) perhaps provides one of the more interesting approaches to modelling future viticulture – climate change. Not only do they capture uncertainty by incorporating model ensembles (23 GCM's), they also calculated climatology comparisons (temperature and precipitation) for the global warming equivalents of ∼1°C, ∼2°C and ∼3°C from a 1980–1999 baseline period (CRU TS 3.10.01: Mitchell & Jones (2005)) for growing season months using time slices and emission scenarios: 2030A1B, 2070A1B and 2070A1FI. These scenarios have now been superseded (Intergovernmental Panel on Climate Change 2013b). Their presentation of future climatologies uses output from all 23 Coupled Model Intercomparison Project Phase 3 project (CMIP3) climate models (Meehl et al. 2007). Within the work they also evaluated inter-annual variability, estimated from the standard deviation of inter-annual variability in the baseline period. This more involved and complex approach allowed them to demonstrate uncertainty within models and across a range of climatic variables relevant to viticulture, and incorporate dynamics, such as variability that is likely to affect yield and potentially quality. They found warming projected for all regions, greater in Northern Hemisphere continental regions and lower for Southern Hemisphere and coastal regions. Projections of annual precipitation varied, with the median result from models indicating a wetter climate for higher latitude regions, such as New Zealand, Mosel Valley and North Oregon and Shandong in China, while Southern European, Australian and South African winegrowing regions had a projected drier climate. Yet, notwithstanding the value that using model ensembles brought to this work, the authors themselves recognise limitations in spatial resolution. Their modelled projections were at a scale of 200–400km resolution and therefore provided a coarse estimate of regional impacts.

Fraga et al. (2013a) used a slightly smaller 16-member ensemble of model transient experiments (conducted with coupled atmosphere-ocean models (AOGCMs), which link, dynamically, detailed models of the ocean with those of the atmosphere), generated by the ENSEMBLES project, under single GHG emission scenario (A1B) and for two future periods (2011–2040 and 2041–2070) to assess climate change projections for six bioclimatic indices. Over southern Europe, they concluded a projected warming combined with severe dryness during the growing season with expected detrimental impacts on grapevine development and wine quality. Over central Europe they found an expected warming and the maintenance of moderately wet growing seasons over most of central Europe. They also concluded that new winemaking regions may develop over northern Europe and higher altitude areas. Lastly they projected an enhanced inter-annual variability over most of Europe.

Another more recent study that deviated from the norm of applying only bioclimatic indices to illustrate modelled change under climate change projections was reported by Hannah et al. (2013). They used 1971–2000 WorldClim data (at 1 km resolution) to assess recent viticulture suitability and 2041–2060 projections for future suitability driven by 17 global climate models (GCMs), downscaled from CMIP5, under two Representative Concentration Pathways (RCPs). This was the first viticulture – climate study to employ the RCPs used in the IPCC AR5. Interestingly, rather than just employing bioclimatic indices to model potential global changes in climatic suitability for viticulture (and impacts on terrestrial and freshwater ecosystem conservation) they used the consensus of multiple wine grape suitability models representing a range of modelling approaches. They combined GST (to assess temperature) and GDD (to determine ripening time), with a Maximum Entropy (MaxEnt) climate – distribution model (also known as species distribution model, niche model, or bioclimatic envelope model). The MaxEnt climate distribution model takes as input a set of layers or environmental variables (e.g., elevation, precipitation), as well as a set of occurrence locations, and produces a model of climatic suitability for a species, in this case *Vitis vinifera* L. Occurrence points (N = 1,129) for viticulture were derived from a georeferenced global dataset of viticulture sites. Here it should be noted that as part of this thesis the data set of occurrence points was examined and interestingly no vineyards in England or Wales were found. This suggests that it was not fully representative of global viticulture distribution. The bioclimatic predictor variables used in their MaxEnt models included; total precipitation in growing season; precipitation seasonality (coefficient of variation); mean maximum temperature of the warmest month during the growing season; and, mean diurnal range (mean monthly maximum − minimum).

Through these multiple techniques Hannah et al. (2013) concluded that suitability is projected to decline in many traditional wine-producing regions (e.g., the Bordeaux and Rhône valley regions in France and Tuscany in Italy) and increase in more northern regions in North America and Europe, under RCP 8.5 and RCP 4.5. Current suitability was projected to be retained in smaller areas of current wine-producing regions, especially at upper elevations and in coastal areas. They identified a potential 25-74% decrease in existing viticultural areas by 2050, depending on emission scenarios used.

However, projected changes by Hannah et al. (2013) were based on the climate – suitability index compiled from grapevine maturity groupings as defined by Jones et al. (2005) (see Figure 1.4). These groupings were constructed from empirical observations collected in premium winegrowing areas and are not based on grapevine physiological modelling. It is therefore very difficult to establish precise upper limits of suitability, by cultivar.

A more recent viticulture – climate study, regarding the future of wine grape growing regions in Europe, also employed a MaxEnt approach. Tóth & Végvári (2015) used HadCM3 and Commonwealth Scientific and Industrial Research Organization MK3 (CSIRO MK3) climate models to obtain potential changes in climatic suitability for growing wine grapes. Each of these models was constrained with SRES scenarios

A1B, A2, and B1. They used a suite of over 20 climatic indices which indicated a loss of suitable land area in Portugal, Spain, France and Italy, and a shift in viticulture suitability, northward. The projected range until 2050 was found to be dynamic, implying that adaptations such as changing of grape cultivar and selection or modification of grapevine management could be necessary, even in regions which remain suitable in the future. Most interestingly, with relevance to the area of study this thesis is concerned with: England and Wales, results presented by Tóth & Végvári (2015) stated that nearly all of the south-east and south-central England were not currently suitable for viticulture but may become so under all three emission scenarios, by 2050. Yet, as illustrated in Section 3.1 – Figure 3.2, these areas currently dominate wine grape production. Furthermore, other areas in England and Wales, in which vineyards currently exist, were not shown to become suitable under the scenarios examined by 2080. These factors cast some doubt on the credibility of their findings.

Here, as with Hannah et al. (2013), the database of current viticulture locations, used to drive the MaxEnt modelling process (CORINE Land Cover database), did not include existing viticulture locations in England or Wales. As such this work, and others that have employed a similar approach, for example Moriondo et al. (2013), may not provide results that are entirely representative of environmental suitability. The MaxEnt process is based on the assumption that the data entered, on which the model is calibrated, provides a full sample of species distribution, in order that it can fully elucidate spatial suitability under different conditions. Furthermore it embraces the inherent assumption that species are optimally distributed (i.e. in the best place) and that their current positioning range is representative of their climatic envelope. Finally, it is noted that MaxEnt processes do not automatically assume that adaptive capacity can be provided, in this case for viticulture – climate suitability, through intervention.

Other works aimed at assessing future climate conditions under different scenarios and for different locations have been undertaken but they have had the same model and scenario limitations. Additionally, research has been restricted by model spatial dimensions, for example, Fraga et al. (2014a) used the commonly applied E-OBS data at ~27km resolution, or by temporal data restrictions, for example the use of the WorldClim data by Jones et al. (2009), that is only available to 2000. As observed by Bonnardot et al. (2012) spatial variability within short distances (in this case observed in the Stellenbosch viticulture region of South Africa) emphasizes the difficulty of validating outputs of atmospheric modelling with accuracy. Bonnardot et al. (2012) showed the importance and relevance of increasing resolution to refine studies on climate spatial variability and to perform climate modelling based on distinguished weather types. These limitations contribute to results that are not necessarily representative of vineyard areas or recent conditions. Whilst they have value as indicators of spatial and temporal change, for those looking to identify local vineyard impacts or opportunities higher resolution and more contemporary data sets would provide greater benefit.

All the projections made to date indicate changes in viticultural regions, driven in particular by thermal shifts, but none of these studies have explicitly investigated new or emerging regions and whether the *prima facie* benefits of warming for 'traditionally' cold or cool-climate areas, with regards to viticulture, have been evidenced. Whilst migration is presented as an adaptation possibility for hotter regions, the issue of exactly where to migrate to has not been explored in work on future climate change impacts. To do so requires an assessment of biophysical as well as climatic potential. These works are also limited in a critical way. They predominantly assess projections about changes, particularly to temperature, in 30–50 year future periods, and at local or macro-scales. In other words they represent analysis of potential changes with coarse resolution and over an average of many decades. The value to wine producers, or those looking to invest in viticulture, and who are concerned more with near-future localised change (Section 1.2.1) is therefore questionable. Where producers are concerned with more imminent weather or seasonal local conditions – as found through adaptation studies – it is likely that this relates to both their focus on yield and also on grape and subsequent wine quality. Climate change impacts on wine quality have surprisingly received little attention (Jones & Davis 2000a; Jones et al. 2005; White et al. 2006). However, along with viability and yield, grape berry and subsequent wine quality, it could be presumed, would be the very impact assessment that wine producers and investors would value most. Furthermore, as previously commented on, none of these works took into consideration adaptive capacity or an evaluation of producers' perceptions of threats and opportunities.

Where relationships between climatic variables and wine prices have been made (Jones & Storchmann 2001) these have been founded on the hypothesis that beneficial climatic conditions will improve a wine's quality and, therefore, lead to higher prices in the short-run. However, as noted by Jones (2005) long-term consistent price data for multiple regions and wine types over many years is not readily available. Vintage ratings, on the other hand, are. These can be easily obtained for many wine styles, regions, and years and are a strong determinant of the annual economic success of a wine region. For example, while Jones & Storchmann (2001) found that vintage ratings are not necessarily efficient predictors of the prices of Bordeaux wines, they determined that vintage ratings do reflect qualitatively the same weather factors that have been documented to be determinants of wine quality. Furthermore, while numerous rating systems, compiled over various time periods and by various sources exist (see Sections 2.5.1 and 2.52), correlations between the various sources have been found to be strong ($r > 0.9$), indicating that this subjective measure of quality is a good quantitative representation of a vintage (Jones & Goodrich 2008).

Viticulture productivity and wine-grape quality can be impacted by changes to medium to long-term conditions that are cumulative in their effect, or by shorter term acute events. Few studies have looked at incidences or trends of acute weather impacts, intra and inter-annual variability, their relationship with climate-change, and localised environmental conditions. In fact the application of bioclimatic indices and length of time-periods explored in existing work effectively filters out localised extreme events. This is despite evidenced concerns about increases in the magnitude and frequency of extreme events (Easterling et al. 2000). In this thesis the majority of work is targeted at understanding more localised impacts of change, in both acute and chronic conditions and changes. It is ultimately the local effects of climate change that are going to drive producer action, and in such studies temporal and spatial resolution is critical to elucidating impacts.

Wine style, and specifically wine quality of a particular style, is what wine producing regions are commonly recognised for (Jones & Davis 2000a). Jones and Davis (2000a) undertook a study of relationships between four climatic variables (precipitation, sunshine hours, days with temperatures above 30°C and water deficits) and wine quality in the Bordeaux region of France covering the 1952–1997 period. Overall the research found that the earlier the phenological events occurred, the higher the vintage rating, which was linked to higher total sugar and acid ratios. The composition and quality trends found by Jones and Davis (2000a) were mostly described by increases in the number of warm days during flowering and veraison (see Figure 1.3), and a reduction in precipitation during maturation. Grifoni et al. (2006) undertook similar research in northern Italy and found a positive correlation between air temperature and wine quality, i.e. wines of the highest quality were produced during warmer years. They also found that rainfall had an inverse relationship with wine quality. In some locations strict rules govern cultivar establishment, viticulture practices and wine 'type'. One such region is Champagne, where Chardonnay, Pinot noir and Pinot meunier dominate the landscape (Comité Champagne 2016), as they form the key cultivars used in the production of Champagne. Were the meteorological conditions in which these cultivars are grown to change beyond those of 'accepted' vintage variability, it is likely that wine style, or/and quality could be affected. Champagne presents a good case study of weather and climate impacts on wine quality as only in the 'finest' years is a vintage declared by producers. Where a vintage is declared it can be assumed that the meteorological conditions that contributed to it were favourable.

This presents an opportunity to examine how, under climate change scenarios, the conditions that lead to these vintage years may change. Specifically, how likely they are to be repeated in the future. And, perhaps even more relevant to this thesis, what the temporal outlook for the likelihood of those conditions occurring in England and Wales are; after all the two dominant cultivars grown in England are the same as those in the Champagne region. Here, therefore, this thesis, in Chapter 6 shifts its attention from purely one of viticulture suitability, to both suitability and wine quality dimensions; albeit under probabilistic future conditions. An assessment of both provides a more complete picture of the effects of climate change on the emerging wine sector in England and Wales and helps to better elucidate future threats and opportunities, as well as those previously explored, for current times.

1.2.6. Understanding climate change modelling and uncertainty

Predictions (the result of an attempt to produce an estimate of the actual evolution of the climate in the future – usually probabilistic) and projections (the response of the climate system to forcing scenarios) (Intergovernmental Panel on Climate Change 2007) of future climates are produced through models based on how the climate system works. These models are complex mathematical and physics based representations of how the earth and atmosphere systems interact, represented through spatial and temporal analysis of the laws of energy, mass, moisture, and momentum.

Although many important studies of temperature change on different wine regions of the world (Jones 2005), and more recently Europe (Moriondo et al. 2013), examined trends using only one GCM, for example: HadCM3, different GCMs produce regionally varying responses resulting in a range of plausible future climates (Watterson 2008). Varying responses could stem from model biases or uncertainties. Climate models can exhibit systematic errors (biases) in their output, which can be due, among others, to: limited spatial resolution (horizontal and vertical); simplified physics and thermodynamic processes; numerical schemes; and, incomplete knowledge of climate system processes. It is assumed that the bias behaviour of the model does not change with time and where model biases are systemic bias corrections can be employed to adjust them to those of observed data using methods such as the delta change approach, multiple linear regression, analogue methods, local intensity scaling, or quantile mapping (Faloon et al. 2014). Biases can also be reduced through improved parametrizations and approaches to defining initial condition uncertainties, using ensemble data assimilation (Slingo & Palmer 2011). Sources of model uncertainties range from future GHG emission uncertainty, the relative role of natural forcings, model structural differences, model parameters and resolution/bias correction, and model internal variabilities (Mitchell 2003; Osborn et al. 2013). Projections of climate change impacts require a comprehensive understanding of uncertainties which can be inferred from variation between model results (Katz et al. 2013). Where only a single GCM is employed in future climate change assessments the range of uncertainty is not represented but model intercomparison projects (MIPs) and multi-member model ensembles, as used by Webb et al. (2013) and Fraga et al. (2013a), can be used to assess them (Taylor et al. 2012).

Climate change and impact assessments treat uncertainty in quantitative terms and describe the range of possibilities and likelihood of their occurrence to give the end user a more informed impact probability distribution. However, whilst adopting a probabilistic approach may present opportunity for accommodating uncertainty it does not resolve the computational expense or time of running GCMs with multiple simulations of possible futures.

Compounding issues associated with 'simplistic' modelling approaches in the majority of viticulture – climate impact work is that whilst future global climate change can be simulated using GCMs, they do not necessarily resolve region-specific, season-specific, and variable-specific changes needed for climate and applications (Mitchell 2001). This is primarily related to the coarser spatial resolution that limits the GCMs' ability to capture regional forcings, such as orography, that play an important role in characterizing regional climate features. Commonly therefore a process of statistical or dynamical downscaling is undertaken to present localised impacts (Quénol & Bonnardot 2014).

Dynamical downscaling requires running high-resolution climate models on a regional sub-domain, using observational data or lower-resolution climate model output as a boundary condition. The individual variables are physically consistent in time and space, and the different variables are internally consistent. These models use the same fundamental physical principles in both the RCM and GCM to reproduce local climates. The main limitations of dynamical downscaling are whilst removing much of the GCM bias related to the coarse resolution, an RCM also adds its own biases to the output data, near the boundary of the RCM domain artefacts and spurious effects occur, and dynamical downscaling is computationally intensive.

Statistical downscaling achieves similar goals by deriving empirical relationships between the observed surface climate and global climate model outputs. Statistical downscaling is a two-step process consisting of i) the development of statistical relationships between local climate variables (e.g., surface air temperature and precipitation) and large-scale predictors (e.g., pressure fields), and ii) the application of such relationships to the output of global climate model experiments to simulate local climate characteristics in the future (Wilby & Wigley 1997). Statistical downscaling is sometimes equated with bias correction, a key strength of the process. There are many different statistical downscaling methods available, allowing for substantial flexibility but one of the key limitations of statistical downscaling is that the approach requires/assumes a stationary statistical relationship, i.e. the relationship must remain constant under climate change. While dynamical downscaling requires high frequency GCM outputs and large computing resources, statistical downscaling is computationally efficient although it demands good quality and high spatial resolution observation data over long periods, and corresponding historical global climate simulation to develop the empirical relationships (Herger et al. 2015).

Computational costs relating to dynamic downscaling and lack of high spatial resolution observational data in vineyard environments have resulted in comparatively few downscaled simulations of future viticulture climate scenarios. Without ability to carry out a very large number of simulations to estimate future climate, it becomes difficult to assess the uncertainties in those estimates (Mitchell 2001). The response of many, as evidenced through viticulture and future climate research, has been to ignore model uncertainties and remain constrained to applying one model for a limited number of emission scenarios (see Section 1.2.5). Doing so results in a presentation of only a single estimate of future regional conditions.

In this work we employ a technique, previously used by Webb et al (2013) to bridge this gap. The technique is called pattern-scaling and is described further in Section 1.2.7.

Climate change models have in the past been driven by one or more SRES scenarios (see Section 1.2.5), as used in the Third and Fourth IPCC Assessment Reports (2001 and 2007), to make projections of possible future climate change. The scenarios make different assumptions for future GHG emissions, demographic, social, economic, technological, and environmental developments and the IPCC did not state that any of the SRES scenarios were more likely to occur than others. However, the SRES scenarios do not take into account current or future measures to limit GHG emissions. More commonly used now are Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011), the scenarios for climate change research that constitute the basis of the IPCC Fifth Assessment Report (AR5), of GHG concentrations emitted by humans in the future as described in Section 1.1.2.

Grapevine phenology varies from region to region and cultivar to cultivar (Smart & Dry 1980) so the impact that projected shifts in phenological timing will have on viticulture could therefore be potentially positive or negative depending on the present climate of the region, and only close examination of localised conditions, now and for the future will improve understanding of potential climate change impacts.

1.2.7. Pattern scaling and climate change model ensembles

Within the framework of RCPs pattern scaling is considered as a tool to generate climate projections not directly simulated by global climate models (GCMs) (Lopez et al. 2014). The pattern scaling technique was first introduced by Santer et al. (1990) with the goal of representing the geographical, seasonal or/and multi-variable structure of patterns, derived from a GCM, as a time-invariant [never changing] response to radiative forcing. Pattern scaling offers a means of addressing uncertainty through handling a large number of climate models in a more rapid and computationally feasible way than dynamical downscaling, and does not require long periods of high spatial resolution observation data needed to undertake a statistical downscaling approach.

Pattern scaling is an attempt to estimate the anomaly in a variable for a particular grid-box, month or season, and year or period that would be obtained if a GCM was forced under a selected forcing scenario. The patterns are then scaled, typically by a global-mean temperature change (ΔT), simulated by GCMs (Mitchell 2001; Osborn et al. 2015) and the estimate is the product of the scaler and the 'response pattern'. This is illustrated in SI Figure 1. For any given global-mean temperature rise, the climate change for a given calendar month and climate variable can be estimated by:

$$\Delta \boldsymbol{V} = \boldsymbol{a} \Delta T \tag{1}$$

where $\boldsymbol{a}$ is the normalised pattern for that month and variable from a selected GCM, and $\Delta \boldsymbol{V}$ is the field of climate change obtained (Osborn et al. 2015).

The response may be obtained from a GCM experiment with the same, or a different forcing scenario (Mitchell 2003). The result is region specific, season-specific, and variable-specific changes for the full range of possible future radiative forcings. Biases in a GCM's simulation of present-day climate are typically ignored by using only the climate change pattern, and applying this to an observed present-day climatology (Osborn et al. 2015).

Where monthly or a higher temporal resolution sequence of weather is required that comprises of climate change added to the initial climate field (V_0) and/or a sequence of anomalies from the mean climate, ClimGen software can be used (Osborn et al. 2015). ClimGen obtains a sequence from a monthly resolution observed climate dataset. Observed records in this case have the advantage that they contain realistic spatio-temporal structures on large scales (e.g. those associated with major modes of climate variability), which may be poorly represented using alternatives such as weather generators or direct (even bias-corrected) GCM output (Osborn et al. 2015).

A future sequence of monthly 'weather' under a changed climate can be generated according to SI Figure 2:

$$\boldsymbol{V_t} = \boldsymbol{V_0} + \boldsymbol{V'_t} + \boldsymbol{a}\Delta T_t \qquad (2)$$

where $\boldsymbol{V'_t}$ is the field of observed anomalies in year t for the given month. ΔT_t is now a global-mean temperature change specific to year t; thus it can represent a transient time series of warming, or if all values are equal it can be used to generate a sequence of unforced monthly climate variability representative of climate under a specific level of global warming.

The technique relies on the assumption that the anthropogenic climate change signal at any region and/or any time horizon, referred to as the response pattern, is linearly related with the global temperature change at the corresponding scenario and period (Cabré et al. 2010). The spatial pattern of change is also assumed to remain constant at any time horizon or forcing scenario (Mitchell 2003), for example a warming pattern for 4°C global warming is the same as for 2°C, but twice as big. An additional assumption, inherent in the pattern scaling technique, is that responses to external forcing and internal variability are independent, implying that anthropogenic forcings do not modify the internal variability of the climate system. As such internal variability is assumed to be constant and is not scaled. Whilst it could be considered unlikely that external forcing won't modify internal variability (Lopez et al. 2014; Osborn et al. 2015), it could also be argued that GCMs themselves may not be good predictors of variability in a highly nonlinear system. Pattern scaling assessments by Mitchell (2003) found that statistically significant non-linearities could be identified with careful use of ensembles of simulations, but that the errors resulting from using pattern scaling were small compared with other uncertainties that exist in future climate scenarios.

Pattern scaling has been used in multiple regional impact studies. Cabré et al. (2010) assessed the 'validity' of the pattern scaling technique in creating regional climate change scenarios for mean temperature and precipitation over southern South America for the 2020s and 2050s. Their results suggest that pattern scaling worked well for estimating mean temperature changes but that the validity of the scalability assumption for precipitation was weaker. Whilst the regional mean temperature changes were linearly related to global mean temperature changes they found the errors of estimating precipitation changes were comparable to those inherent in the regional model (fifth-generation Pennsylvania-State University-NCAR non-hydrostatic Mesoscale Model), and to the projected changes themselves. They attributed this to the large inter-decadal variability evidenced in regional precipitation. In order to avoid this limitation, instead of scaling 10-year means, they recommended scaling 30-year means to reduce the error. They concluded that, when the cost of performing a regional climate simulation was considered, the pattern scaling technique was a good approach to estimating regional scenarios of climate change for temperature, and to a lesser extent for precipitation.

Webb et al. (2013) employed a pattern scaling approach to modelling future climate analogues (2030 and 2070) of temperature and precipitation for 23 wine producing regions worldwide. Comparisons for the global warming equivalents of 1, 2, and 3°C were taken from simulations of 23 CMIP3 GCMs. They multiplied regional changes per degree of global warming by global warming estimates for a given future period to obtain the projected regional climate. Their work was limited to seasonal (summer and winter) and annual projections. Unlike in this thesis (Section 6.4) monthly projections were not calculated separately from the GCMs. Their projections were presented at a resolution of 200–400 km. Within their work they did not comment on limitations of the pattern scaling approach to projecting future climate conditions. Webb et al. (2013) was the only study regarding climate change and viticulture that was found to have employed a pattern scaling method.

More recently Osborn et al. (2015) assessed a new approach to incorporating changes in the inter-annual variability of monthly precipitation, simulated by climate models, into the pattern scaling technique. They diagnosed simulated changes in the shape of the gamma distribution of monthly precipitation totals and applied the pattern-scaling approach to estimate changes in the shape parameter under a future scenario. They then perturbed sequences of observed precipitation anomalies so that their distribution changes according to the projected change in the shape parameter. Their approach cannot represent changes to the structure of climate time series (e.g. changed autocorrelation or teleconnection patterns), but was shown to be more successful at representing changes in low precipitation extremes than previous pattern-scaling methods. The new developments by Osborn et al. (2015) were implemented into the ClimGen software (see Section 2.5.6) to generate pattern-scaled climate projections. The software is used within this thesis (Section 2.5).

However, the pattern scaling technique has not always been found to be fit for purpose. Lopez et al. (2014) applied pattern scaling to quantify the risk of heat waves in Southern Europe and compared model output with the original ensemble model runs they were derived from. They concluded that the assumptions that local climate responses to changes in external forcing are linear functions of the induced global mean temperature changes, that model simulated changes are not affected strongly by errors in the base climate and, that the external forcings do not modify the internal variability of the climate system, resulted in errors large enough to mislead adaptation decisions. Lopez et al. (2014) noted, referencing the snow-albedo feedback at high latitudes that at regional/local spatial scales processes other than radiative transfer are important in determining local climate, and that when non-linear physical processes are invoked, models with significant biases cannot be expected to reliably simulate plausible future changes in climate. Lopez et al. (2014) also noted that external forcings can change the mean response of the natural internal variability of the climate system, giving the example of the significant contribution of El-Niño Southern Oscillation to related variations in the observed long term warming trends over the oceans. In conclusion Lopez et al. (2014) recognise that deploying the pattern scaling approach is a computationally convenient way to generate scenarios of climate change but its use in modelling impacts, adaptation and vulnerability is problematic in some cases. They reinforce the necessity of clearly evaluating the consistency of the method before embarking on particular analyses that can otherwise end up with misleading information.

Osborn et al. (2015) also recommended additional assessments of the performance and limitations of the pattern-scaling approach but noted that Lopez et al. (2014) found reasonable agreement for the frequency of hot summers in 30-year sequences but poor agreement when using 10-year sequences with only one realisation of climate variability. Osborn et al. (2015) pointed to changing variability of global precipitation and the ability to generate multiple realisations of variability as an advantage of the pattern scaling approach, that they felt addressed this particular concern. Osborn et al. (2015) went on to demonstrate that the uncertainty in their approximation was less than the inter-model differences for the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012) ensemble, and that their uncertainty estimate was conservative, because internal climate variability contaminates the estimated patterns of climate change and thus enhances the difference between patterns diagnosed from separate GCM simulations, and because pattern scaling performance can appear poor where the CMIP5 ensemble spread is narrow. Osborn et al. (2015) concluded that pattern scaling remains an important technique for generating projections, especially for probabilistic approaches to dealing with uncertainty.

By employing several GHG emission scenarios, combined with varying climate sensitivities (a measure of by how much the climate will warm for a given increase in climate forcing), a range of possible future climate projections can be analysed using the pattern scaling technique. Using the technique this thesis incorporates the spatial variability of projected climate change and quantitatively reports how impacts of temperature and precipitation may affect spatial suitability and wine quality in England and Wales.

The pattern scaling tools employed in this work are further discussed in Section 2.5.6.

1.3. Summary and research aims

The scientific community is in overwhelming agreement on key aspects of climate change, namely that global warming is occurring and can be attributed in-part to mankind, and that the earth will experience further warming, potentially up to 4^{o}C above a 1986–2005 baseline by the end of the current century (Intergovernmental Panel on Climate Change 2014).

Commercial growing of *Vitis vinifera* L. for wine production is largely controlled by atmospheric forcing, since wine 'type', yield and quality are strongly dependent on weather conditions, mainly during the growing season (Jones & Davis 2000a; Malheiro et al. 2010). There has been a focus, in viticulture – climate research, on applying aggregated bioclimatic indices to evaluate climatic 'suitability' now and under a range of projected climate change scenarios. However, where there are strong seasonal contrasts in climate (i.e. the mid-latitudes) the atmospheric conditions on a day-to-day basis regulate phenological responses that ultimately determine final yield and quality (Jones & Davis 2000b). Therefore in this thesis intra-annual growing-season conditions and variability are examined more closely for England and Wales, as these are likely to better elucidate threats and opportunities for viticulture. Numerous studies support the fact that warmer temperatures are affecting viticultural processes, providing opportunities for quality improvement, cultivar adaptation and improved wine quality in some areas; and, providing threats in the form of uneven phenological events, decreased quality, and crop losses in others. Most future climate change – viticulture impact studies have spatial, temporal, data and model limitations, addressed in Sections 1.2.6 and 1.2.7. Notwithstanding these, all indicate significant potential for change over time. Yet, in relation to impact studies that producers or investors can extract decision making value from there are very few studies available, not least because few have aligned current or future climate suitability models with the biophysical landscape that is paramount to commercial viticulture potential. It is a core goal of this thesis to derive value from data analysis for those established or seeking to establish vineyards in England and Wales.

Whilst viticulture migration is touted as a means of adaptation for those at the warm or hot end of current climatic suitability few studies have investigated the 'suitability' of regions to migrate to, or indeed the possible effects of climate change on those regions. Consequently, adaptation through migration is not necessarily a means of reducing risk associated with climate change. This work focusses therefore on evaluating new 'cool-climate' regions, namely England and Wales as possible, time-dependent, migratory hot-spots. Here recent changes in viticulture present a chance to develop a case study of biophysical and climatic threats and opportunities in 'new' regions, whilst also exploring potential for wine quality, as this is both tangible to evaluate and critical to investment decisions.

Through an evaluation of relationships between sparkling wine quality and seasonal growing conditions this thesis presents comparative future potential for England and the Champagne regions.

There is little research into intra- or inter-annual variability or the role of other climatic factors such as precipitation, wind, solar radiation, or extreme weather events with regard to viticulture (Easterling et al. 2000). These phenomena are all potentially influenced by climate change and besides temperature may present challenges for existing and future regions. Although within the scope of this work there is not the opportunity to assess each of these variables in each viticulture region worldwide, using England and Wales as a case study this work will examine recent changes and trends in thermal dynamics, precipitation, extremes and variability, and their relationships with yield. Doing so allows for an illustration of recent changes but also adds value to data incorporated into a suitability model for viticulture in England and Wales, as produced in Chapter 5.

Located between the mid-latitude westerly wind belt on the edge of the Atlantic Ocean and the continental influences of mainland Europe, the UK is sensitive to small changes in the positioning of major atmospheric pressure systems. Therefore, large intra-annual and inter-annual weather variations may impact productivity between years, and impact viticultural viability. Kenny and Harrison (1992) evaluated the frequency of viticulturally suitable or unsuitable years (1951–1980) in Europe and based their work on the premise that the frequency of ‘good’ or ‘bad’ years is more important than average conditions over a 30-year period. Here, it is suggested that, particularly in the UK’s marginal climate (Kenny & Harrison 1992), vulnerability to weather variability is a limiting factor to viticultural viability, at annual or longer timescales. Additionally, we question whether the prima facie opportunities presented by higher latitudes, in this case England and Wales, under warming conditions, according to bioclimatic index values, mask or understate threats from shorter term weather conditions, extreme events and climate variability.

Whilst much of the research into viticulture – climate and climate change relations to date has focussed on observed or modelled trends of both climate and phenology, little research has been guided by or directed towards producer’s perceptions of production risks associated with climate change. When data is combined with producers’ perspectives of climate change impacts then conclusions can be drawn about both climate change effects, sector risk appetite, and adaptation potential – all of which are critical response mechanisms to threats that are otherwise presented as absolute. In this work an attempt has been made to breach the ‘pipeline’ model of scientific research and communication, where scientists work in isolation and then transfer results to potential users; the research has in the first instance been driven by producers’ concerns regarding weather, climate, climate change and viticulture in England and Wales, and through engagement with producers regarding biophysical suitability for viticulture.

Climate change will likely affect the organoleptic character of regional wines, terroir, and the socio-economic conditions within existing wine regions. Whilst viticultural management techniques and strategic business decisions will provide climate change adaptation potential, long-term investments in vineyards will ultimately require risk analysis based on vulnerability to climate variability and change. The goal of this research is to integrate tools and approaches in an interdisciplinary framework to quantify the risks, vulnerability and opportunities associated with climate change for viticulture in England and Wales. In doing so this work should advance understanding and contribute useful knowledge about English and Welsh suitability for viticulture. Furthermore this research adds new evidence for the climate sensitivity of *Vitis vinifera* L. using quantitative measures. It provides a regional scale case study of vine yield responses to weather and climate phenomena and illustrates adaptation potential in viticulture, and from other forms of agriculture to viticulture.

Significantly, this work is only the second viticulture – climate impact study (Webb et al. 2013) to employ a pattern-scaled approach to modelling future climate scenarios, in this case as an ensemble, to project future climate change threats and opportunities for viticulture at both a regional and global scale. To demonstrate climate change impact in a tangible way to producers and investors the pattern-scaled output is directly correlated with recent and future wine quality, as a case-study. It should also be explicitly stated that this is the first work to investigate in detail a range of weather and climate risks to viticulture in the England and Wales.

Much of the work undertaken for this thesis is not embedded in the classical hypo-thetico deductive model of empirical science, but in post-normal science grounded in geography, weather and climate science where system uncertainties can be high and decision stakes increase (Hulme 2011). Collectively this research links top-down climate change model outputs and bottom-up producers' perspectives on climate risks to present an integrated risk modelling exercise for a new viticulture region.

To achieve these goals the following research aims were adopted:

1. To highlight the relationship between weather, climate, climate change and viticulture in England and Wales (Chapter 3) by:
    a. Establishing the scale and nature of recent viticulture development

    b. Determining producer’s perspectives of weather, climate and climate change impacts and risks

2. To identify the climate threats and opportunities for viticulture in England and Wales (Chapter 4) by:
    a. Quantifying correlations between a bioclimatic index based on high temporal resolution weather data and English and Welsh wine grape yield
    b. Modelling spatial variability in a bioclimatic index across England and Wales
3. To develop a tool that aids in resilience and investment planning for viticulture in England and Wales (Chapter 5) by:
    a. Modelling suitable viticulture areas in England and Wales, from biophysical and climate perspectives
    b. Identifying an analogue of wine producing regions, taking a Fuzzy Logic approach, with similar climatic conditions to those in the England and Wales
4. To assess the impacts of projected future climate change on spatial suitability and wine quality in England and Champagne (Chapter 6) by:
    a. Assessing historic relationships between wine quality, seasonal weather and climate conditions in both England and Champagne
    b. Using a climate change pattern scaled modelling approach to ascertain future likelihood of seasonal conditions that historically resulted in high vintage quality

Chapter 2

Tools, Data and Methodology

This thesis chapter introduces the data, tools and methods used to: 1) analyse relationships between weather, climate, climate change and viticulture in England and Wales, presented in Chapters 3 and 4; 2) model, map and classify viticulture suitability in England and Wales, presented in Chapter 5; and 3) model future viticulture suitability and wine quality impacts under climate change scenarios, for England and the Champagne region of France, presented in Chapter 6.

Data from a wide range of sources, in different formats, and for different analytical purposes were sourced and analysed. Whilst the majority of these data types were numerical and formatted for integration into Geographic Information Systems (GIS) (wine production data; meteorological and climate data; biophysical data), others were qualitative in nature (producers perspectives of climate impacts on UK viticulture; viticulture 'suitability' parameters; wine quality ratings). The combination of both 'types' of data facilitated a fuller assessment of climate change impacts and helped position this thesis within the socio-economic context in which wine producers operate.

2.1. Tools

A host of modelling and analytical tools are employed in this thesis to facilitate meaningful assessment and scientific scrutiny of variables and relationships between them. The tools used in multiple chapters are presented first (Sections 2.1.1 – 2.1.4), followed by a chapter by chapter breakdown of datasets and methods.

2.1.1. Bioclimatic indices

As identified and discussed in Chapter 1 (Section 1.2.2) the assessment of spatial suitability for viticulture, and zoning viticulture regions is commonly aided by the application of thermal-based bioclimatic indices (Kenny & Harrison 1992; Tonietto & Carbonneau 2004; Duchêne & Schneider 2005; Hall & Jones 2010; Anderson et al. 2012). These are utilised as crude indicators of commercial suitability (Hall & Jones 2010).

In this thesis three bioclimatic indices were employed: Growing season average temperature (GST), Growing degree days (GDD); and, the Heliothermal index of Huglin (HI). Further details regarding their development and previous use can be found in Section 1.2.2.

GST was selected for application in this study because of the availability of observed monthly averaged daily temperature data, from which it is calculated (Table 2.1), and because it has been widely used in inter- and intra-regional comparisons of viticulture climates and suitability (Schultze et al. (2014) – Southwestern Michigan (USA), Xu et al. (2012) – Burgundy, Neethling et al. (2012) – Loire Valley, Montes et al. (2012) – Chile, Anderson et al. (2012) – New Zealand, Santos et al. (2012b) – Europe, Tomasi et al. (2011) – Veneto, Hall & Jones (2010b) – Australia, Jones et al. (2009) – Worldwide, Jones & Goodrich (2008) – Western US, Ramos et al. (2008) – NE Spain, and Webb et al. (2007) – Australia).

GST values have previously been classified into four climate/maturity groups for grapevines, as shown in Figure 1.4 and Table 2.1 (Jones 2006). This index classification correlates broadly to the maturity potential for wine grape cultivars grown across many wine regions and provides the basis for placing latitudinal boundaries on viticulture zones in both hemispheres (Schultz & Jones 2010). Specific cultivar 'maturity' parameters are not measured in this thesis, and instead, these groupings relate solely to conditions in which cultivars are grown and to relationships with wine yield. Deriving historical GSTs for south-east and south-central UK enabled valuable regional viticultural climate comparisons and also provided a regional benchmark of macroclimatic conditions, presented in Chapters 3 and 4. Importantly, when used in conjunction with higher spatial and temporal resolution weather data, its value as an indicator of suitability can be further assessed. In Chapter 5 GST is calculated from monthly gridded UKCP09 5 x 5km data sets (1981–2010) (Met Office 2015a) to integrate into a viticulture suitability model for England and Wales.

The GDD and HI indices were used in this thesis to assess differences between European vineyard areas, Section 5.6.1. Both indices have been commonly applied previously (see Section 1.2.2), and require computation with daily data. These could be derived from the WRF model and observational resources employed.

The 10-year (2004–2013) climatologies of these three bioclimatic indices, most relevant to the time period in which most English and Welsh vineyards were established, facilitated a climate analogue approach (Section 5.6) where bioclimatic similarities across regions are investigated.

Table 2.1: GDD, HI and GST equations and classifications (Source: Adopted from Hall & Jones 2010)

Bioclimatic Index	Equation	Time period	Classifications
Growing Degree Days (GDD)	$\sum_{d=1}^{n} \max\left[\frac{Tmax + Tmin}{2} - 10{,}0\right]$	1 April – 31 October	Too cold <850 Region 1. 850 – 1389 Region 2. 1389 – 1667 Region 3. 1667 – 1944 Region 4. 1944 – 2222 Region 5. 2222 – 2700 Too hot >2700
HI	$\sum_{d=1}^{n} \max\ [(Tmean - 10 + Tmax - 10)/2{,}0]\ K$ Where *K* is an adjustment for latitude/day length Latitude *K* 49 1.0552 50 1.0600 51 1.0651 52 1.0704 53 1.0760 54 1.0820 55 1.0883	1 April – 30 September	Too cool <1200 Very cool = 1200 – 1500 Cool = 1500 – 1800 Temperate = 1800 – 2100 Warm temperate 2100 – 2400 Warm = 2400 – 2700 Very warm = 2700 – 3000 Too hot >3000
GST	$\frac{\sum_{d=1}^{n}[Tmax + Tmin]/2}{n}$	1 April – 31 October	Cool = 13 – 15°C Intermediate= 15 – 17°C Warm = 17 – 19°C Hot = 19 – 24°C

2.1.2. Geographic information systems (GIS)

ArcGIS (ESRI 2014) is a geographic information system (GIS) for working with maps and geographic information. It is used for: creating and using maps; compiling geographic data; analysing mapped information; sharing and discovering geographic information; using maps and geographic information in a range of applications; and managing geographic information in a database. In this work version 10.3 was used for the purposes of Chapters 3 – 6.

2.1.3. The Weather Research and Forecasting (WRF) Model

The WRF model was used to derive data for this thesis because it enabled the generation of temporally relevant (2004–2013) monthly gridded datasets (9 x 9 km) of bioclimatic indices and April – May air and ground frost days for England and Wales. Although higher spatial resolution (5 x 5 km) data was available, for example UKCP09, it did not encompass data post-2010 and did not provide the daily data required to calculate bioclimatic indices. As such the WRF model was selected as appropriate for achieving the aims of this thesis. The model runs themselves were not conducted by the author but by Chris Steele from Weatherquest Ltd. (see acknowledgements). The WRF model is the product of a multi-agency effort to build a next generation mesoscale model with the potential for both forecasting and research capabilities (Skamarock & Klemp 2008). It is employed in Chapters 5 and 6. WRF has a high degree of flexibility, offering a wide range of model physics and set-up options that the user can use to control the model design in a range of computing environments (Steele et al. 2013; Powell 2014). The model consist of two dynamical cores: the Advanced Research WRF (ARW) and the Non-Hydrostatic Mesoscale Model (NMM). Both operate with terrain-following vertical co-ordinates. The ARW is adaptable to very high resolutions (≤1 km) with the aid of telescopic nested domains, but this is constrained by computer power, resolution of terrain, soil and land-use data and skill in accurate parameterisations of physical processes in specific spatial areas (Powell 2014). The model integrates the equations for atmospheric motion, and uses physical parameterisations for unresolved, complex, non-linear processes to predict temperature, pressure, wind fields and water vapour for three-dimensional domains. For the purpose of this research version 3.3.1 was used in conjunction with the ARW dynamical core. For a detailed explanation of the model formulation see Skamarock & Klemp (2008). In model runs for this thesis the NOAH land surface model was used (Mitchell et al. 2005). The model domain was originally created for other climate applications and does not quite extend to the south-west tip of Cornwall. A temperature bias adjustment of +1°C was applied to the model as validation by Steele et al. (2014) revealed a cold bias in this climatology, which was based upon the use of the YSU planetary boundary layer scheme (see their Figure 4). A similar bias was also reported by Hu et al. (2010). Steele et al. (2014) found that the negative model bias associated with temperature (2m) simulations was a persistent feature across all months (May – September) with the monthly average bias being -1.09 °C. Although Steele et al. (2014) found variation in the model bias within a diurnal cycle (less difference during daylight hours) the purpose of employing the WRF model in Sections 4.3, 5.6 and 5.7 of this thesis was to generate bioclimatic index values based on daily or monthly temperature averages, aggregated across the growing season (April – October). The temporal variation in WRF model bias found by Hu et al. (2010) and Steele et al. (2014) indicates that were the model to be used for a specific examination of daily or monthly temperatures (2 m) the relevant biases would need to be applied. Further explanation of the WRF model validation for the purpose of this thesis can be found in Section 5.7.

2.1.4. Statistical analysis

Chapters 4 includes a statistical analysis (linear regression and stepwise regression analysis, see Section 2.3.3) to determine correlations and the strength of relationships between weather phenomena, wine yield, and quality. They are also used to determine temporal dispersion in temperature and precipitation time series. To undertake these analysis IBM SPSS statistics (v22) software was used.

2.2. Data collection and methodologies for Chapter 3

2.2.1. English and Welsh wine producers' perspectives on the impact of weather, climate and climate change on viticulture

This thesis was initially informed by the responses of English and Welsh grape growers / wine producers to a questionnaire about UK climate – viticulture relationships (Appendix A). As identified in Section 1.2.1, observations and perceptions of 'practitioners' enable a more complete understanding of weather, climate and climate change impacts. In their absence analysis would be restricted to modelled relationships without the 'ground-truthing' ability that qualitative feedback provides. Furthermore, a better understanding of weather and climate factors that concerned grape growers / wine producers, facilitated through the questionnaire and engagement with them, enabled this thesis to be targeted at research that would be of benefit to the English and Welsh wine production sector. To achieve this all grape growers / wine producers in England and Wales were invited to respond to the questionnaire that was advertised in early 2014 through a combination of emails to producers, notices to regional vineyard associations, regional vineyard manager meetings, and an advertorial in the UK Vineyard Association publication: *The Grape Press*. These multiple communication channels were used to gain as many responses as possible. The questionnaire (Appendix A) could be completed in hard copy or online. Of specific relevance to this thesis, grape growers / wine producers were asked for the following: (i) their views on causes of specific high and low yielding years; (ii) whether climate change had contributed to the growth of the UK wine production industry; (iii) which other factors had contributed to its growth; and (iv) their perspectives on whether climate change is a threat or an opportunity for wine production in the UK, and why? As with similar surveys conducted by Battaglini et al. (2009) in France, Germany and Italy, and by Alonso & O'Neill (2011) in Spain, the questionnaire provided a quantitative component in the form of selected fixed responses to the questions posed, and qualitative components through comment boxes.

It is the consensus of opinion and general themes presented through questionnaire responses that have been adopted and investigated in this thesis. Responses to questionnaires were extracted into a results database and anonymised prior to analysis.

2.2.2. Viticulture and wine production data

Grapevine phenology and yield data from individual vineyards were sought at the outset of this study in order that historic relations between meteorological conditions and yield could be analysed at a vineyard scale (assuming vineyard or localised weather data was available). Data was supplied by seven vineyards in England; however, the data provided were limited in terms of historical length, robustness and overall volume so could not be used with confidence. This lack of robust vineyard, or even regional, specific cultivar, phenology and yield data availability is recognised in Chapter 7 as a potential risk to investment, as it limits capability for analysis.

Regional wine yield data for south-east and south-central England were not available, so nationally aggregated data, the only official wine yield data that were available in the UK, were used to examine the relationship with weather and climate parameters in these regions (Chapters 3 and 4). UK yield data (1989–2013; hectolitres per hectare [hL/ha]) were obtained from the Wine Standards Branch of the Food Standards Agency (Food Standards Agency 2014). Yield data collection officially began in 1989; data were previously voluntarily provided by producers and were not deemed sufficiently complete for use in this analysis. Here it should be noted that although termed 'UK wine yield data', the absence of any vineyards in Scotland or Northern Ireland that were large enough to be required to submit harvest information to the FSA (>0.1 ha: Food Standards Agency 2014) effectively means that national aggregated data is derived only from England and Wales.

Data on historic vineyard numbers, hectarage under vine, and hectarage in production for England and Wales was required to assess changes and trends in the development of viticulture in England and Wales. Requests for data from regional and national vineyard associations (the United Kingdom Vineyard Association – UKVA) yielded no data as they had no records of production. The only available source of information: the Wine Standards Branch of the Food Standards Agency, had limited data that had been compiled from harvest returns from wine producers (English and Welsh vineyards are required to submit a harvest declaration stating vineyard size and wine yields, on an annual basis). This data (Appendix B) is not subject to checks or verification, but was the only source of historic production information, and was analysed (Section 3.1), for the first time through this thesis, to assess trends and changes in the scale of English and Welsh viticulture.

2.2.3. Cultivar data

Data regarding vine cultivars (type and volume) grown in England and Wales is not readily available. For this thesis historic data was compiled from the only accessible sources, the Wine Standards Branch Vineyard Registers (1990, 1999, 2007 and 2013) and data published in Skelton (2008, 2010 and 2014). Data for intervening years were not available. Once complied it was subjected to a trend analysis to identify recent trends in cultivar production across England and Wales, see Section 3.1.

Cultivar information preceding 1990 was collected by the then Ministry of Agriculture, Fisheries and Food (MAFF) through voluntary surveys but was not deemed sufficiently comprehensive to present in this thesis. Yield data from 1989 is however referred to in Section 4.6 as there is no evidence of a significant change in dominant cultivars in production between 1989 and 1990.

2.2.4. English and Welsh vineyard locations

No 'official' database of vineyards in England and Wales was publically available so the UK Vineyards List (Skelton 2015), although not independently verified, was deemed the most reliable and up-to-date (November 2015) source and was used to obtain vineyard address and size (ha) information. Postcodes from this list were often found, using Google Earth (Google 2015a), to relate to the business premises (buildings) and not the precise vineyard location, so to ensure model accuracy, each (367) individual vineyard (≥1 ha) was visually located, where possible, utilising a combination of Google Earth (Google 2015a), Google Maps Street View (Google 2015b), and DigiMap Roam (Edina 2015).

2.3. Data collection and methodologies for Chapter 4

2.3.1. English and Welsh historic weather and climate data

Previous viticulture – climate studies have used local weather station data (Blanco-Ward et al. 2007; Jones & Goodrich 2008; Bonnardot et al. 2012) or relatively low spatial resolution (≥25 km) modelled climate data (Webb et al. 2008; Jones et al. 2010; Fraga et al. 2013a), to undertake viticulture – climate analysis. However the proximity of weather stations to vineyards (not specified in Blanco-ward et al. 2007 or Jones & Goodrich 2008) and the resolution of models used may mean that the data was not entirely representative of vineyard meso-climates (Anderson et al. 2012; Fraga et al. 2013a). At the outset of this study data from weather stations in vineyards in England and Wales were sought from producers as these would have provided highly localised information from which to analyse relationships with viticulture phenomena. However, none of the vineyards in England and Wales that were contacted had site-specific weather data records available for analysis. This was largely attributed to the relatively newly-established nature of vineyards.

In the absence of site-specific weather data, Met Office regional data (for south-east and south-central England) for monthly average temperature, monthly days of air frost (≤0^{o}C) and rainfall (1954–2013) was sourced for use in calculating growing season (April – October) averages and totals, identifying extremes, trends, and variability. Regional (south-east and south-central England) monthly temperatures and precipitation totals had been derived from the mean of the gridded product, see below, providing a macroscale climatic dataset used to calculate results in Chapter 4.

The Met Office regional monthly average temperature and precipitation volume data are derived from station daily means ([T*max* + T*min*]/2) and summed daily totals respectively. The density of stations varied through time, and for the different climate variables — for example, for temperature the number of stations rose from about 270 in 1914 to 600 in the mid-1990s, before falling to 450 in 2006 (Met Office 2015b). The station data had been subjected to multiple regression and inverse-distance weighted interpolation techniques to generate values on a regular grid (5 x 5 km), taking into account factors such as latitude, longitude, elevation, terrain shape, coastal influence, and urban land use. This alleviated the impact of station openings and closures on homogeneity, but did not remove it entirely, especially in areas of complex topography or sparse station coverage (Perry & Hollis 2005). In the viticulture suitability model (Chapter 5) monthly temperature data for a 1981–2010 period was used, obtained from this UK Climate Projections 2009 (Met Office 2015a) 5 x 5 km gridded dataset, to calculate growing season average temperatures (GST) and their inter-annual variability (expressed as standard deviation – SD), and days of air frost (≤0oC) in April and May, across England and Wales. The data, provided as text file point-data with latitude / longitude coordinates, was imported into ArcGIS v10.3 (ESRI 2014) and converted into a 5 x 5 km gridded raster (see Section 2.4.5). The 1981–2010 period is a commonly used climatological averaging period (Met Office 2015c), and encompasses the period in which English and Welsh vineyard area started to increase (see Section 3.1).

Both the regionally averaged and gridded products were freely available (Met Office 2014b; Met Office 2015c) and of a suitable length for the purposes of this study.

To enable a comparison between regionally-averaged and gridded temperature data and in-situ vineyard temperature, 15 temperature data loggers (Tiny Tag Talk 2 TK-4023: Gemini (2015)) were established in a vineyard in East Sussex by the author as part of the Adapting Viticulture to Climate Change (ADVICLIM 2015) project. Hourly minimum, mean and maximum temperature (^{o}C) were recorded (April 2015 – April 2016) by the loggers, and downloaded to facilitate a comparative analysis. Results are presented in Section 5.7.

In the viticulture suitability model (Chapter 5) monthly temperature data for a 1981–2010 period was used, obtained from the UK Climate Projections 2009 (Met Office 2015a) 5 x 5 km gridded dataset, to calculate growing season average temperatures (GST) and their inter-annual variability (expressed as standard deviation – SD), and days of air frost (≤0^{o}C) in April and May, across England and Wales. The data, provided as text file point-data with latitude / longitude coordinates, was imported into ArcGIS v10.3 (ESRI 2014) and converted into a 5 x 5 km gridded raster (see Section 2.4.5). The 1981–2010 period is a commonly used climatological averaging period (Met Office 2015c), and encompasses the period in which English and Welsh vineyard area started to increase (see Section 3.1).

Sunlight and radiation energy are also identified as important climatic variables in the cultivation of *Vitis vinifera* L. (Chapter 1). Whilst solar radiation can be estimated in ArcGIS v10.3, accurate cloud cover data is required to extend the model (Olsen et al. 2011) beyond the theoretical. In the absence of such data historical sunshine data (duration of bright sunshine during the month – hours per day) for 1981–2010 was obtained from the UKCP09 dataset as a 5 x 5 km gridded product (Perry & Hollis 2005).

Rainfall data (1981–2010), used in Chapter 5 for suitability modelling, was derived from monthly 1 x 1 km Gridded Estimates of Areal Rainfall (CEH – GEAR) (Centre for Ecology and Hydrology 2014; Tanguy et al. 2014), which itself is derived from a national database of historical Met Office weather and rain-gauge observations (Keller et al. 2015) The UK network of rain gauges grew from around 450 in 1860 to approximately 3500 by 1900 and peaked at around 6250 in 1974, by 2009, data were recorded at 3285 sites (Keller et al. 2015). The natural neighbour interpolation methodology, including a normalisation step based on average annual rainfall, had been used to generate the monthly rainfall grids. To derive the monthly estimates, rainfall totals from monthly and daily (when complete month available) rain gauges were used in order to obtain maximum information from the rain gauge network.

2.3.2. Regional focus

Chapter 4 of this thesis addresses viticulture – climate relationships in the south-east and south-central region of England, covering the counties of Berkshire, Hampshire, the Isle of Wight, Kent, Surrey, East and West Sussex and Wiltshire. Since 1989, these regions have represented ~50–60% of national vineyard area (Skelton 2001; Skelton 2008; Food Standards Agency 2013). However, vineyard locations (Section 3.1, Figure 3.2) and potential viticultural opportunities are more spatially diverse and therefore the attention of this thesis then extends in Chapters 5 and 6 particularly, to a larger geographical area, covering all of England and Wales.

2.3.3. Climate-yield relations

Numerous factors can affect yield, but analysis in this thesis is limited to weather and climate. Here, yield and average temperature (growing season and monthly), and yield and frost days (April and May), were subjected to linear regression analysis to elucidate relationships, and then yield, average temperature (growing season and monthly) and total precipitation (growing season and monthly) to stepwise regression analysis to determine the independent variable(s) that produce(s) models with a statistically significant P-value (P = <0.05) and the highest coefficient of determination (r^2). Two time periods (1989–2003 and 2004–2013) were distinguished for analysis because cultivar changes play an important role in yield, because of their contrasting climatic suitability; from one time period to the next, there was a change in mix of cultivars grown in the UK, see Figure 3.3.

The combination of regionally averaged weather/climate data and national, non-regionally specific yield data could lead to some distortion of climate – wine yield relationships, but national yield values were deemed indicative of those in the regions of interest because of their significant (~50–50%) contribution to total UK vineyard area, see Figure 3.2 and Table 3.1. In this thesis therefore relationships between regionally averaged weather/climate data and national wine yield data were analysed. The use of nationally averaged weather/climate data would have disproportionally included areas where few or no vineyards exist.

2.3.4. Recent climate change

Anomalies and comparisons of growing season monthly mean temperature and rainfall for 1898–2013 against a 1961–1990 baseline period were calculated from the Met Office regional dataset (Met Office 2014b) to illustrate climate trends in south-east and south-central England. This baseline has been widely used in climate change research and in previous climate and wine work (Hulme et al. 1999; Webb et al. 2008; Giorgi & Lionello 2008). Met Office regional air frost (<0°C) data (1961–2013) for days with air frost in April and May, the critical months for budburst and initial shoot growth, were used to calculate trends and quantify variability for the same geographical region.

2.3.5. Weather variability and extremes

Inter-annual weather variability in Chapter 4 was quantified as the standard deviation (SD) and coefficient of variation (CV) for GST and precipitation in south-east and south-central England. The CV was used to enable a comparison between the relative variability of temperature and precipitation. To assess changes to the degree of variability, the results for 1989–2013 were compared to a 1961–1990 baseline period. The range of growing season monthly average temperature and monthly total precipitation was calculated for the periods 1961–1990 and 1989–2013.

Using box plots (Figures 4.6 and 4.7) to show the degree of dispersion allows for an illustration of changes to monthly average temperature and total precipitation. They also enable conditions during critical phenological periods to be more closely examined.

To illustrate the spatial and inter-annual variability in growing season air temperature (2m), GSTs across England and Wales (2004–2013) based on dynamically downscaled outputs from the WRF model climatology, created by Steele et al. (2014), at 9-km resolution are presented in Figure 4.3.

Inter-annual weather variability (GST and growing season rainfall) was incorporated into the suitability models presented in Sections 5.3 and 5.4. It was calculated as the SD for the 1981–2010 period of data included in the model.

2.3.6. WRF model bioclimatic and spring air frost data integration into ArcGIS

To enable a comparative assessment of bioclimatic values (GST, GDD, and HI) across the UK and other European wine growing areas (Section 5.6), bioclimatic and spring (April and May) air frost values for 2004–2013 (9 x 9 km resolution) were produced from the WRF model output. These were generated in text file format with corresponding latitude and longitude co-ordinates. Values were imported to ArcGIS as point data, transformed to the operating layer co-ordinate system (WGS1984) and exported as shapefiles before being converted from point to raster layers for analysis. During this process, to align the WRF derived curvilinear point-data (Lambert Conformal structure) to the ArcGIS rectilinear (one-dimensional) grid structure the point-to-raster conversion required that attributed grid-cell size was increased from its 9,000 origin to 10,000m, see Figure 2.1, to ensure all cells had values. By assigning the cell type to mean, where cells overlapped, the output value was the mean of the inputs. In doing so whole domain coverage was provided but some areas of data accuracy reduced.

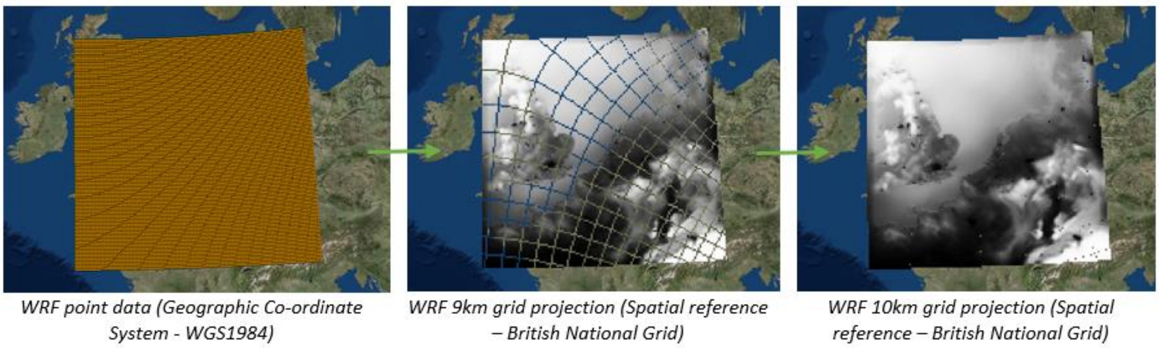


Figure 2.1: WRF model data integration into ArcGIS through a point to raster grid conversion and a 9 x 9 km to 10 x 10 km cell resampling.

2.4. Data collection and methodologies for Chapter 5

2.4.1. Vineyard mapping

Once vineyards were located (see Section 2.2.4) coordinates (British National Grid (BNG)) of their approximate centres were imported as point features into ArcGIS v10.3 (ESRI 2014) to enable subsequent analysis of their existing spatial distribution, validate suitability model alignment, and evaluate their model parameters. Of the 384 ≥1 ha vineyards in England and Wales, 17 (with a combined total of ~23 ha), could not be found using this visual identification process and were therefore excluded from the mapping and analysis exercise. The inability to find these vineyard sites was mainly attributed to their unplanted or newly planted status and therefore omission from the various base imagery used due to its age (2003–2015). The remaining 367 vineyards ≥1 ha, plotted and shown in Figure 3.2, accounted for 1850 ha of land under vine, almost 93% of vineyard land in the British Isles (Skelton 2014). To facilitate a climate analysis and further climate analogue approach to viticulture – climate suitability modelling the boundaries of 13 larger (≥25 ha) vineyards were traced from an earth image base map (ESRI 2014) using the ArcGIS Editor tool, and saved as polygon features. Details of cultivars grown in these vineyards were provided by producers and they were subsequently related to bioclimatic values integrated into the model using ArcGIS Spatial Analyst tools.

Defining viticulture suitability through spatial zoning is not uncommon (Jones et al. 2010; Fraga et al. 2013a) and the geo-political boundaries utilised in the process provide an artificial but useful means of depicting the appropriateness of relatively large areas. In this work, in the absence of any appellations or defined viticulture zones, Unitary Authority (UA) boundaries (Ordnance Survey 2013) were used as a means of representing spatial suitability for viticulture at a regional scale, and to define model classifications in Chapter 5. Unitary Authorities provide services for counties and district councils, and although they vary in scale their geo-political nature was relevant to the modelling purpose as it provides outputs that could inform Unitary Authority land-use policy.

2.4.2. European vineyard areas

Chapters 5 and 6 present analogue approaches to modelling viticulture – climate suitability, now and in the future, by comparing bioclimatic variables and cultivars between vineyard locations in Denmark, England and Wales, France, Germany and Switzerland, see Section 2.4.3. Locations in the latter three countries were identified from the CORINE Land Cover 2012 (v18.4) raster dataset (Copernicus 2012), which includes a vineyard class. Location identification for England and Wales is previously described in Section 2.2.4, and for Denmark vineyard sites were obtained from mapped locations provided by the Danish Vineyard Association (Danskevingaarde 2015). The Corine Land Cover map (2012) did not contain vineyard data for England and Wales, or Denmark indicating a lack of accurate representativeness of these regions.

2.4.3. European vineyard data integration

2004–2013 mean bioclimatic values for England and Wales, derived from the WRF model, were compared with the Champagne Region in France, Mosel-Saar-Ruwer and Franken in Germany, Neuchatel in Switzerland and Eastern Denmark. Vineyard locations in France, Germany and Switzerland were identified from the CORINE Land Cover 2012 (v18.4) raster data-set (Copernicus 2012) which includes a vineyard class, overlain onto the WRF domain in ArcGIS. The Corine Land Cover map did not contain vineyard data for England or Denmark, these were identified visually from an ArcGIS base-map overlain with semi-transparent WRF 9 x 9 km grids. Cultivars grown in these areas were obtained from (Johnson & Robinson 2001), and from the Danish Vineyard Association (Danskevingaarde 2015).

2.4.4. English and Welsh biophysical data

Biophysical data applied to the viticulture suitability modelling processes in this thesis included soil, elevation, aspect, percent slope, land cover, and designated areas.

Soil

No one prescriptive 'ideal' set of soil properties exists for viticulture, rather a broad and generalised range is presented as being suitable under different environmental circumstances, and for different rootstocks, clones and cultivars, as outlined in Section 1.2.3. However, in an attempt to best represent the range of soil characteristics deemed desirable for viticulture three soil datasets were initially considered to evaluate their suitability in reflecting soil properties in English vineyards, see Section 5.1.

The results from this initial data trial, see Section 5.1, lead to the selection of the Soilscapes (Landis 2015) dataset that incorporates the key factors of texture, drainage, acidity, and soil depth through 27 simplistic soil descriptors (Figure 5.3), 11 of which were adopted for the suitability model in this thesis. The Soilscapes data series provides a useful, concise, easily interpreted and applicable description of the soils of England and Wales with simple-to-understand soil information at a 1:250,000 scale. The soil suitability analysis in this thesis (Chapter 5) does not discriminate against specific texture, pH values or soil depth, and does not specifically include soil organic matter content, due to the lack of threshold data and its omission from the Soilscapes dataset descriptors. Instead it applies Soilscapes descriptors for existing vineyards and models viticulture suitability based on their occurrence.

Topography

The key viticulture topographic parameters of elevation, aspect, and slope were derived from the freely available OS Digital Terrain Model (DTM) 50 x 50 m gridded open source database (Edina 2015), for England and Wales. This dataset is composed of a series of ASCII (American Standard Code for Information Interchange) 10 x 10 km tiles containing mean elevation in 50 x 50 m grids. OS Terrain 50 has been compared with GPS points in a range of sample areas to provide a Route Mean Square Error value for the height points in each geographic area as a means of validation.

There is no stipulated 'ideal' elevation for vineyards in England and Wales but guidance suggested vineyards would be best sited below 100 and not above 150 m (Skelton 2014), and with between 25–80 m the preferred range (Skelton personal communication, 2015). Currently the highest established vineyard in England and Wales (Holmfirth Vineyard in West Yorkshire) is just over 250 m but it is established with cold resistant hybrid varieties that are not permitted in the English and Welsh Quality Wine Schemes (QWSs) (DEFRA, 2011). The QWSs exclude wines produced from non-Vitis vinifera cultivars and vineyards higher than 220m, a limit selected to encompass all English and Welsh vineyards at the time the initial QWSs were established – 1992 (Skelton 2010), rather than an indication of 'suitability'. Elevation suitability is restricted by decreasing temperatures at higher altitudes and the greater potential for wind exposure (Skelton 2014). In this work a 150 m elevation suitability restriction is applied, see Table 2.2.

During the course of this thesis the UK government's Department for Environment, Food and Rural Affairs (DEFRA) released LIDAR (Light Detection and Ranging) data for public use. This was investigated as it offered 1 x 1 m resolution topographical imagery and height information, however it was found to only cover ~70% of England and Wales and was therefore not suited to the viticulture suitability evaluation across England and Wales.

At higher latitudes (in the northern hemisphere) south facing slopes have greater direct solar radiation gain potential (Coombe & Dry 2004; Jackson 2014) due to their reduced angle of incidence (the angle between the sun's beam and an imaginary line perpendicular to the slope), particularly during the ripening period when the sun is higher in the sky, and are deemed favourable for vineyards (Jackson 2014; Skelton 2014). They are also conducive to reducing the lag phase during which a site heats up and dries out after a cold night (Jackson 2014). The azimuth angle of the slope (the direction to which the slope is oriented) was set at 180^{o} (south) for highest viticulture suitability, with an acceptable range of 90–270^{o} (east-west), see Table 2.2. The slope, calculated using ArcGIS was derived using the D8 algorithm (ESRI 2015a).

The angle of slope also affects the quantity of diffuse radiation but ideal slopes for viticulture are considered to be 5–15% (Jones et al. 2004) and within this range angle was considered unlikely to have any significant effect on diffuse radiation capture. Because the potential for mechanical vineyard-management activity becomes limited on slopes above 10% (Jackson 2014) and erosion risk increases, and because below 1% there is an increased risk of cold air accumulation and potential frost damage, angle suitability was restricted to 1–15%, see Table 2.2.

Land cover

Land cover information for England and Wales was obtained from the Centre for Ecology and Hydrology (CEH) Land Cover Map (LCM) 2007. This data-set contained 25 x 25 m raster grids of 23 different land cover types. The LCM2007 land parcels come from generalised digital cartography refined with image segments, whereas its predecessor – LCM2000, uses only image segments. Those selected for use in the suitability model are listed in Table 2.2.

Designated areas

It was assumed in this work that where land areas had been awarded a special designated status, e.g. Site of Special Scientific Interest (SSSI), and were therefore 'protected', that they would be unlikely to be available for viticulture. Spatially representative data of designated areas in England and Wales were obtained from a variety of sources (see Table 2.2) and integrated into the suitability model, in order that they could be excluded from suitability analysis.

Table 2.2, below shows the data type, source, and where integrated into the suitability model, suitability parameters and model membership type of biophysical data. Section 2.4.5 of this chapter details the modelling approaches used. The parameter values and suitability model membership types were selected based on guidance from Jones (2004), Skelton (2014), and Skelton (personal communication, 2015).

Table 2.2: Environmental suitability model biophysical constraints, data source, type and resolution, and model membership types.

Physical Variable	Suitable parameter values	Original data type	Data source	Suitability model membership type
Soil	• Shallow lime rich soils over chalk or limestone • Freely draining lime-rich loamy soils • Freely draining slightly acid loamy soils • Freely draining slightly acid but base-rich soils • Slightly acid loamy and clayey soils with impeded drainage • Freely draining slightly acid sandy soils • Freely draining sandy Breckland soil • Freely draining acid loamy soils over rock • Freely draining very acid sandy and loamy soils • Slowly permeable seasonally wet acid loamy and clayey soils • Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils	1:250,000 polygons	LandIS 2015	Boolean
Elevation	1–150m	10 x 10 km ASCII tiles	(Edina 2015)	• Fuzzy • Type: Near • Mid-point: 52.5m • Spread: 0.001
Aspect	east–west (90°–270°)		Derived from elevation using ArcGIS V10.3 Spatial Analysis	• Fuzzy • Type: Near • Mid-point: 180° • Spread: 0.001
Slope gradient	1–15%		Derived from elevation using ArcGIS V10.3 Spatial Analysis	• Fuzzy • Type: Near • Mid-point: 5% • Spread: 0.001

Land cover	• Arable & Horticulture • Improved Grassland • Rough Grassland • Neutral Grassland • Calcareous Grassland	25 x 25 m raster layer	Centre for Ecology and Hydrology Land Cover Map 2007	• Boolean • Type: Boolean AND
Designated areas	• Registered battlefields • Registered parks and gardens • Country Parks • World Heritage Sites • Local and national nature reserves • Sites of Special Scientific Interest • Special areas of conservation • Special protected areas	Shapefiles	Historic England 2015; Natural England 2015; Natural Resources Wales 2015	• Boolean • Type: Boolean AND

2.4.5. Viticulture suitability model construction

In this thesis two suitability model sub-sets (biophysical and climatic) were constructed using both fuzzy membership with imposed anchor points, and Boolean logic for defined variables with limited range (e.g. land-cover classification) or where no accepted 'preference' existed (e.g. soil type), and then combined to produce a spatial suitability model for viticulture in England and Wales. Key steps of the model construction process are set out in Figure 2.2.

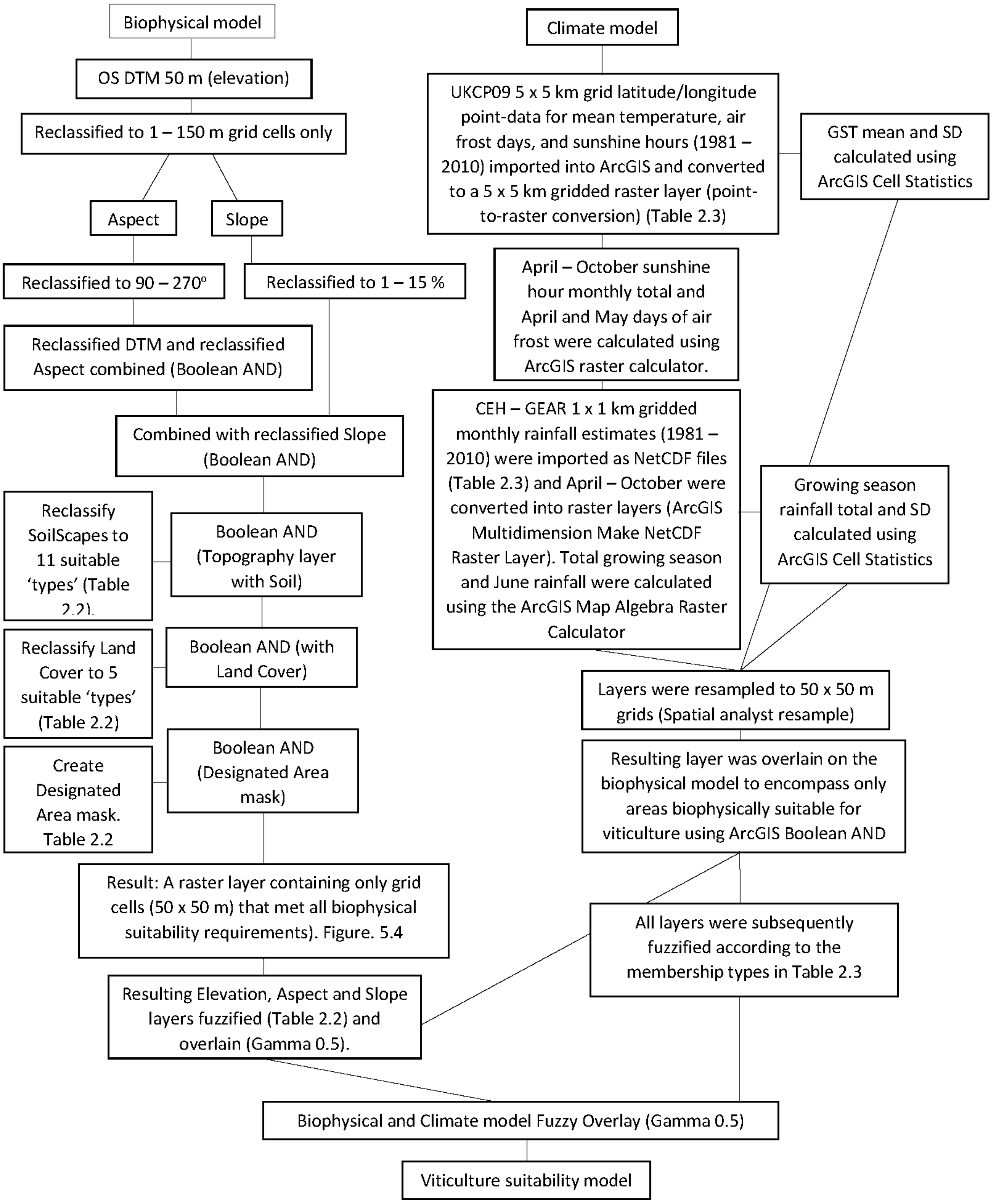


Figure. 2.2: Viticulture suitability model construction flow-diagram of key steps and ArcGIS tools employed.

Biophysical data

The biophysical model itself was formed from OS Terrain 50 DTM ASCII tiles (Edina 2015), imported into ArcGIS and converted to raster datasets using the ArcGIS v10.3 Conversion tool. The OS Digital Terrain Model (Edina 2015) (DTM) 50 x 50m grid structure was retained for all data variables and analysis. The 50 m resolution was deemed more meaningful at a landscape scale than the available 5 x 5 m resolution dataset (Edina 2015), which would have been significantly finer than the coarser resolution datasets employed in the suitability model.

Using the ArcGIS V10.3 Mosaic to New Raster tool these tiles were then mosaicked to a new raster dataset, i.e. all the raster DTM tiles were merged into one large dataset, which was projected to the British National Grid (BNG) coordinate system, and then reclassified to 1–150 m. The reclassification process used in the development of this suitability model was undertaken to exclude 50 x 50 m grid-cells with values outside the 1–150 m range by attributing them 'NoData' and excluding them from the model. The remaining cells (those with an elevation between 1 and 150 m), were awarded a value of 1 during the reclassification process and were subsequently multiplied with the original dataset to obtain their elevation values. From this new raster layer slope and aspect were calculated using the ArcGIS v10.3 Spatial Analyst geoprocessing Aspect and Slope tools. Aspect is derived in ArcGIS by identification of the downslope direction of the maximum rate of change in value from each cell to its neighbours, i.e. Aspect can be thought of as the slope direction (ESRI 2015). Slope is calculated as the rate of maximum change in z-value from each cell (ESRI 2015). The same re-classification and delimitation process was then applied to aspect and slope as was applied to elevation. To identify 50 x 50 m grid-cells with combined (elevation, aspect and slope) topographic suitability (see Table 2.2) the Spatial Analyst 'Boolean AND' function was used. First elevation and aspect layers were combined to identify only those 50 x 50 m grid cells that contained both 1 – 150 m elevation and 90 – 270^{o} Aspect. Then the resulting layer was combined with the slope layer to identify and delineate only those cells which also had a slope of 1 – 15 %. Multiplying the resulting grid-cells with their original dataset values produced three new raster layers.

The model was progressed from the resulting topographic layer by removing cells that did not contain prescribed soil and/or land-cover values (Table 2.2), using the Boolean AND process. The 11 soil 'types' encompassed all existing vineyards (≥1 ha) in England and Wales including those situated on land described by the data as being seasonally wet or with impeded drainage. Accepting that vineyards on such soils may not be considered 'ideal' the suitability model is subsequently analysed for viticulture suitability with and without these and other soils.

Biophysical suitability for viticulture in England and Wales was also refined by constraining the model to land classified in the 2007 Land Cover Map (LCM2007; Centre for Ecology and Hydrology (CEH) 2011) as: Agriculture, Horticulture, or Grassland. Doing so excluded areas classified as woodland, urban, suburban, montane, rocky, or that were wet or coastal (fen, marsh, swamp, bog, salt or freshwater). The LCM2007 was developed using a range of data sets including satellite imagery, national cartographic products, agricultural census data, ground reference data, digital elevation models, soil data sets, and urban extent. It was selected for use in this work as, when validated by Rowland et al. (2011), it was found to have a high level of correspondence between ground reference points and classifications.

Finally designated areas were converted from individual shapefiles to a single raster layer using ArcGIS conversion tools and a mask was created for areas with no designated area status. Boolean AND was again used to refine the model and delimit suitable grid cells.

Biophysical model fuzzification

Once all biophysical layers had been refined to only contain cells which encompassed all the suitability parameter values prescribed in Table 2.2 the elevation, slope and aspect raster layers were individually subjected to fuzzy membership functions in order that they could be attributed a suitability value between 0 and 1 (0 = low suitability; 1 = high suitability). The ArcGIS Fuzzy membership tool, used in this process, reclassifies or transforms the input data to a 0 to 1 scale based on the possibility of being a member of a specified set. 0 is assigned to those locations that are definitely not a member of the specified set, 1 is assigned to those values that are definitely a member of the specified set, and the entire range of possibilities between 0 and 1 are assigned to some level of possible membership (the larger the number, the greater the possibility) (ESRI 2015)

For elevation a Near membership type (ESRI 2015) is imposed on the data with a mid-point of 52.5 m (25–80 m median value) and a spread value of 0.001 (see Table 2.2 and Figure 2.3). The Near function is defined by a midpoint defining the centre of the set, identifying definite membership and therefore assigned a 1. In this case 1 was assigned to grid cells with a 52.5 m elevation. As values move from the midpoint, in both the positive and negative directions, membership decreases until it reaches 0, defining no membership, in this case for cells below 1 m or above 150 m. The spread defines the width and character of the transition zone. The 0.001 spread was selected for this model to allow a wide transition zone, illustrated in Figure 2.3. Doing so gave a broader spread of values across all grid cells than say a spread of 0.1 which would give much lower values to cells only marginally outside of the 52.2 m mid-point. The broad spread in this model indicates that an elevation of say 25 m or 80 m may not be significantly less suitable than 52.2 m. Figure 2.3 is an illustrative example of the Fuzzy Near transformation function using three spread values with a mid-point of approximately 150 and a range of 10 – ~ 330.

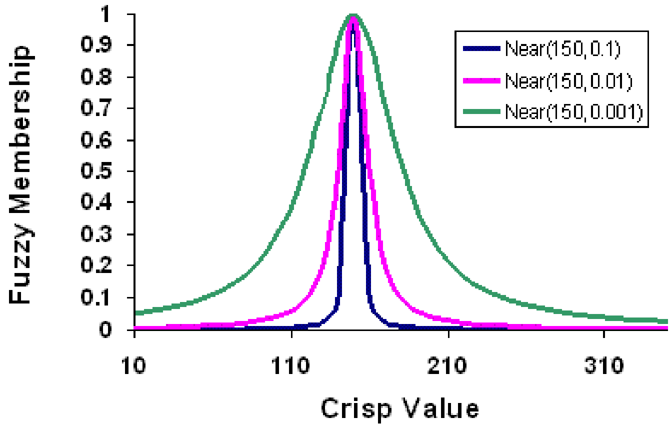


Figure 2.3: Near fuzzy membership functions (ESRI 2015b)

The elevation fuzzy membership parameters used in this model were selected following a sensitivity test with Small fuzzy (sigmoidal) (Figure 2.4) membership types, mid-points of 50 – 80, and spread values of 5 – 10, and a Gaussian membership application with spread values of 1 – 0.05.

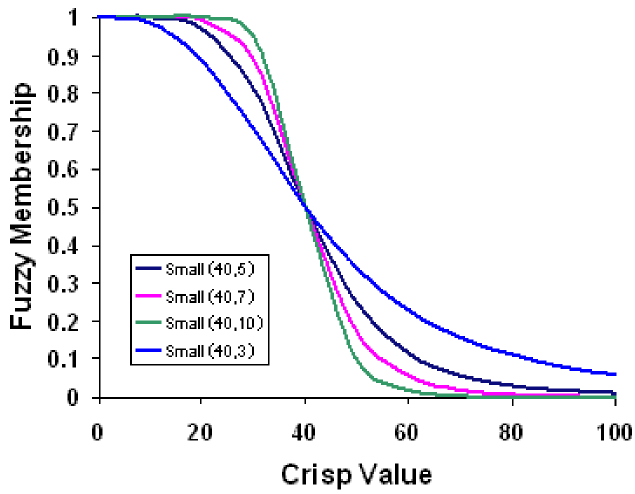


Figure 2.4: Small fuzzy membership functions (ESRI 2015b)

The Small membership function was tested to assess its suitability in awarding higher values to land at lower elevations. The function assigned increasingly steep fuzzification around the mid-point (non-linear) and higher suitability values to land under the mid-point. However, when the fuzzification models were assessed with existing vineyards (≥25 ha) there was little discrimination within or between suitability values (mean: 0.92 and Standard Deviation (SD): 0.12). In other words the Small membership function was not found to be suitable in distinguishing variation in 'suitability'. Furthermore, even with a spread of 5 it awarded significantly higher 'suitability' values to grid cells with say a 10 m elevation than a 50 m elevation which was not in agreement with parameters set out in Table 2.2. As can be seen in illustrative Figure 2.4, with a range of 1 – 100 and a mid-point of 40, a spread of 5 awards much higher values below 40 than above.

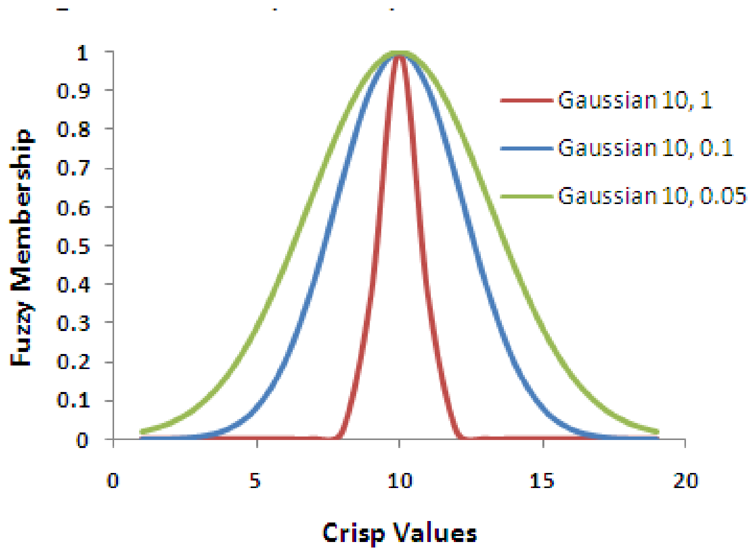


Figure 2.5: Gaussian fuzzy membership functions (ESRI 2015b)

Similarly the Gaussian membership (Figure 2.5), which transforms values into a normal distribution, allowed for little discrimination between values and awarded a mean fuzzy membership of 0.05 with a SD of 0.2.

The Near membership function gave a more even spread of suitability (mean – 0.5) and wider SD (0.3), from which to assess suitability.

Slope aspect and angle datasets were also transformed and integrated into the fuzzy model using the Near function, with spread values of 0.001. Slope was imposed with a mid-point 'optimisation' of 5%, and aspect with 180^{o}, see Table 2.2.

Subsequently these fuzzified datasets were integrated using the Fuzzy Overlay tool in ArcGIS v10.3. The Fuzzy Overlay tool combines fuzzy membership rasters data together and allows the analysis of a phenomenon, in this case biophysical suitability for viticulture, which belongs to multiple datasets (ESRI 2015b). For the purpose of this analysis the Fuzzy Gamma (Gamma – 0.5) overlay type was selected to establish the relationships between the multiple input criteria and award cell values in-between the fuzzy Product (multiplied values) and Sum (an increasing linear combination), awarding a broader range of values (ESRI 2015b).

Climatic data

Temperature is accepted as being the main climatic variable affecting the viability and quality of viticulture (Jackson & Lombard 1993; Jackson 2014) as it has the greatest effect on the physiological behaviour of grapevines and on berry chemical composition (Tonietto & Carbonneau 2004; Jackson 2014). However, other meteorological and climatic phenomena have also been shown to affect both yields and grape berry quality (see Section 1.1.1), and the viticulture suitability model presented in Chapter 5 of this thesis therefore includes six climate variables identified in Table 2.3.

Table 2.3: Environmental suitability model weather and climate constraints, data type, source and model membership type

Climate variable	Data type	Source	Model membership type
GST	Gridded 5 x 5 km txt file	UKCP09	• Fuzzy membership • Type: Linear
Mean growing season total precipitation	Gridded 1 x 1 km NetCDF files	CEH-GEAR Monthly summations	• Fuzzy membership • Type: Small • Spread: 5
June precipitation	Gridded 1 x 1 km NetCDF files	CEH-GEAR CEH – Gridded Estimates of Areal Rainfall (CEH – GEAR) Mean June rainfall	• Fuzzy membership • Type: Small • Spread: 5
GST and precipitation inter-annual variability	Gridded 5 x 5 km txt file	Inter-annual variability expressed as the standard deviation (SD)	• Fuzzy membership • Type: Small • Spread: 5
Spring air frost	Gridded 5 x 5 km txt file	UKCP09 Days of air frost (≤0°C) in April and May	• Fuzzy membership • Type: Small • Spread: 5
Sunlight	Gridded 5 x 5 km txt file	UKCP09	• Fuzzy membership • Type: Linear

GST and precipitation inter-annual variability (expressed as SD, see below), April and May air frost values, and sunlight data (UKCP09 point data – Section 2.3.1) were converted into gridded raster products at 5 x 5 km resolution using the ArcGIS v10.3 'Point to Raster' Conversion tool. The output was resampled to 50 x 50 m using the Spatial Analyst resample function. Inter-annual variability is calculated through the Standard Deviation (SD) (the average distance of values to the mean) of temperature and rainfall (1981–2010) variables. However, the use of SD does not indicate the relative magnitude of the standard deviation and the Coefficient of Variation (CV) would potentially illustrate the relative variability more clearly. The use of CV as a means of calculating inter-annual variability was not undertaken in this work as no CV function was available in ArcGIS V10.3 but it may deliver slightly different results as grid-cells with a higher SD could have a low CV and vice versa. Therefore in section 7.3 it is recommended that further refinement of the suitability model incorporates CV to compare results.

High levels of rainfall, usually accompanied by reduced sunlight, can negatively affect vine growth, berry quantity and quantity through associated issues such as increased disease pressure, reduced flowering, millerandage (where grape bunches contain berries that differ greatly in size and maturity, sometimes referred to as 'chicken and hen'), coulure (flowers fail to set and are shed at or after flowering), and a sugar/acidity imbalance. However, specific thresholds of precipitation totals that constitute problematic or 'extreme' conditions annually, over the growing season, or during flowering, are rarely defined (Gladstones 1992, Jones 2012) and are not drawn on here. CEH-GEAR rainfall data (1 x 1 km) was imported into ArcGIS v10.3 from a series of annual NetCDF files with extractable monthly data. Using the Multidimension 'Make NetCDF Raster Layer' tool, growing season (April–October) monthly data was extracted for each year (1981–2010) as individual raster layers and exported as 50 x 50m grid cells to the climate suitability model. The mean growing season and June precipitation totals for 1981–2010 were calculated using the Map Algebra Raster Calculator tool.

Hourly sunlight data (1981–2010) from the UKCP09 dataset (Perry & Hollis 2005) was integrated into the climatic suitability model using a Linear fuzzy membership function (Table 2.3).

Wind can cool air temperatures through perception (wind chill), not physically, and disrupt vine canopies and the flowering process, hampering vine management and potentially affecting grape yield (Skelton 2014, Jackson 2014). Conversely 'breeze' can be desirable in vineyards to help reduce moisture levels, humidity and associated fungal disease risk (Skelton 2014; Jackson 2014). Although both positive and negative effects of wind on vineyards are documented it remains unclear what the 'optimal' vineyard wind speed is, which makes incorporating it into a viticulture suitability model very challenging. Compounding this, although historic wind speed data for 10 m above ground is available (UKCP09) for England and Wales, data representative of vine canopy height was not. Therefore in this model the awarding of lower fuzzy membership values to higher elevation land was relied on as an indicator of likely wind exposure. Whilst elevation is not a prescriptive surrogate for wind speed the UKCP09 wind speed data (available as a 5 x 5 km gridded product) was unlikely to be representative of complex patterns of wind speed created by terrain variability at vineyard scale for suitability assessments. In

Section 7.3 it is recommended that the 10 m wind speed dataset is subjected to a logarithmic or power law correction to estimate canopy height wind speed.

All climatic variables were derived from UK wide datasets so were subsequently clipped to a Unitary Authority boundary map (Ordnance Survey 2013) layer using the Raster Processing Clip tool to limit them to England and Wales. For the purpose of viticulture suitability analysis they were further subjected to the Boolean AND function to restrict output solely to the areas in England and Wales that had been considered biophysically suitable. Data was re-classified (value 0 = NoData; value 1 = 1) and multiplied by the original dataset to give final cell values.

Climate model fuzzification

The climate datasets were fuzzified using the Small and Linear fuzzy membership types indicated in Table 2.3. The Small function has been described previously in this section. The Fuzzy Linear transformation, used for the GST and Sunlight datasets, applies a linear function between the minimum and maximum values of the dataset. Grid cells with the highest GST or Sunshine hours will be awarded a value of 1, and those with the lowest a value of 0.

Once the fuzzification process was complete the climate datasets were integrated into a model again using the Gamma overlay function, with a Gamma of 0.5.

Suitability model sub-set integration

The resulting fuzzy biophysical and climate suitability models were combined using the Fuzzy Overlay Gamma function (Gamma – 0.5) and viticulture suitability factors were subsequently derived from both individual and combined models using the Spatial Analyst Zonal Statistics tool.

Unlike some viticulture-climate studies that present bioclimatic values for zones or regions which in reality are not entirely biophysically suitable, for example Hall & Jones (2010) and Webb et al. (2013) the spatial viticulture suitability analysis presented in Chapter 5 is restricted to values only from cells that fall within the biophysical suitability parameters of this study. This way both regional and localised suitability can be more accurately determined.

The suitability model presented in Chapter 5 was subjected to validation by using a comparison between vineyard biophysical observations, mapped elevation, aspect and slope, and model output for the 13 largest vineyards in England and Wales. A full description of the validation process and outcomes are presented in Section 5.5

WRF model validation, previously referred to in Section 2.1.3 and Steele et al. 2014, was extended further through an analysis of downscaled experiments and their relationships with observed temperature data in a Sussex vineyard. Results are presented in Section 5.7 and form part of an initial investigation into the reliability of high resolution WRF model output for analysis of localised historic modelled weather data.

2.4.6. Viticulture and Sugar beet finance

Section 5.8 of this thesis presents a rudimentary analysis of the potential for land conversion from sugar beet production to viticulture. The analysis employs the biophysical suitability model to illustrate spatial potential, and it employs high level financial data to present an economic comparison. The aim within the Section (5.8) is to illustrate, as a case-study, the additional push and pull factors (in this case financial) that could be used to complement the viticulture suitability model and which form an essential part of the decision-making process regarding viticulture suitability, beyond those of biophysical and climatic realms. Where the suitability model is employed by those within agro-economic policy or land use sectors, or indeed by land owners or potential investors, data regarding financial viability of viticulture is likely to be highly valuable.

Conversion opportunities for land dedicated to sugar beet were estimated by overlaying the biophysical suitability model with locations of sugar beet producers, using data provided by British Sugar. The sugar beet grower locations were provided as a set of coordinates (latitude / longitude), from which point data could be extracted using ArcGIS. ArcGIS Spatial Analyst was subsequently used to calculate how many sugar beet producers fell within land deemed suitable for viticulture.

To provide a rudimentary analysis of production economics and returns, finance data for sugar beet production was obtained from the National Farmers Union (National Farmers Union 2016) and an existing sugar beet grower (Hugh Mason. Pers. comm., 2016). The economics of viticulture and wine production in England and Wales has received very little attention, perhaps surprisingly as the sector has shown recent significant growth – see Section 3.1. For the purpose of this thesis production costs and potential returns were obtained from the only available source – Skelton (2014). The data within Skelton (2014) were derived from the authors own experience of working as a consultant with many English and Welsh vineyards and are therefore not ‘official’ costs. No such official or industry recognised data exists.

2.5. Data collection and methodologies for Chapter 6

2.5.1. Wine quality

Chapter 6 is underpinned by an assessment of the likely repetition of high quality and high value vintages in the Champagne region and England. Defining and selecting historic vintages from the Champagne region, for which growing–season meteorological conditions are analysed, involved obtaining vintage ratings from several sources. No one source of information has overall authority on what constitutes a 'high-quality' vintage. As such, high quality vintage years were derived from an assessment of vintage ratings by 'experts'. In this case the following sources of information / vintage ratings were used: Jancis Robinson Purple Pages (Robinson 2015); Robert Parker Vintage Ratings (Parker 2015); The Wine Society Vintage Chart (The Wine Society 2015); Decanter Magazine Vintage Guides (Decanter 2015); The Wine Spectator Wine Ratings (The Wine Spectator 2015); and, Berry Bros. & Rudd Vintage Charts (Berry Bros. & Rudd 2015). A similar process of identifying high quality vintages was used by Jones & Goodrich (2008) although they only use one source – the Wine Spectator.

2.5.2. Champagne vintage quality determination

Vintage ratings are commonly declared through a process of sensory evaluation by judges or a panel of judges, who use experience and expert opinion to determine a wine quality score relative to its 'typicity' of a style. Cumulatively these build to agreement or disagreement regarding a region's vintage (year of grape harvest) quality. Where there is alignment in perceptions of high quality, amongst various judges or panels of judges, an 'accepted' indication of vintage quality is achieved. Although somewhat subjective it is the general consensus of expert opinion that drives wine and vintage ratings, and which ultimately contribute to wine value. Where agreement is reached on regional quality of a vintage there is opportunity to investigate the weather conditions that occurred during that growing-season, as all else being equal these likely contributed to vintage quality, and an opportunity is presented to employ future climate scenarios to assess the likely repetition of these conditions.

Vintage ratings are representative of the whole Champagne region and not specific vineyards, by combining data from different sources, any possible biases due to taster bias or potential 'one offs' was reduced. For the purpose of assessing conditions in only the best vintages those with the highest scores were selected, see Table 2.4.

Table 2.4: 1989–2008 Champagne vintage quality ratings

Vintage	The Wine Society (Notable vintages)	Berry Bros and Rudd (10 = outstanding)	The Wine Spectator (95-100 = classic)	Decanter (5 = excellent)	Jancis Robinson (19.5+/20 = Outstanding)	Robert Parker (96-100 extraordinary)
1989	✓	9	90	5	-	95
1990	✓	10	97	5	✓	93
1991	-	4	-	-	-	-
1992	-	7	-	-	-	-
1993	-	6	87	-	-	88
1994	-	5	-	-	-	-
1995	✓	9	94	-	-	95
1996	✓	8	96	5	✓	97
1997	-	7	87	-	-	90
1998	✓	8	91	-	✓	93
1999	-	6	89	-	✓	92
2000	-	6	89	4	-	92
2001	-	4	-	3	-	88
2002	✓	10	94	4	✓	95
2003	-	6	88	3	-	88
2004	-	8	92	4	-	90
2005	-	7	90	4	-	88
2006	✓	7	94	3	--	-
2007	-	5	89	3	-	-
2008	✓	8	-	5	-	-

1990, 1996, and 2002 are all years in which at least 4 out of 6 ratings award a top possible score or classification. Vintage ratings post 2008 were not available.

A closer examination of the monthly mean temperatures and precipitation totals that occurred in the Champagne region during the growing season in these years (see Section 2.5.3), and the growing season of high and low yielding years (Section 4.1) in the viticulturally dominant areas of England (Figure 3.2) enables a projection of future likely repetition of relevant monthly conditions both in the Champagne region and in England. To undertake such modelling a pattern scaled approach was used, see Sections 1.2.7 and 2.5.6. Additionally historic analysis of monthly growing season mean temperature and rainfall volumes in the Champagne region and viticulturally dominant areas of England allow for a comparison between regions.

2.5.3. English and Champagne historic and future climate data

To first derive historic growing season monthly mean temperature and monthly precipitation values for the Champagne region of France and south-east England the CRU TS 3.23 (1901–2014) dataset (Harris et al. 2014) was used. The CRU TS 3.23 gridded dataset follows updates to the earlier high-resolution

(0.5° × 0.5° latitude/longitude) observed monthly datasets (Mitchell 2003). CRU TS 3.23 provides a globally complete (except the Antarctic) land-only dataset for commonly used surface climate variables (mean temperature, diurnal temperature range, precipitation, wet-day frequency, vapour pressure and cloud cover), although for the purpose of this study mean temperature and precipitation were the only variables used. Infilling, to make the dataset as complete as possible, took place based on more distant station data or on relationships with other variables. If no infilling was possible, the value for that variable for the grid box in question is relaxed to the 1961–1990 average (Harris et al. 2014). However, most infilling was required for central Africa and areas within the Southern Hemisphere. Europe was considered most complete (Craig Wallace. Pers. comm., 2016).

To model likely repetition of growing season conditions found in historic Champagne vintage years and high yielding English and Welsh wine years, using a pattern scaled approach (Section 2.5.6), regional patterns representing changes in temperature and precipitation were taken from simulations of 12 CMIP5 GCMs (resolution of 0.5 x 0.5° latitude/longitude (~33 x 33 km); see Table 2.5). These particular model simulations were selected for use as they were promoted through the Coupled Model Intercomparison Project Phase 5 (CMIP5) (used in the IPCC AR5) set of experiments. Model output was derived from the spatial climate scenario generator GlimGen (Osborn et al. 2015; Osborn 2016). ClimGen is based on the pattern scaling approach to generating spatial climate change information and was principally designed to explore the considerable variation between different AOGCMs. Further scientific details are provided in Osborn et al. (2015). ClimGen required data from all four representative concentration pathways (RCPs) (see Section 1.2.7) to make the patterns for the GCM which were then scaled by RCPs 2.6 and 8.5 to get the final output. Only 12 models were used because only 12 centres made their data available (via the CMIP5 portal) for all four RCPs (Craig Wallace. pers. comm., 2016).

2.5.4. Emission scenarios

The IPCC use a series of greenhouse gas RCPs to provide a framework for climate model scenarios. The pathways describe four possible climate futures, which depend on the concentration of greenhouse gases emitted in the future, that in turn depend on likely pathways of human development until the end of the 21st century, covering a feasible range of uncertainty (van Vuuren et al. 2011). RCP2.6, RCP4.5, RCP6.0, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial era values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively). In this thesis only RCPs2.6 and 8.5 were employed to present 'best' and 'worst' case scenarios for radiative forcing. For example, the radiative forcing in RCP8.5 increases throughout the twenty-first century before reaching a level of 8.5Wm^{-2} by 2100. In RCP2.6 radiative forcing reaches a maximum near the middle of the twenty-first century before decreasing to an eventual nominal level of 2.6Wm^{-2} (Taylor et al. 2012). Global surface temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850–1900 for all RCP scenarios except RCP2.6. CMIP5 experiments are integrated using atmosphere–ocean global climate models (AOGCMs), that respond to specified, time-varying concentrations of various atmospheric constituents (e.g., greenhouse gases) and include an interactive representation of the atmosphere, ocean, land and sea ice (Taylor et al. 2012).

2.5.5. Climate models

The World Climate Research Programme's Working Group on Coupled Modelling is responsible for CMIP5, and the climate modelling groups (listed in Table 2.5) produced and made available their model output. Other modelling groups provided data to CMIP5.

Table 2.5: Global climate models used to project future growing season conditions in Champagne and south-east England

Modelling Centre (or Group)	Institute	Model Name
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1
National Center for Atmospheric Research	NCAR	CCSM4 CCSM1CAM5
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-H GISS-E2-R
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	HadGEM2-ES
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR IPSL-CM5A-MR
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5
Norwegian Climate Centre	NCC	NorESM1-M

2.5.6. Pattern scaling mean monthly temperature and precipitation volumes in Champagne and south-east England

Critical to the analysis of climate in the Champagne region of France, and of climate in England, is that the projected future changes in temperature and precipitation are not spatially uniform (Malheiro et al. 2010). To demonstrate projected changes for 2021–2040 (i.e., 20 years centred on 2030) and 2041–2060 (20 years centred on 2050) a pattern scaling approach was adopted. A description of this approach can be found in Sections 1.2.6 and 1.2.7. Pattern scaling was selected for use in this thesis due to limited availability of time and resources, see Section 1.2.6. Furthermore, Section 1.2.6 of this thesis identifies limitations within many existing climate change and viticulture studies due to single or limited climate change models being employed. Where that was the case the inherent uncertainties across models were not demonstrated. The value in taking a multi-model approach, as done in this work (12 GCMs) was realised through multi-model output presented in Chapter 6 that addresses issue of uncertainty.

In this study the observed CRU TS v.2.23 gridded time-series dataset (1901–2014) (Harris et al. 2014) was used for historic monthly growing season temperature and rainfall in high quality Champagne years (1992, 1996, and 2002), and high and low yielding years in south-east England (2006 and 2012 respectively). The observed data were extracted from CRU TS v2.23 using ClimGen (Section 1.2.7). In ClimGen CRU TS 3.23 was also used as the 1961–1990 baseline from which observed anomalies and the pattern of change were simulated by GCMs (Harris et al. 2014; Osborn et al. 2015). Subsequently ClimGen was re-run for all RCPs and GCMs for future years up to 2060. Like other pattern-scaling approaches, ClimGen attempts to emulate the results of more complex GCMs by separating the geographical, seasonal and multivariate patterns of climate change from their amplitude, with the latter represented by the global-mean temperature change.

Values from the 24 model outputs (12 for mean monthly temperature and 12 for monthly precipitation totals) were then extracted from the grid-cells (0.5° x 0.5°) that covered the majority of vineyards in south-east England and Champagne – see Figure 6.1.

Chapter 3

Recent trends in English and Welsh viticulture and an assessment of wine producers' perspectives of climate change

This chapter is comprised of work published in the *Australian Journal of Grape and Wine Research* (Nesbitt et al. 2016), with some additional material. It presents results from a gathering, analysis and review of data into the emergence, scale and distribution of recent wine production in England and Wales, and an assessment of grape-growers / wine producers' perspectives on weather, climate and climate change impacts, risks, and opportunities for English and Welsh viticulture. The findings offer an analysis of recent sector growth, for the first time, and a benchmark of producers' views and observations regarding the relationships between sector growth, yields, and perspectives on climate change. These results form an initial assessment, compiled from the only available raw data, of a young emerging agriculture sector in England and Wales, and steer the direction of the thesis.

3.1. Recent trends in English and Welsh viticulture

Evidence of past English and Welsh viticulture – climate connections (Section 1.1.4) is independent of assumptions regarding historic wine quality, but does suggest that in periods of warmer conditions increased viticulture potential would follow.

The revival of English and Welsh viticulture began in the early 1950s, and the planting of a vineyard (0.4 ha) in 1952 at Hambledon in Hampshire (Skelton 2014), marked a turning point in the history of grape growing in England and Wales. This vineyard was the first commercial vineyard planted in England since the Castell Coch, South Wales vineyard seventy-five years earlier (Skelton 2001), but which was subsequently grubbed up. Hambledon vineyard, established by Major-General Sir Guy Salisbury-Jones, was conceived following experiments by Ray Barrington Brock at his 'Oxted Viticultural Research Station', which he launched in 1945 to test whether grapes for wine production could be successfully grown in the existing climate, for the production of wine (Skelton 2014). Brock, in the preface to *'Report No. 1 – Outdoor Grapes in Cool Climates'* (1949), noted "We felt equally sceptical about the comments on Grapes", referring to the received horticultural wisdom of not being able to grow grapes outdoors in England. Brock had obtained François de Castella's *Handbook on Viticulture for Victoria (Australia)* (de Castella 1981), which contained observations on growing vines in cool regions and he setout to disprove such perceived wisdom. Over a 25-year period Brock trialled over 600 different table and wine grape cultivars (Skelton 2001).

From 1951 up until 1993, the volume and spatial distribution of UK vineyards increased (Skelton 2010). However, analysis of Food Standards Agency data (Appendix B), performed for this thesis, shows that from 1993 to 2004 a 29% decline in both vineyard total area (ha) and number occurred. This decline can be seen in Figure 3.1. It has been attributed to an overwhelming combination of issues including sub-optimal cultivars for the climatic conditions, poor vineyard site selection, poor winemaking, poor quality, high costs, low yield, international competition and marketing difficulties (Skelton 2010). The reduction in vineyard area, area in production and vineyard number, evidenced in Figure 3.1, indicate a grubbing up or abandonment of vines during 1999–2004 but since then a significant increase in area under vine has been accompanied by an increase in vineyard numbers from 333 to 448 in 2013, as illustrated in Figure 3.1. The Food Standards Agency (FSA) data available in Appendix B indicates 470 vineyards were registered with the FSA in 2013 but through anecdotal conversations with wine producers this figure was deemed inaccurate. By 2014 the FSA recorded 466 registered vineyards in England and Wales (Food Standards Agency 2014), and by 2016 English Wine Producers estimated there were nearly 500 vineyards (English Wine Producers 2016b), taking the present number above the previous peak of 479 in 1993.

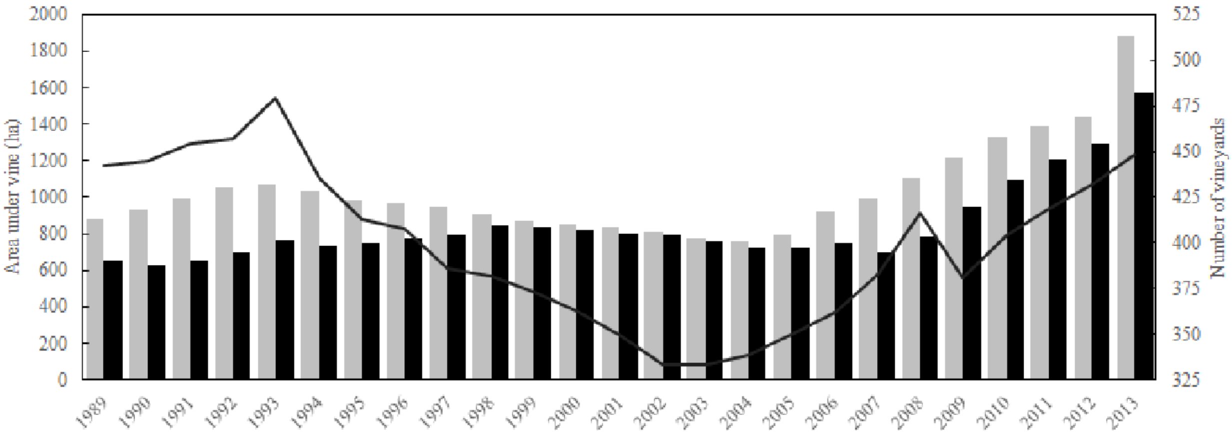


Figure 3.1: Area under vine in the United Kingdom (■), area in production (■), and vineyard numbers (1989–2013) (—), based on data from the Wine Standards Branch of the Food Standards Agency (see Appendix B).

Further data (Appendix B) analysis also demonstrates that average vineyard size has also risen from 2.24 in 2004 to 4 ha in 2013 and area in production, shown in Figure 3.1, lags total area. It rose until 1998 before dropping 14.3% to 722 ha in 2004 and subsequently started to rise again. By 2013, total UK vineyard area (1884 ha) was greater than that of another emerging cool climate sparkling wine producing region: Tasmania (ca. 1500 ha) (Wine Tasmania 2014). The short-term reduction in UK vineyards between 2008 and 2009 follows low yields in 2007 and 2008 (see Figure 4.8), but the precise reason for the decline is uncertain. In 2009/10, the Wine Standards Branch of the Food Standards Agency re-categorised vineyards into ‘commercial’ and ‘amateur/hobby’. From this time onwards, the data on vineyard number, presented in Figure 3.1, relate solely to commercial vineyards and may partly explain the reason for the decline (Stephen Skelton, pers. comm., 2014).

An analysis of vineyard planting records performed for this thesis, from data found in Skelton 2001, 2008, 2010, and 2014, showed that recent vineyard plantings have predominantly occurred in southern England (50–52°N) with vineyards in south-east (East and West Sussex, Kent, and Surrey) and south-central (Berkshire, Hampshire, the Isle of Wight, and Wiltshire) England accounting for approximately 820 and 270 ha of the UK’s vineyard area respectively, almost 58% of the total. Locations of vineyards ≥1 ha, and their size (based on vineyard location details and scale data from the UK Vineyard List (Skelton 2015), are presented in Figure 3.2, and Unitary Authority vineyard hectarage in Table 3.1. Figure 3.2 shows that the majority of larger commercial vineyards are positioned within south-east and south-central England, however the overall spatial distribution of vineyards within England and Wales is much larger.

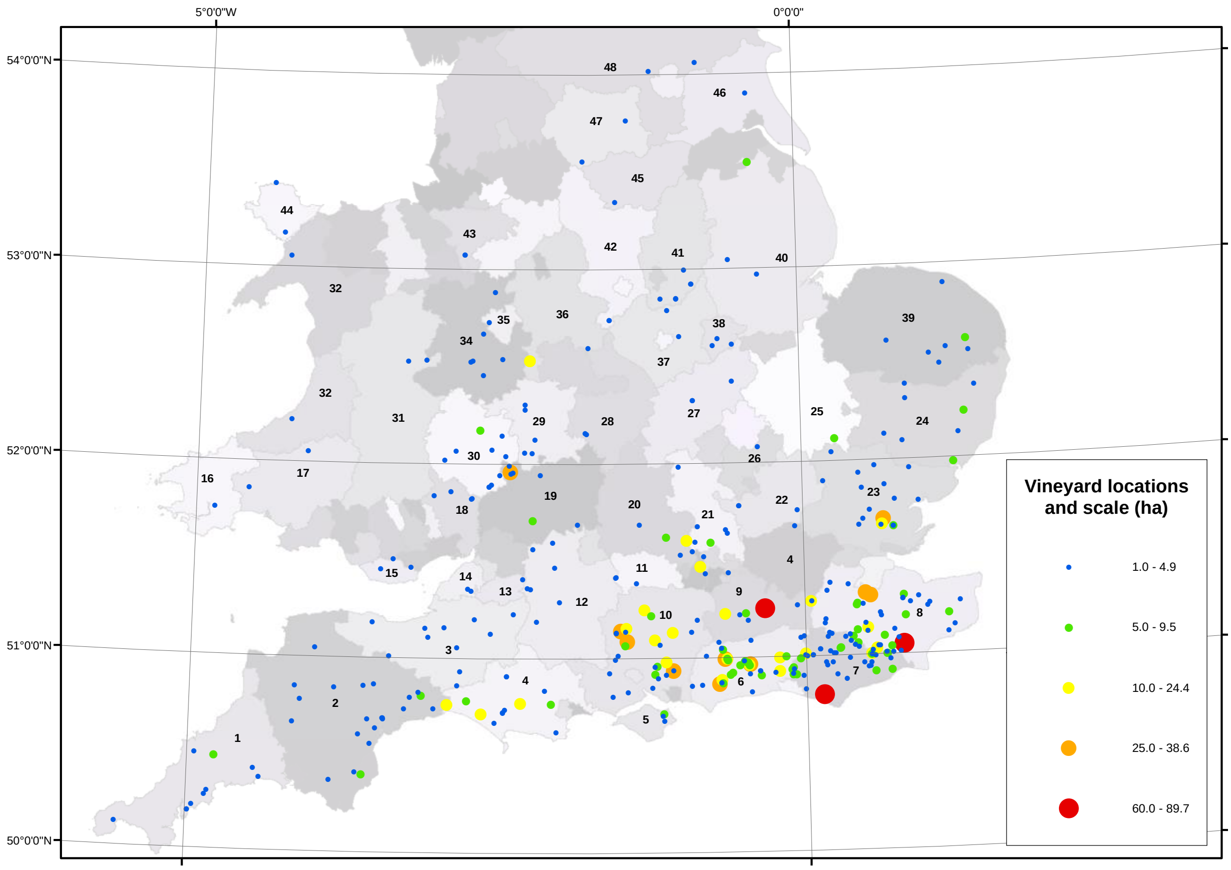


Figure 3.2: English and Welsh vineyard (≥1 ha) distribution and scale (ha) in November 2015. Numbers denote Unitary Authorities identified in Table 3.1.

Table 3.1: English and Welsh vineyard (≥1 ha) hectarage by Unitary Authority in November 2015. Source: UK Vineyards List (Skelton 2015)

Vineyard area (ha)	Unitary Authority	Figure 3.2 reference	Vineyard area (ha)	Unitary Authority	Figure 3.2 reference	Vineyard area (ha)	Unitary Authority	Figure 3.2 reference
313.9	Kent	8	15.2	Buckinghamshire	21	4.6	North Somerset	14
310.2	West Sussex	6	14.5	Wiltshire 14.5	12	4.6	Rutland	38
253	East Sussex	7	14.4	Lincolnshire	40	4.2	Leicestershire	37
221.1	Hampshire	10	12.9	Staffordshire	36	4.1	West Yorkshire	47
121.6	Surrey	9	12.4	Worcestershire	29	2.8	Gwynedd	33
100.5	Essex	23	11.5	Shropshire	34	2.6	Isle of Anglesey	44
69.7	Devon	2	11.1	Nottinghamshire	41	2.4	Ceredigion	32
62.9	Dorset	4	10.4	Isle of Wight	5	2.1	Central Bedfordshire	26
49.8	Gloucestershire	19	8.8	Monmouthshire	18	2.1	East Riding of Yorkshire	46
31.1	Oxfordshire	20	8.4	Cambridgeshire	25	1.6	Bath & North East Somerset	13
30.1	Suffolk	24	6.5	North Yorkshire	48	1.6	Telford & Wrekin	35
29.6	Cornwall	1	6.3	Vale of Glamorgan	15	1.2	Derbyshire	42
25.5	West Berkshire	11	5.7	Warwickshire	28	1.2	Cheshire West & Chester	43
22.2	Herefordshire	30	5.2	Powys	31	1	Pembrokeshire	16
19.9	Somerset	3	5	Hertfordshire	22	1	Carmarthernshire	17
18.7	Norfolk	39	4.7	Northamptonshire	27	1	South Yorkshire	45

Cultivars

Analysis of historic vineyard cultivar records (Section 2.2.3) indicates that the dominant cultivars during the period 1990–2003 (Müller-Thurgau, Seyval Blanc and Reichensteiner) were superseded during 2004–2013 by Chardonnay and Pinot noir, as presented in Figure 3.3. This change is indicative of the wine production sector shifting increasingly to sparkling wine production, for which these latter cultivars are used. Chardonnay and Pinot noir are also the dominant cultivars of the Champagne region (Comité Champagne 2016), along with Pinot meunier – also used in Champagne and English Sparkling Wine (Table 3.2). It is potentially also indicative of the problems suggested by Skelton (2010), associated with quality and marketing of traditionally dominant cultivars, i.e. Müller-Thurgau, Seyval Blanc and Reichensteiner.

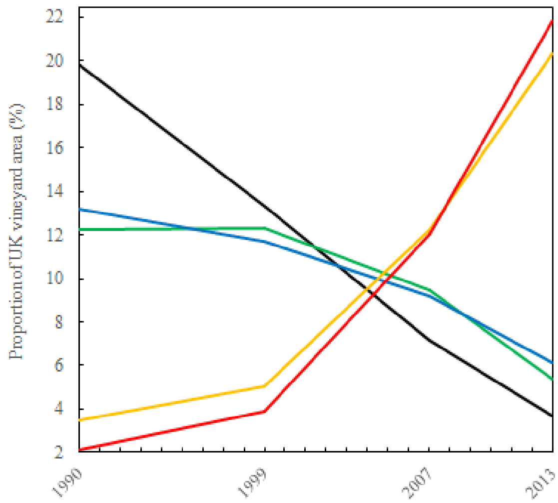


Figure 3.3: Changing distribution of dominant vine cultivars (1990–2013), Müller-Thurgau (—), Reichensteiner (—), Seyval Blanc (—), Pinot Noir (—) and Chardonnay (—) in the United Kingdom, as a proportion of total vineyard area. Source: Wine Standards Branch Vineyard Registers (1990, 1999, 2007 and 2013) and Skelton 2008, 2010 and 2014.

Despite a growing dominance of Chardonnay and Pinot noir cultivars, it remains the case that a broad range of cultivars are grown in England and Wales, evidenced in Table 3.2. This wide range may reflect a particular brand focus or market demand, or represent vineyards established when such cultivars were 'in vogue'; unlike annual crops *Vitis vinifera* L. grapevines are perennials and are commonly planted with a >35-year life-span (Jackson 2014). This could lead to production inertia where producer and brand are synonymous with specific cultivars and wine style, potentially making change both difficult and expensive. In addition, the broader range of cultivars found across England and Wales may represent a targeting of cultivars 'suitable' to the weather or climate conditions experienced in the areas in which they are grown.

Table 3.2: Top 15 cultivars in 2013 by vineyard area in England and Wales (Skelton 2014)

Cultivar	Hectarage (2013)
Chardonnay	327
Pinot noir	305
Bacchus	131
Seyval blanc	92
Reichensteiner	80
Pinot meunier	69
Müller-Thurgau	56
Rondo	47
Madeleine Angevine	46
Schönburger	35
Ortega	35
Pinot blanc	25
Regent	24
Pheonix	24
Pinot noir Précoce	20

No assessment of the 'rationale' behind such a broad distribution has been made, but a clear shift towards Chardonnay and Pinot noir, and a large presence of Pinot meunier, indicates market demand for Sparkling Wine, and suggests an increasing 'suitability' for such cultivars, if suitability can be determined by their mere presence. As discussed in Section 1.1.1 climate, and growing season temperature in particular, are critical determinants of viticultural and cultivar suitability. The observed change in dominant *Vitis vinifera* L. cultivars in England and Wales may also be an indicator of changing climate conditions, influencing what is being planted. This observation and interesting hypothesis is analysed further in Chapter 4.

3.2. English and Welsh grape-growers / wine producers' perspectives on weather, climate and climate change impacts, risks, and opportunities for English and Welsh viticulture

Anecdotal drivers behind the recent expansion of English and Welsh viticulture, presented in Section 3.1, included increased wine quality and improved marketability of English wines and changes in climate altering cultivar suitability (Skelton 2014). However, no actual evidence was available or research published, prior to this thesis, to elucidate and explain the observed changes in cultivars and sector expansion. Without such information, production risks associated with weather and climate cannot be elucidated, and threats and opportunities relating to future climate scenarios cannot be analysed. This section of the thesis presents results from a survey of English and Welsh wine producers (see Appendix A) designed to illuminate their perspectives of weather and climate impacts on English and Welsh viticulture. This was the first attempt to better understand the drivers behind sector growth and demonstrate the impacts of weather and climate on viticulture viability in England and Wales. Further evidence of relationships between climate change and increasing vineyard presence in England and Wales is presented in Chapter 4.

Survey results

All 448 grape growers / wine producers in England and Wales were invited, via means outlined in Section 2.2.1, to respond to the survey. The survey resulted in 42 responses from producers (9.4 %) responsible for 313 ha of vineyards (17 % of the UK total). The response sample was deemed representative of the sector as most of the respondents (31) were from south-east and south-central England where most vineyards were located (Section 3.1 and Figure 3.2), five were from south-west England, one from Wales, two from East Anglia, and three from the Midlands. All respondents owned or managed vineyards ranging in size from just over 1 to more than 20 ha. Survey responses can be summarised as follows:

Producers' views on factors that have contributed to the growth of the UK wine production industry.

Of the survey responses, 66% stated that climate change had, or maybe had, contributed to the recent growth of the industry; 28% stated that it had not or were doubtful that it had contributed, and 6% did not know (Figure 3.4).

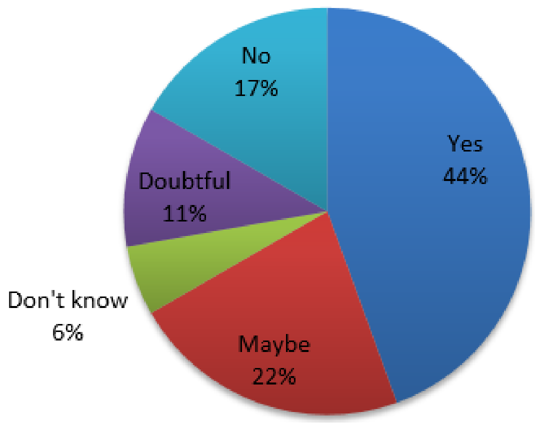


Figure 3.4: Producers' responses to the question: 'Has climate change contributed to the growth of the UK wine production industry?'

Producers were subsequently asked: '*What other factors have contributed to its growth?*'

Responses, shown in Table 3.3, provided some insight into the structural adaptation associated with expansion of the sector. The majority concerned increasing awareness of quality and associated awards;

further marketing; increasing cultivar suitability; education and better management; and support for 'buy local'.

Table 3.3: Producers' responses to the question 'What other factors have contributed to its growth?'

Factors contributing to the growth of the UK wine production industry	Responses
• Increasing awareness of quality, awards and more marketing	7
• Increasing varietal suitability for the UK	5
• Education and better management	5
• Increasing investment	4
• The fashion for the style of wines produced in the UK	3
• Support for 'buy local'	3
• Mechanisation and imagination	1
• Limited space in France	1
• Vineyard scales	1
• Competitiveness	1
• Maturing age of vines	1

Producers' perspectives on whether '*climate change is a threat to or opportunity for wine production in the UK, and why?'*

Of the responses, 64% thought climate change was a threat to wine production in the UK; 29% viewed climate change as both a threat and an opportunity, and 7% saw it as an opportunity. Reasons for attributing threats and opportunities are presented in Table 3.4. These may seem surprising results considering the significant increase in viticulture in the UK, and an assumed positive relationship with climate change expressed in answers to the first question. This apparent contradiction might be explained through producers' perceptions of increasing average temperature being accompanied by extreme weather events, which they attribute to climate change, contributing to low yield in some years. This is discussed in Section 3.3 and is a key driver for this research.

Table 3.4: Producers' responses to the question 'Is climate change a threat to or opportunity for wine production in the UK, and why?'

Threats	Responses	Opportunities	Responses
Inter-annual variability in climate suitability	7	Warmer growing season weather improving yields and quality	3
Extreme weather	5	More viable varieties	2
Increased disease pressures due to warm and wet weather	5	Later harvest dates and increased ripening potential	1
Weather during critical periods of flowering and maturation	4	Average temperatures will go up in 10-20 years	1
Unpredictable weather	4	Weather may settle over time	1
Increased disease pressures due to mild, wet winters and lack of winter frost	3		
Wind affecting physiological development	2		
Increasing gulf between good and bad years	1		
One year affecting the next	1		
Gulf Stream may end	1		

Producers were also asked about factors that they thought had contributed to high and low yielding years. Historic (1989 – 2012) English and Welsh wine yield data was sourced from the Wine Standards Branch of the Food Standards Agency (Appendix B), and presented to producers for comment – see Appendix A and Figure 3.5.

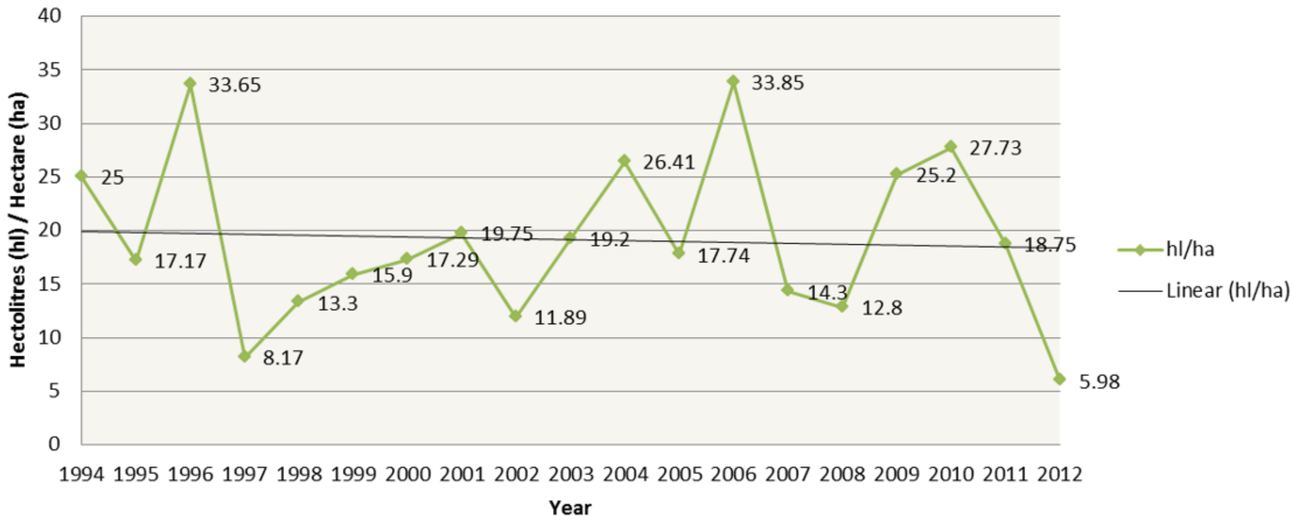


Figure 3.5: Wine yield data presented to producers in the questionnaire (Appendix A). Data supplied by the Food Standards Agency (2013)

Producers' perspectives on reasons for high and low yielding years are presented in Table 3.5. High yielding years (Figure 3.5; 1996, 2006 and 2010) were primarily attributed to good or 'optimum' temperature and weather conditions at flowering and fruit set, both in the seasons referred to and in the previous season. Warm springs, autumns and growing seasons, and the absence of frosts were also given as reasons. Low yielding years (Figure 3.5; 1997, 2007, 2008 and 2012) were primarily attributed to wet and cold weather during flowering and fruit set, wet and cold growing seasons, low levels of sunlight, poor summers in preceding years and spring frosts.

Table 3.5: Producers' perspectives on reasons for high and low yielding years

Year	Yield (hL/ha)	Attributed causes of high or low yield	Responses
		High yielding years	
2010	27.73	• Optimum temperature and moisture at flowering and fruit-set • Good weather between flowering and fruit-set in 2009 • Long warm growing season • Large and plentiful inflorescence • Warm autumn • Warm spring	7 3 2 2 2 1
2006	33.85	• No frosts and good weather during flowering • Good all round summer	1 1

1996	33.65	• No frosts, good weather during flowering and good management of diseases	1
Low yielding years			
2012	5.98	• Poor flowering due to weather • Poor fruit-set due to weather • Wet and cold growing season • Low sun-light levels • Cold wet summer • Cold wet spring	16 5 5 3 2 1
2008	12.80	• Wet and cold during flowering • Poor summer in 2007 • Low bud numbers • Cold spring and late frost	1 1 1 1
2007	14.30	• Wet weather in flowering • Poor fruit-set • High yield in 2006	2 1 1
1997	8.17	• Spring frost (May) • 11 year solar cycle low	4 1

3.3. Discussion

This chapter highlights both a lack of existing vineyard and wine production data for England and Wales, and an absence of any prior analysis of the limited data that is available. When collated and analysed, for the purpose of this thesis, it presents evidence of a rapid and significant expansion of English and Welsh vineyard numbers, an increase in vineyard scale, and an increase in overall hectarage under vine. It also shows a recent (2004) change in dominant *Vitis vinifera* L. cultivars established in English and Welsh vineyards. These findings require explanation as they suggest a growth in confidence in the sector, increased investment and, superficially, an improved climatic suitability for the establishment of *Vitis vinifera* L, particularly Chardonnay and Pinot noir.

The survey of English and Welsh wine producers sheds some light on reasons for sector growth. Whilst the responses received identified the critical roles of up-skilling, marketing and investment, climate change was highlighted as a contributory factor. However, nearly all wine producers / grape growers who responded to the survey did not perceive climate change entirely as a positive factor. Key threats were an increase in inter-annual variability, extreme weather and increased disease pressures due to warm and wet weather, and weather during the critical periods of flowering and maturation. Key opportunities related to the potential for warmer growing season weather improving yields and quality.

The perceptions that climate change presents both threats and opportunities, but that it had driven sector growth, and the observation that it was largely intra-seasonal weather conditions that affected yields presents a mixed picture of viticulture suitability, and of production risks. These merited further research as the trajectory of viticulture sector growth indicates that an increased knowledge-base could usefully underpin investment decisions and vineyard management activities to raise yields and sector sustainability.

As evidenced in Section 3.1, the change in dominant cultivars to those used for Sparkling Wine production indicates a significant shift in production and wine style that is presumably driven by market demand. Growers / producers themselves commented, through the questionnaire, about an increase in quality and recognition through awards for wines. A combination of increased production and quality could lead to growth in product demand, which in turn could fuel further investment in the sector. However, the spatial distribution of vineyards in England and Wales (Figure 3.2) is not being guided by a comprehensive analysis of climatic or biophysical suitability for viticulture in England and Wales, and potentially there is a failure to optimise viticulture positioning which could lead to high investment risks. Chapter 5 is therefore dedicated to a first assessment of viticulture suitability in England and Wales, and builds on findings from analysis of weather and climate relations with viticulture, presented in Chapter 4.

Through the survey producers recognised both low and variable historic wine yields, furthermore they attributed these to weather and climate conditions during the growing season. These results drive a closer analysis of historic relations between weather, climate and wine yields in England and Wales, presented in Chapter 4, to help identify for the first time both threats and opportunities that growing season conditions in England and wales present for the viticulture sector.

Dominant survey feedback regarding climate change threats elicits further investigation, and the seeming contradiction between positive and negative attributions of climate change and viticulture in England and Wales requires further research. Chapter 5 explores recent (1954–2013) temperature and precipitation changes in the main viticulture areas of south-east and south-central England. Future changes in these variables are explored in Chapter 6 to assess climate change model predictions against producers concerns of change and variability. Furthermore, the issue of wine quality, raised by survey respondents, but which receives little research attention (Section 1.2.5), under future climate change scenarios is also explored in Chapter 6, with specific reference to the dominant cultivars of both the Champagne region of France, and England – Chardonnay and Pinot noir.

Chapter 4

Impacts of recent climate change and weather variability on the viability of viticulture in England and Wales

This chapter comprises of work published in the *Australian Journal of Grape and Wine Research* (Nesbitt et al. 2016), with some additional material.

Weather variability and associations with climate change were raised by producers as threats to viticulture in England and Wales (Section 3.2). Before this thesis determines whether potential future climate change may make viticulture more or less viable in England and Wales this chapter first analyses sensitivity to past climate variability. It presents results from a quantification of averages, extremes, trends and variability in growing season (April – October) temperature and precipitation since the revival of English and Welsh viticulture (1954–2013), in the main grape growing regions, south-east and south-central England (Figure 3.2). It also employs modelled growing season temperature data (2004–2013) for all of England and Wales to explore spatial variance. Results in this chapter assess producers' perceptions of weather and climate risks through a statistical analysis of temperature and precipitation relationships with available wine yield data (1989–2013). It also evaluates the reliability of GST as a bioclimatic indicator of English and Welsh viticultural suitability, and establishes a relationship between GST, wine yield and dominant English and Welsh vine cultivars.

4.1. Temperature and precipitation trends in south-east and south-central England (1954–2013)

Temperature and precipitation trends were calculated using Met Office (2014b) data as described in Section 2.3.1. For 1989–2003, mean GST was 13.7°C, and for 2004–2013 was 14.0°C, both within the 'cool climate' climate/maturity grouping (Jones 2006 – see Figure 1.4). The equivalent period's average growing season precipitation totals were 416 and 427 mm, respectively. Over the 60-year period (1954–2013), linear trend lines reveal increasing GST (Figure 4.1), with 31.5% of variation in GST 'explained' by its relationship with time, and a slight decrease in precipitation. However, these trend lines mask far from linear temperature and precipitation trends, evidenced in Figure 4.1.

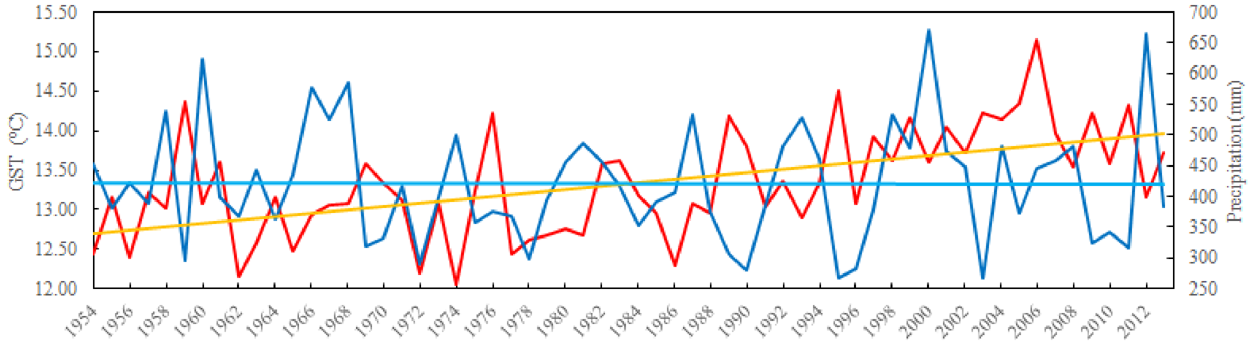


Figure 4.1: GST (—) and growing season precipitation (—) for south-east and south-central England (1954–2013) with linear trends for GST (—) and precipitation (—).
GST, y = 0.0216x + 12.674, R^2 = 0.3153; precipitation, y = -0.0271x + 421.52, R^2 = 2E-05. Data source: Met Office (2014b)

The standard deviation of inter-annual GST (1954–2013) is 0.7°C, reflecting variability between years that prior to 1993 has taken GST perilously close or below the critical threshold of 13°C (Jones 2006 – see Figure 1.4) Strong inter-annual variability (standard deviation = 96 mm) in growing season precipitation is also visible, but no positive or negative linear trend in precipitation totals for the 1954–2013 period was found.

4.2. South-east and south-central England growing season precipitation and temperature anomalies for 1989–2013 against a 1961–1990 mean

When GST and precipitation for individual years during the period 1989–2013 are presented as anomalies against a 1961–1990 baseline of 13°C and 407 mm, respectively, as in Figure 4.2, all years, except 1991 and 1993 – potentially influenced by the Mount Pinatubu volcanic eruption (Parker et al. 1996), were warmer than the baseline average. However a relatively even spread of positive and negative precipitation anomalies was found, typically ±30% (excluding the wet outliers in the years 2000 and 2012) suggesting little change in total or variability. Since 2000, 8 years have had a GST of >1°C above the 13°C cool climate/maturity baseline deemed suitable for high-quality wine production, with a peak in 2006 of 15.1°C, just reaching the intermediate classification (Jones 2006, 2007 – see Figure 1.4).

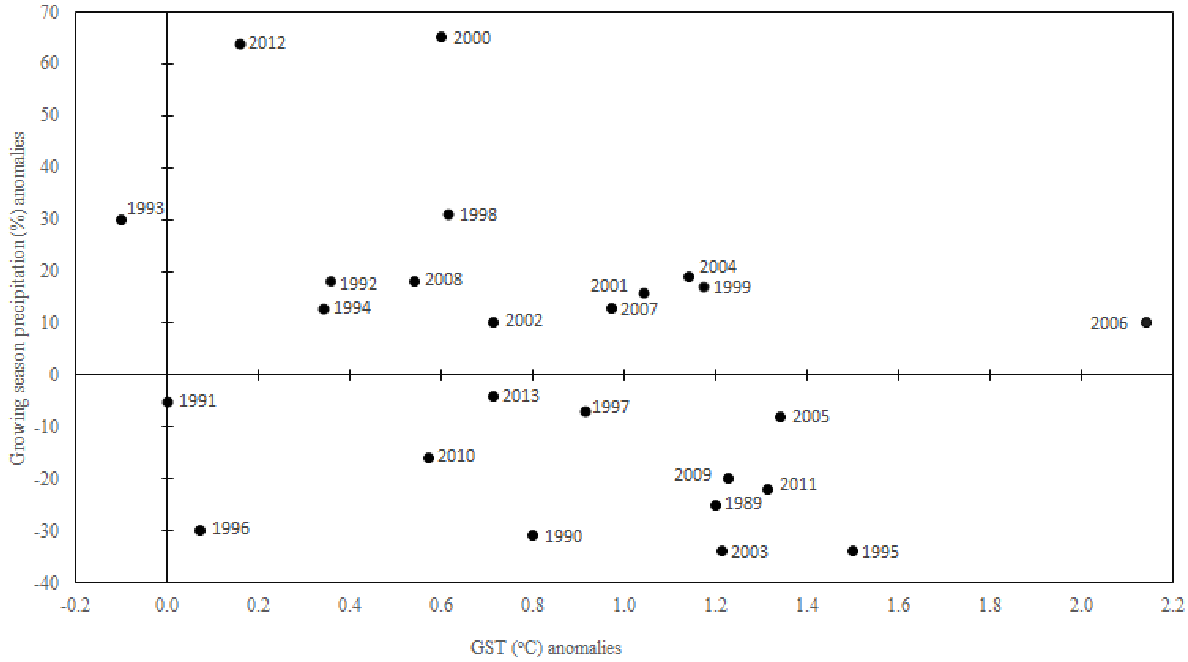


Figure 4.2: South-east and south-central England growing season precipitation (%; y-axis) and growing season temperature (°C; x-axis) anomalies for 1989–2013 against 1961–1990 means of 407 mm and 13°C, respectively. 0.0 = 13°C, 1.0 = 14°C and 2.0 = 15°C GST. Data source: Met Office (2014b)

Growing seasons in subsequent years (2014 and 2015) recorded GST's of 14.6 and 13.5°C respectively, and precipitation totals of 461 and 413 mm respectively, i.e. both growing seasons were wetter and warmer than the 1961–1990 means.

4.3. GST for 2004–2013 over England and Wales

GST is a commonly used bioclimatic index (Section 1.2.2) and the non-linear changes to growing season temperature, observed in Figure 4.1, suggests an increase in viticultural suitability in south-east and south-central England if GST is considered a reliable indicator of suitability. Maps based on WRF model output (Figure 4.3), described in Section 2.1.3, show GST for 2004–2013 and illustrate inter-annual GST variability over the wider England Wales geographic area. This series, with a 9-km resolution, depicts temperature in some years above 13°C in areas well beyond south-east and south-central England. The years 2006 and 2012, identified by questionnaire responses as 'extreme' high and low yielding years respectively (Section 3.2), can be seen to remain 'extreme' at a national scale. The tendency for higher regional GSTs can be seen for south-east, south-central and eastern England. Southern areas with greater coastal proximity can also be seen to have higher GSTs in general, with cooler areas showing in northern England, central Wales and central south-west England. Interestingly, Figure 4.3 also indicates similar or slightly higher GSTs in parts of East Anglia, to those found in south-east and south-central England.

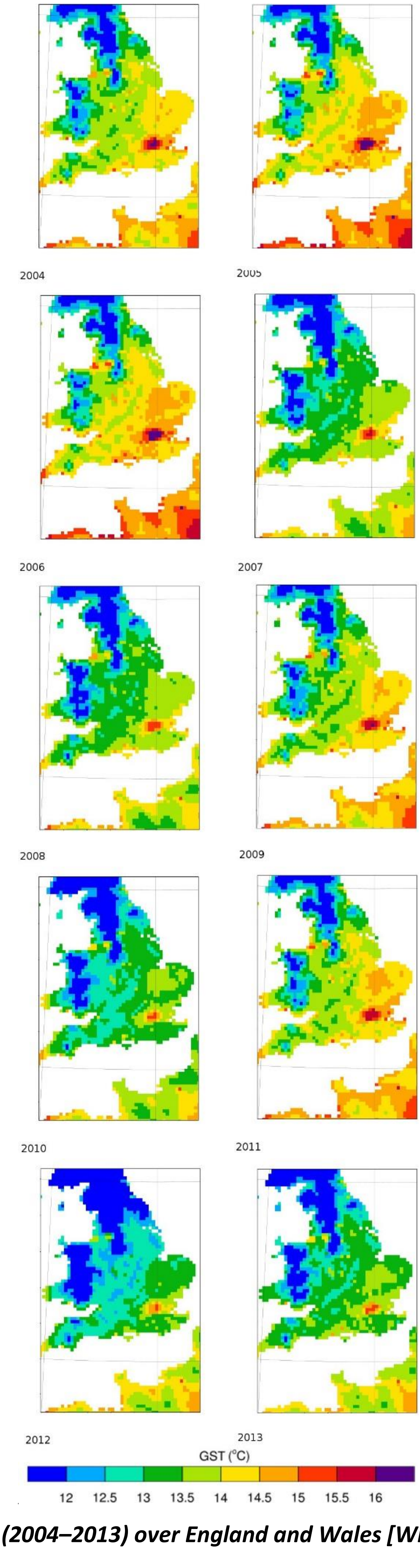


Figure 4.3: GST (2004–2013) over England and Wales [WRF model output]

4.4. South-east and south-central England spring air frosts

Average growing season (April – October) conditions obscure shorter periods of fluctuation in temperature and precipitation, which are significant for grapevine phenology and potentially for yield. One thermal phenomenon deemed potentially limiting to viticulture and identified by producers (Section 3.1) as negatively affecting yields is spring air frost. Damage caused by spring air frosts not only puts at risk the current season's crop but also, because of the perennial nature of grapevines, can influence the productivity of vines for two to three seasons (Trought et al. 1999). Air frost, measured at 1.25m above ground level (Met Office 2016), represents temperatures below 0°C at a height above the vine bud and fruiting zone, usually around 70–90 cm in English and Welsh vineyards (Skelton 2014). It is these areas of the vine that are critically sensitive to freezing temperatures during the phenologically sensitive months of April and May when buds are bursting and shoots emerging (Trought et al. 1999). Spring radiation frost normally results in lower temperatures at lower heights (Hammersmith 2014) so it might be that the vine experiences a frost when the 1.25m temperature is higher than 0°C. Whilst the likelihood of air frosts within a vineyard will partly depend on site topography and cold air drainage (Hammersmith 2014), observed occurrence (interpolated and regionally averaged; Met Office 2015b) provides a signal of regional risk. Analysis of the number of days in April and May, in south-east and south-central England, when air frosts have historically occurred (1961–2013) provides an indication of both scale of risk and trends in frequency over time. It can be seen from Figure 4.4 that the number of days with air frost is both higher (3–4 days) and more variable in April than in May (<1 day). A slight linear trend line indicates a reduction in air frost days over time, particularly in April, but no significant decreasing trend in the frequency of air frost days was found in either month. A downward trend has also been observed in annual air frost day frequency (1961–2007) for UK regions (Jenkins et al. 2008). During the recent period of interest (1989–2013) to this thesis, combined April and May air frost days have ranged from 0.6 in 2011 to 7.4 days in 2013, with an average of 3.6 days. It is acknowledged that air frost severity and the length of an air frost event could also be important factors, and that spring air frost risk is largely dependent on localised climate and vineyard topography, but these are not discussed here as the relevant data was unavailable. Furthermore it is recognised that means of frost protection are available to producers to help mitigate risks (Hammersmith 2014). Here, it is regional inherent risk that is presented in order to assess trends and relationship with national wine yield, see Section 4.6.

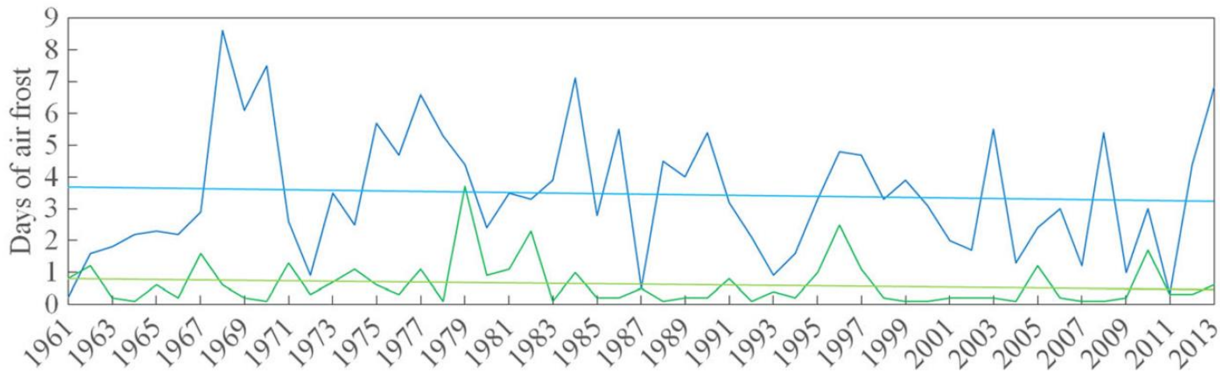


Figure 4.4: April (—) and May (—) air frost frequency (1961–2013) across south-east and south-central England with linear trends for April (—) and May (—).
April, y = -0.0087x + 3.6946, R^2 = 0.0046; May, y = -0.0069x + 0.8171, R^2 = 0.0221. Data source: Met Office (2014b).

Air frost occurrence, under radiation conditions (clear sky and little air movement (Hammersmith 2014; Trought et al. 1999)), is likely preceded by a ground frost (temperatures of <0°C at 3.5 cm above ground level (Met Office 2016)), which whilst not indicative of immediate risk to the grapevine fruiting or bud zone, could, if allowed to accumulate, reach the critical height (70–90 cm) to cause damage. Ground frost observation data is less easily available than air frost data but simulated ground frost (WRF model) demonstrates, in Figure 4.5, spatial and temporal variability in April and May (2004–2013) over England and Wales. Figure 4.5 generally indicates 5–15 air frosts in April and May (combined) per year in south-east and south-central England. These findings are slightly higher than air frost occurrence observed in Figure 4.4 which suggests 2–10 air frosts per year, potentially indicative of the point that ground frosts are likely higher in number than air frosts.

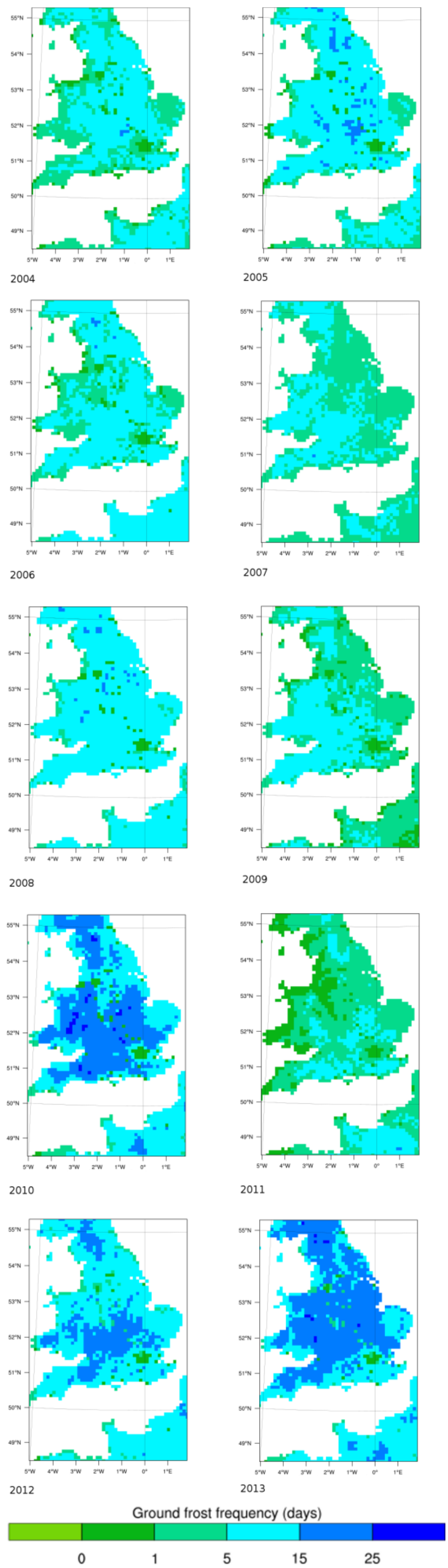


Figure 4.5: April & May ground frosts (2004–2013) over England and Wales [WRF Model Output].

From Figure 4.5 it is interesting to note that areas with lower April and May ground frost occurrence, such as Norfolk, south-west England, and west Wales, have lower vineyard numbers (see Figure 3.2). This suggests opportunities for viticulture in areas less exposed to spring frost risk than the currently dominant areas of south-east and south-central England. The existing spatial distribution and opportunity for viticulture expansion are explored and discussed further in Chapter 5.

4.5. South-east and south-central England monthly temperature and precipitation change for 1989–2013 against a 1961–1990 mean

While calendar months do not equate directly to phenological stages in grapevines, they are used in this thesis as temporal indicators because no data of any length was available for analysis that provided time-stages or phenology dates. Section 4.1 examined changes in mean growing season temperature and total precipitation. In this section individual growing season months are examined for change between two periods, 1961–1990 and 1989–2013, the later period being that for which wine yield and production data was available for analysis (Section 2.2.2). This higher temporal resolution focus, on monthly data, allows for an analysis of relationships between monthly temperature and precipitation phenomena, and wine yield (Section 4.6).

South-east and south-central England mean temperature and total precipitation values for individual growing season months in 1961–1990 and 1989–2013 are presented using box plots to reveal changes in quartile values and extremes. Figures 4.6 and 4.7 refer to temperature and precipitation, respectively. Median temperature values rose in all growing season months except October (-0.3 °C). The greatest median increase occurred in May (+1.4 °C), which also saw its interquartile range move entirely into the upper quartile of the 1961–1990 period. Interquartile median temperature rose most in April (+1.2 °C), a month that also saw two positive temperature outliers in 2007 and 2011. Additionally, the interquartile temperature range expanded 100 % in April, as well as in October. These changes in April and May occur at a sensitive time when budburst and initial shoot growth occur. Outlying and extreme low temperature values in May and June 1996 were not identified through questionnaire results (Section 3.1), and 1996 was identified as a high yielding year, evidenced in Figure 3.5, suggesting temperatures in May and June were not defining variables for yield. Conversely, the low yielding years of 1997 and 2007 both experienced outlying high temperature values in August and April, respectively. Producers attributed the low 1997 yield to frost (Figure 4.4) and the poor 2007 yield to wet conditions during flowering – Section 3.2. There appears to be little correlation between outlying or extreme temperature and yield at this monthly scale.

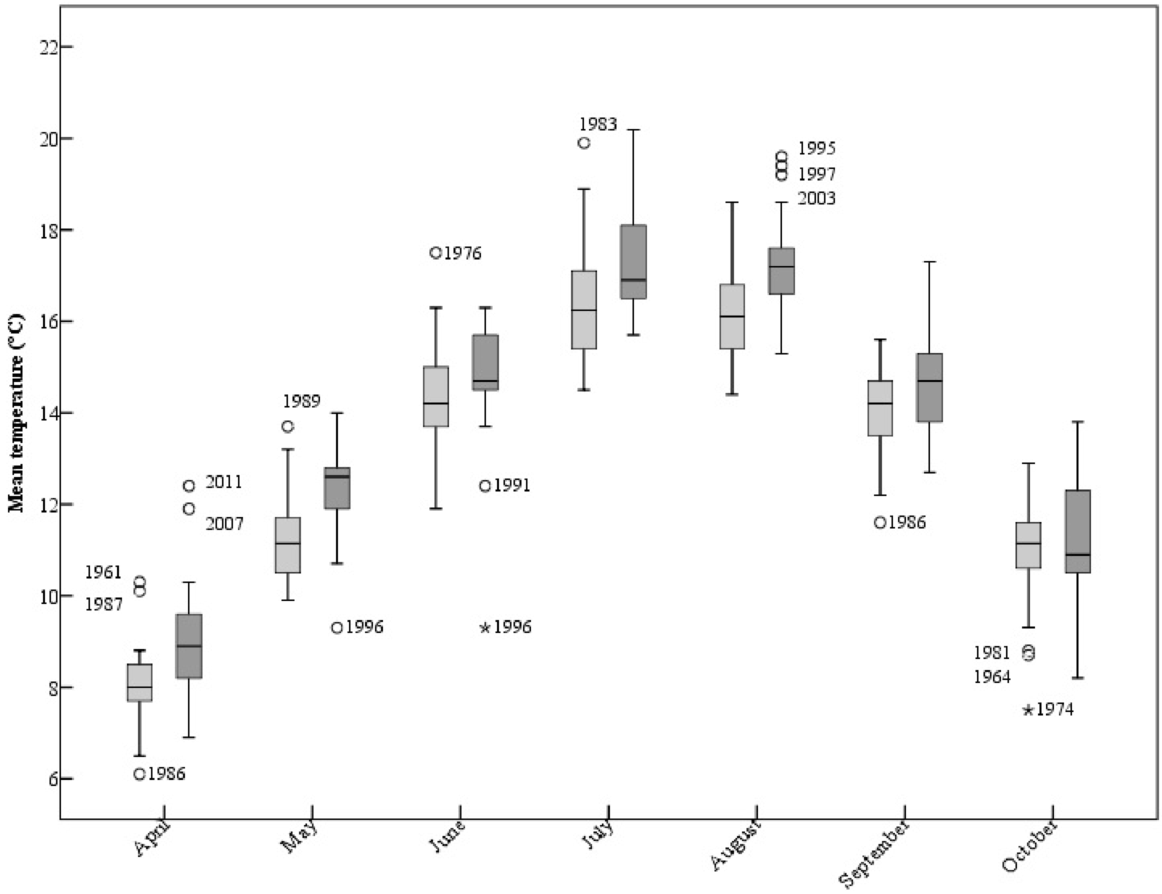


Figure 4.6: South-east and south-central England growing season monthly mean temperature dispersion for 1961–1990 (■) and 1989–2013 (■). ○, outlier (1.5–3 x box length), *, extreme (>3 x box length). Data source: Met Office (2014b)

Between 1961–1990 and 1989–2013, October precipitation totals rose in all quartiles. Median precipitation rose 16 % (10.8 mm). Precipitation during October can be particularly problematic due to the potential for increased disease pressure during the harvest period. April and July saw the greatest increase in maximum precipitation (44.2 and 32.9 mm, respectively). April also experienced an interquartile precipitation range expansion of 53 %. Significantly, little change was observed to the interquartile range or overall distribution (including the 2012 outlier) of precipitation in June during the critical flowering period. The years 1997, 2007 and 2012 were low yielding (Figure 4.8) and had June precipitation in the top six of the last 100 years.

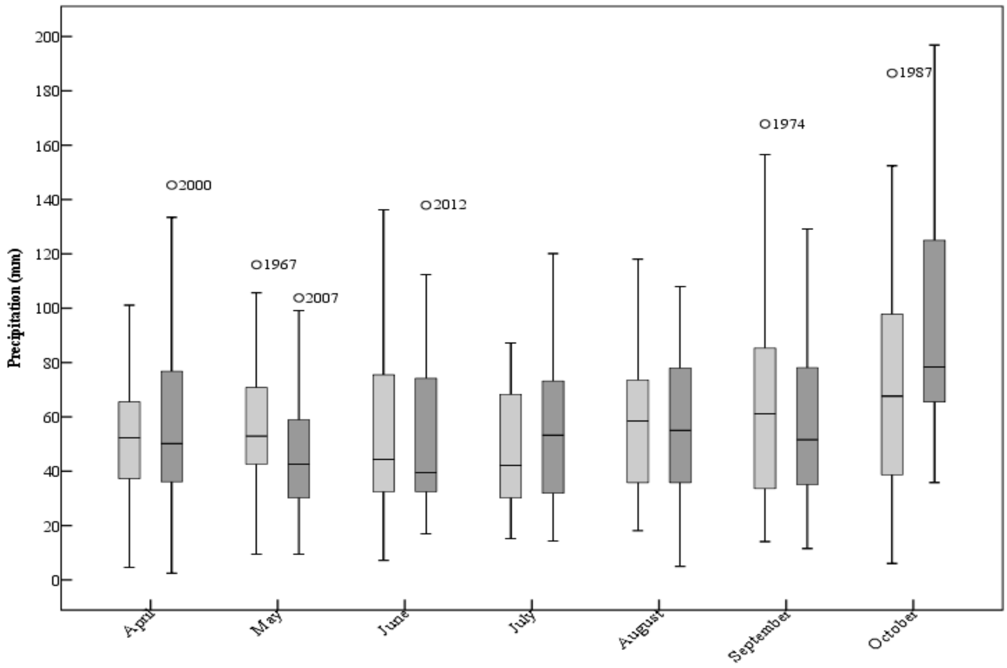


Figure 4.7: South-east and south-central England growing season monthly precipitation dispersion for 1961–1990 (■) and 1989–2013 (■). ○, outlier (1.5–3 x box length). Data source: Met Office (2014b).

4.6. Wine yield

Wine yield (1989–2013) in England and Wales exhibits marked inter-annual variation, with a standard deviation of 8.5 hL/ha and a range from 5.98 (2012) to 37.7 hL/ha (1992) (Figure 4.8). Average yield for the period was 21.5 hL/ha. When examined for 1989–2003 and 2004–2013 [periods distinguished by cultivar differences (Section 3.1 and Figure 3.3)], mean yield was 21.43 and 20.70 hL/ha, respectively.

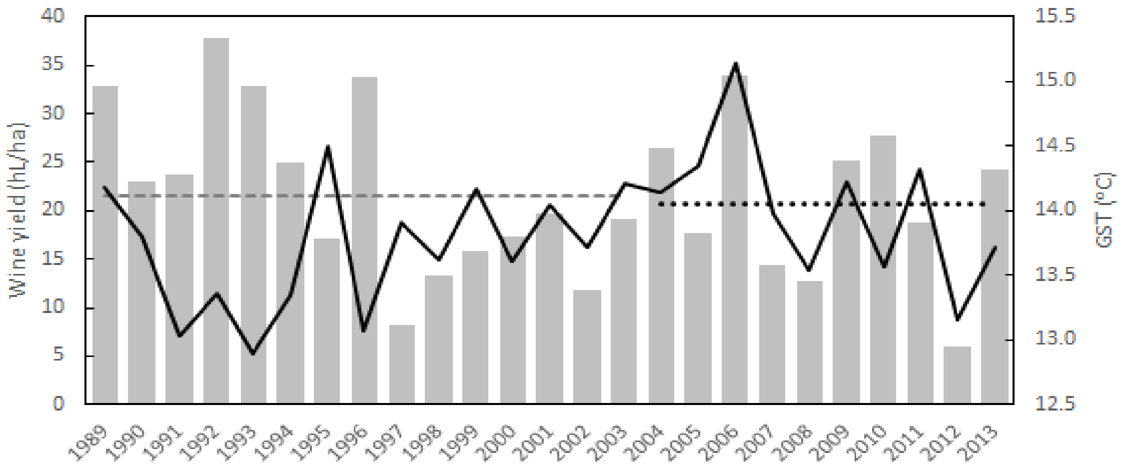


Figure 4.8: Wine yield (left axis) in England and Wales (■) including the average in 1989–2003 (- - - -) and 2004–2013 (· · · ·), with GST (right axis) for south-east and south-central England (—). Data source: Met Office (2014b) and English Wine Producers (2015b).

The inter-annual variability in English and Welsh wine yield and south-east and south-central England GST can be seen in Figure 4.8, but the relationship between them is not immediately clear. For example, 1993 had the lowest GST (12.9 °C) and the fifth highest yield (32.8 hL/ha) for the 1989–2013 period, whilst the highest wine yield (37.7 hL/ha) was in 1992 when the GST (13.4 °C) was the sixth coldest.

To help determine the form and strength of relationship between GST and wine yield, and subsequently the value of GST as an indicator of viticultural suitability expressed through yield, GST values and wine yield were subjected to a standard linear regression analysis for the periods, 1989–2003 and 2004–2013, two periods dominated by two different sets of *Vitis vinifera* L. cultivars (Figure 3.3). Table 4.1 shows that a significant relationship was established only for the period 2004–2013 in which 44 % of wine yield variation can be accounted for, with a positive linear correlation and a statistical significance of 0.038 (P =<0.05). When periods were further analysed, again using standard linear regression, but this time by individual growing season monthly temperature averages, significant relationships, presented in Table 4.2, were found.

Table 4.1: Linear regression results between GST and wine yield (1989–2003, and 2004–2013)

Period	*P*-value	r^2 (%)
1989–2003	.070	23
2004–2013	.038	44

Table 4.2: Significant linear regression results between monthly temperature and wine yield (1989–2003 and 2004–2013)

Period	Variables	*P*-value	r^2 (%)
1989–2003	August	.034	30
2004–2013	July	.018	52

These results indicate that, stronger than GST, the average temperatures in August and July account best for the variation in wine yield within the two respective periods. While the July temperature–yield relationship is positive, the August temperature–yield relationship (1989–2003) is negative. Possible reasons are examined in Section 4.7.

The relationship between days with air frost, in April and May, and yield was also analysed using a standard linear regression for the 1989–2013 period; no relationship, however, was found. The inability of the regional air frost data to represent high-resolution spatial occurrence, severity and length, and the potential ability of some producers to protect against frost may go some way to explaining this result. To further investigate the relationship between climatic conditions and yield, GST, growing season precipitation totals, growing season monthly average temperature and monthly total precipitation values for the different time periods were subjected to multiple stepwise regression analysis. In addition, three exceptionally high yielding years (1996, 2006 and 2010) and four exceptionally low yielding years (1997, 2007, 2008 and 2012), identified because they fell outside of the interquartile yield range, were also subjected to the same statistical analysis. Where significant relationships were identified, results are presented in Table 4.3. For all other variables, no discernible linear relationship between yield and any of the predictors was found.

Table 4.3: Significant stepwise regression relationships between GST, monthly temperature, monthly/seasonal precipitation and wine yield for 1989–2013, 1989–2003 and 2004–2013.

Period	**Variables included**	**Indicators and relationship**	***P*-value**	**r^2 (%)**
1989–2013	GST, monthly temperatures, seasonal and monthly precipitation	1. June precipitation (negative)	.002	34.7
1989–2003		1. August temperature (negative)	.034	30.1
		2. August temperature and total season precipitation (negative)	.002	64.6
2004–2013		1. June precipitation (negative)	.005	64.1

Table 4.4: Growing season average temperature (GST) and precipitation variability (1961–1990 and 1989–2013)

Variable	**Period**	**Standard deviation**	**Coefficient of variation (%)**
Variability in GST	1961–1990	0.6°C	4.3
	1989–2013	0.5°C	3.8
Variability in total precipitation	1961–1990	81 mm	20
	1989–2013	112 mm	27

For the full 1989–2013 period and the 2004–2013 period June precipitation had a significant negative relationship with yield, that is the greater the precipitation the lower the yield. It was found to be the single statistically significant variable explaining 34.7 and 64.1% of the variability in yield, respectively. During 1989–2003, August mean temperature (a negative relationship) and total seasonal precipitation (when combined with August temperature — also a negative relationship) explained 30.1 and 64.6% of the variability. Possible reasons are discussed in Section 4.8.

Results demonstrate that when precipitation and higher temporal resolution temperature data are included in the statistical analysis GST is not the most powerful ‘predictor’ of yield.

4.7. Weather variability and extreme weather

One of the producers' perceived threats to wine production in England and Wales (Table 3.4) was weather variability. GST and total precipitation variability were compared for 1989–2013 against a baseline period of 1961–1990 to identify degrees of variability and any recent changes. Inter-annual variability in GSTs was found to have decreased by 0.5% between the periods, whilst precipitation variability had increased by 7% (Table 4.4). However, these findings stem from a comparison in variability in periods of different lengths, 25 and 30 years respectively. In Section 7.3 it is recommended that to overcome this limitation future research post-2018, be undertaken to provide a comparison of 20 or 30–year periods.

Producers also expressed concerns about threats from extreme weather associated with climate change (Table 3.4). Although extreme weather was not defined by survey respondents it was restricted in this thesis to consideration of April and May air frosts, and growing season monthly mean temperature and total precipitation outlier and extreme years, identified in Figures 4.6 and 4.7. Changes in the occurrence of air frosts are presented in Section 4.4. Outlying and extreme monthly temperatures, presented in Figure 4.6, were relatively evenly distributed between periods (1961–1990 = 10, and 1989–2013 = 8) but again changes to extremes here are inappropriately reliant on two differing time periods and are therefore inconclusive.

4.8. Discussion

Sixty-six per cent of grape-growers and wine producers who responded to the questionnaire stated they thought climate change had contributed to the growth of the viticultural sector in England and Wales (Section 3.2). Evidence presented in Figures 4.1 and 4.2 shows a warming of climate in south-east and south-central England, during the grapevine growing season (1954–2013 as a linear trend, and 1989–2013 as anomalies against a 1961–1990 climatic normal), supporting the majority of questionnaire responses. The climate in the south-east and south-central England, and more widely in other parts of England and Wales (Figure 4.3), has reliably exceeded the 13°C GST base of a cool climate maturity grouping since 1993. The 1961–1990 average for south-east and south-central England was 13°C, but four years during the 1989–2013 period were ≥ 14.3°C, and 10 years ≥ 14°C. To place this in the context of another sparkling wine producing region, Champagne, its 1961–1990 GST was 14.3°C (based on historic climate data from one station [Reims-Courcy] by Briche et al. (2014), who regarded the station data as being representative of the climate of Champagne), that is 40% of growing seasons in south-east and south-central UK during 1989–2013 had an average temperature (≥14°C) similar to that of the 1961–1990 Champagne average. The hypothesis that follows the observation of warming during the growing season is one of increased viticultural suitability. If suitability is, however, to a degree, determined by wine yield (hL/ha) then its relationship with GST needs explaining because as Figure 4.8 and Table 4.1 illustrate GST does not closely correspond to yield in all years.

In the context of Champagne, English and Welsh wine yields are low (yield maxima in Champagne are artificially fixed for any given year, and planting density is generally higher, but yield can be up to 146 hL/ha, as in 2004 [Stevenson 2008]). Mean English and Welsh wine yield was 21.43 (1989–2003) and 20.70 hL/ha (2004–2013). The small reduction between these two periods may in part be due to the extremely low yield in the cool and wet 2012 growing season (6 hL/ha); excluding 2012 the average yield for the period is 22.3hL/ha. In addition, during the latter period, there was an increase in young vines coming into production associated with an increase in area under vine and the change in dominant cultivar mix (Figure 3.3); initial production yields are likely to be lower than in more established vines/vineyards, potentially influencing the overall mean yield. However, the change in dominant cultivars since 2004 (Figure 3.3), to those grown predominantly for sparkling wine production, may also play a role. Since the mid-1990s, but more clearly since 2004 (through this analysis), the relationship between GST and yield becomes clearer and without consideration of precipitation or individual growing season monthly average temperature, and GST has a statistically significant relationship with yield during the 2004–2013 period, explaining 44% of yield variation (Table 4.1). Most significantly, this change in dominant cultivars appears to have increased sensitivity to temperature variability.

While there is no significant evidence for change in the variability of inter-annual growing season temperature (Table 4.4), these results suggest that following the 2004–2013 trend, all else being equal, years with lower GST can expect to experience lower yield. Before the change in dominant cultivars, in years with a lower GST such as 1991, 1992, 1993, 1994 and 1996, yield remained above the average for the period. The lack of a clear relationship between yield and GST across the whole period of interest appears to be explained in part through an analysis of higher temporal resolution temperature and precipitation data. Median monthly temperature has increased in all growing season months (1989–2013) against a 1961–1990 norm, except for a small decline in October. The spring months of April and May have seen relatively large increases in temperature that are significant because this is a time when budburst and initial shoot growth occur. A warmer temperature at this time indicates advancement and lengthening of the grape growing season. The 100% expansion of the interquartile range for April suggests increasing inter-annual variability during this important month. Where a warmer temperature occurs in April, there is the potential for May air frost events to cause greater damage. Without considering precipitation, temperature in July for the 2004–2013 period explained 52% of yield variability (Table 4.2). This could be related to more suitable flowering conditions in years where flowering occurs in July, or as a result of cool weather during years with protracted flowering resulting in coulure or millerandage (see Figure 4.9). Its most common cause stems from poor grape flower fertilisation, caused by cold and wet weather during the flowering stage (Jackson 2014)). It is, however, likely that the significance of this relationship depends on other growing season weather events and viticultural impacts.

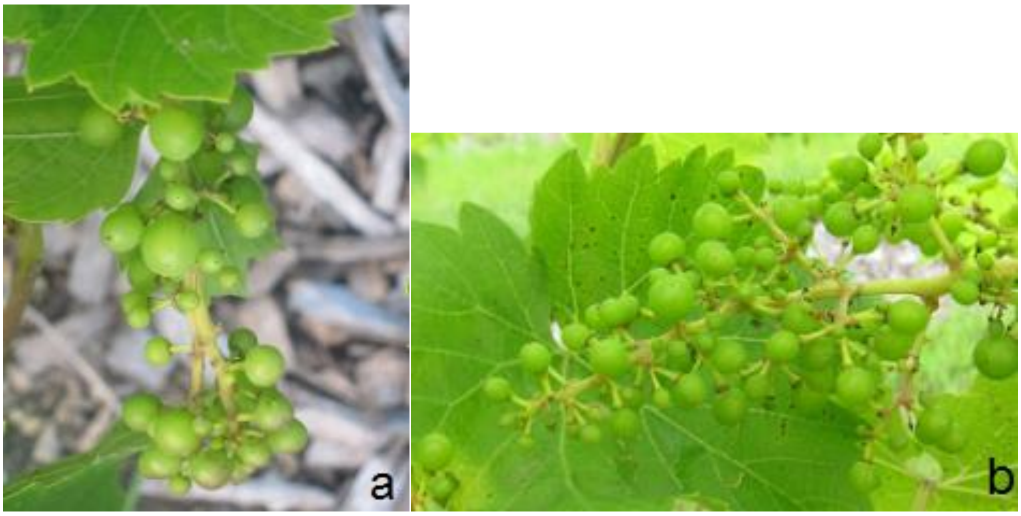


Figure 4.9: Grape berry Coulure (a), and Millerandage (b).

The negative relationship between August temperature and yield, for the 1989–2003 period, cannot be rationally explained by August temperature alone. All else being equal a warm temperature in August would support maturation. Earlier season weather conditions, perhaps contributing to disease pressures exacerbated by August temperature, may play a role in this relationship, but a closer examination of conditions during years in this period would be required to fully elucidate it.

Total precipitation during the growing season has increased from 407 (1961–1990) to 420mm (1989–2013). The 16% rise in median precipitation during October (Figure 4.7) could contribute to increased disease pressure during the harvest period. Importantly, the critical flowering month of June has seen no significant change in precipitation range or dispersion but has a significant negative relationship with yield for the whole 1989–2013 period and the 2004–2013 period (Table 4.4). This result confirms producers' comments regarding reasons for low yielding years, namely the impact of conditions at flowering. The recent outlying precipitation event in June 2012 (138mm; the wettest June since 1910) and corresponding lowest yield on record, demonstrates that damaging precipitation at this sensitive phenological time remains a critical threat. May 2007 witnessed the fifth highest precipitation total since 1910, followed by the sixth highest precipitation total in June, since 1910 (Met Office 2015b). Combined, these conditions were attributed by producers to the low yield. June precipitation in 1997 was the fourth highest since 1910 (Met Office 2015b). This followed the acute frost event in May 1997 (discussed later) and could have further reduced yield. Most significantly precipitation during this critical phenological stage has a stronger relationship with UK yield and explains more of the variability than GST or the monthly temperature of the individual growing season. Notwithstanding acute events, June precipitation is shown to be the single most determining variable in English climatic suitability for viticulture, when expressed through wine yield.

Furthermore, the negative relationship between August temperature and total growing season precipitation and yield, for 1989–2003 (Table 4.4), also suggests that precipitation during the season as a whole, is a critical yield determining factor. This possibly supports growers/producers comments (Section 3.2) about the effects of precipitation and temperature on disease and yield. Seven of the 15 years during the 1989–2003 period were both warmer and wetter than the 1961–1990 norm (Figure 4.2).

Producers expressed concerns about increasing variability. It can clearly be seen from Figures 4.1 and 4.2 that GST inter-annual variability is high, and as previously determined for the more recent 2004–2013 period, affects yield. Interquartile temperature ranges have risen 100% in April and October, suggesting increased variability in these months, but ranges have decreased to date in May, July and August. Inter-annual variability of GST has dropped 0.5%, from 4.3 (1961–1990) to 3.8% (1989–2013), but the shorter time of the latter period does not allow for equitable comparison. There was a 7% increase in the variability of the total growing season precipitation between the periods. The October interquartile precipitation range has always been greatest, and where high precipitation events do occur this could affect harvest conditions. Crucially, the lack of significant change in temperature and precipitation variability in June suggests that the threats to flowering and fruit-set posed by June precipitation events and weather conditions remain unchanged.

Producers also stated that air frosts had significantly affected yield, citing the early May air frost in 1997 as an example. The GST in 1997 was 13.9°C, just above the 1989–2013 average of 13.8°C, but yield was low (8.7 hL/ha) (Figure 4.8). A closer examination of historic Royal Meteorological Society weather logs for May 1997 reveals that a short heat wave at the beginning of the month (27 and 26°C in London on the 2 and 3 May, respectively) was followed by 'sharp night' air frosts in southern England on the 6 and 7 May (Royal Meteorological Society 1997). This demonstrates how the acute nature of short frost events is unlikely to be easily detected through seasonally averaged temperature but could significantly affect yield, depending on their temporal and spatial occurrence. In this case the air frost event may have contributed to a higher level of wine-grape damage than would have been the case had the preceding temperature been lower, that is phenological development is likely to have been advanced due to warmer spring temperature. The number of days (1961–2013) in which an air frost occurred during April and May indicates significant spring frost risk in south-east and south-central England that could affect yield where protection strategies (including site positioning) are not employed. While there is an apparent downward trend in April and May air frost days, it is not significant, and no years have been without a day in which a frost event occurred. A subsequent examination of Met Office regional data for 2014 and 2015 (Met Office 2015b) confirmed that there were 1 and 2 days of air frost respectively.

It should be noted that the lowest yielding year during the 1989–2013 period (2012) was not attributed to a frost event. Rather, as can be seen in Figures 4.1, 4.2, and 4.7 and as indicated in questionnaire responses, Section 3.2, this was due to the wet and cold spring. Combined, these weather conditions remain a threat to productivity.

One of the aims of the analysis presented in this chapter was to assess the ability of GST to adequately describe viticultural suitability in the UK. It was found that while it can act as a general indicator of thermal suitability, in the sense that *Vitis vinifera* L. is grown within a cool (13–15°C) GST climate/maturity grouping (Jones 2006, 2007), key results all indicate that when precipitation and higher temporal resolution temperature data are included in the statistical analysis, GST is not the most powerful 'predictor' of yield.

Results presented in this chapter provide an analysis of historic growing season temperature and precipitation conditions in south-east and south-central England, where most vineyards are established, and their relationships with historic wine yield. Where yields are so low and so variable (Figure 4.8) they indicate inherent exposure to weather or climate risks. At a monthly scale some of those risks have been elucidated through results in this chapter. Depictions of GST and ground frost (2004–2013), presented in Figures 4.3 and 4.5, indicate climatically similar or better viticultural opportunities outside of south-east and south-central England. The rationale behind the existing spatial distribution of viticulture in England and Wales is discussed in Chapter 5, but from results in this Chapter it is hypothesised that there may be opportunities for increased sector resilience to climate variability, spring air and ground frost occurrence, rainfall during flowering, and GST, through establishment of viticulture in areas with higher degrees of climatic suitability. To date no analysis of spatial variability in climatic suitability for viticulture in England and Wales has been undertaken. Such an analysis is seemingly even more critical given the observation that whilst trends in demand for English Sparkling Wine have driven a cultivar change to Chardonnay and Pinot Noir, their sensitivity to weather and climate conditions places the sector at greater risk of low yields than previously observed. Chapter 5 of this thesis therefore builds on results from this chapter to integrate weather phenomenon and variability associated with threats to productivity into a model of climatic and biophysical suitability for viticulture in England and Wales. Although biophysical factors regarding viticulture suitability have not been analysed in this chapter, their relationships with climatic suitability, for example frost risk and precipitation, are likely to affect viticulture suitability and productivity.

Subsequently the subject of future climate scenarios and relationships with both viticulture suitability and wine quality can be discussed (Chapter 6) relative to knowledge obtained in this Chapter and Chapter 5.

Chapter 5

Modelling spatial variability of biophysical and climatic suitability for viticulture in England and Wales

This thesis, through Chapters 3 and 4, has presented research into key climatic enablers for the growth of the English and Welsh wine production sector, and threats to yields posed by short-term weather events and inter-annual climatic variability (Section 4.6), over the last ~25 years. Yet despite the apparent association between recent warming of growing season (April – October) GST and monthly mean temperatures, and sector growth, average English and Welsh wine yields have remained relatively low and highly variable from year to year (Section 4.6). This suggests an inherent exposure to weather and climate risks that could affect the sustainability of production.

Having identified, at a monthly scale, both the acute (e.g. spring air frosts, and rainfall during flowering) and chronic (e.g. relatively low growing season temperatures, and inter-annual variability) meteorological conditions that can negatively affect yield, and conversely the growing season conditions that help realise potential for viticulture, there was an opportunity to incorporate those findings into a spatial suitability model for viticulture in England and Wales – presented in this chapter. Based on the premise that biophysical (topography, soil and land-use) and climatic suitability for viticulture is spatially variable (see Figures 4.3 and 4.5), a viticulture suitability model could aid the growth of the English and Welsh wine production sector by informing decisions about where to establish vineyards. Identification of areas in England and Wales that are biophysically suitable but which are less vulnerable to inter-annual weather variability, spring air frosts, low growing season mean temperatures, relatively high volumes of rainfall (seasonal and in June), and more aligned to positive climatic variables including sunlight (Gladstones 1992; Downey et al. 2006; Kemp et al. 2011) and those identified in Sections 1.1.1 and 4.6, enables a more optimised distribution of viticulture to boost sector resilience to weather and climate risks.

The viticulture suitability model for England and Wales, developed for this thesis, is a valuable research tool but its endpoint is envisaged to be as a commercial online resource, as part of a package of weather and climate services, to benefit the English and Welsh wine production sector. The structural methodologies (data integration and employment of Fuzzy Logic – Section 2.4.5) applied in its development are novel to viticulture suitability modelling; the quantification of spatial variance in growing season climatic conditions and biophysical suitability in England and Wales are new, and the integration of inter-annual weather variability into viticulture suitability models is unique. High biophysical model resolution (50 x 50 m) was chosen to provide accuracy in determination of land suitability for viticulture (Table 2.2), and 5 x 5 km gridded climatic variables (Table 2.3) to provide indicative values of viticulturally relevant climatic conditions for land within a given grid-cell. The model is not a microscale portrayal of vineyard site specific climatic suitability, but rather a mesoscale assessment of variability and land availability designed to inform sector development.

The grape growing to wine production continuum is influenced by climatic, biophysical, cultural, and economic factors. The climate and biophysical considerations that influence the process include matching a given grape cultivar to an appropriate climate, and selecting vineyard sites with optimum elevation, slope, and aspect characteristics, and suitable soil properties, all of which play critical roles in grape quality and yields (Section 1.2.3). While some regions, globally, have had hundreds or even thousands of years to define, develop, and understand their best combinations, newer regions, in this case England and Wales, have typically faced a trial and error phase of finding the best cultivar, climate and site match (Jones et al. 2005). Through results presented in this Chapter it is anticipated that the 'trial and error' stage referred to by Jones et al. (2005) can be shortened and informed through employment of contemporary mapping techniques, incorporating findings from Chapters 3 and 4, to model viticulture suitability.

The conventionally deemed temperature limited latitudinal extreme for commercial viticulture is 50°N (Jackson 2014); Section 2.2.4 and Figure 3.2 show that the majority of vineyards are located closer to 51ºN, northward of 50ºN, and a majority are clustered around south-east and south-central England. This spatial distribution is attributed to relatively warmer and drier growing conditions in these regions (Skelton 2014). However, this attribution of viticulture site selection in England and Wales has not been exposed to a regional or national scale biophysical (soil, slope, aspect, elevation and land-cover) or climate suitability analysis; suitability of land for viticulture in England and Wales is presently decided on a case-by-case basis sometimes using 'expert opinion' to assess site characteristics. Numerous overviews exist that detail vineyard site selection criteria in general (Gladstones 1992; Coombe 2004), or for specific regions (Smart & Dry 1980 – Australia; Jones & Hellman 2002 – Oregon) and focus mostly on climate, topography, and soil factors. Others have addressed site suitability issues as a collection of factors that reveal insights into a region's unknown potential (Boyer & Wolf 2000) or as a measure of prediction for new areas to plant in existing regions (Jones 2004). These studies, combined with experience, can help inform decision-making about where to best establish a vineyard, or the cultivars which are most likely to 'thrive' in a given location. Nevertheless when elements of such studies are adopted for England and Wales, site analysis remains on an ad-hoc basis, lacking an illustration of spatial comparativeness which could help direct investment, strategy, and policy relevant actions. Value judgements and site specific assessments regarding suitability are inevitable and can merit serious consideration, but using techniques that minimise bias and improve the objective merit of suitability evaluations is both complementary and beneficial at local, regional and national scales. These techniques have been employed in other fields, for example: for the identification of suitable locations for maize production (Braimoh et al. 2004), photo-voltaic site suitability assessments (Charabi & Gastli 2011), and sustainable development planning (Romano et al. 2015), and they form the basis of this chapter.

When the viticulture suitability parameters of local environmental characteristics (biophysical land properties, climate, and inter-annual weather variability) are defined, high-resolution spatial and temporally representative data can be mapped, overlaid and analysed, and results classified and visualised to spatially illustrate viticulture opportunities and land value. Elements of such spatial modelling resources exist for more established wine producing regions, focussing primarily on climatic potential for viticulture and zoning of varietal suitability (for example: Irimia et al. 2011 – Huşi, Romania; Hall & Jones 2010 – Australia; Jones et al. 2006 – Oregon, USA), but a detailed and integrated viticulture climate and biophysical suitability model for England and Wales has not previously been developed. This chapter presents the first biophysical, climatic, and combined viticulture suitability analysis, derived from a GIS model that employed Fuzzy Logic and Multi Criteria Decision Analysis (MCDA) (Section 2.4.5), for England and Wales.

The viticulture biophysical suitability model presented in this chapter (Section 5.2) benefitted from validation, undertaken using 13 large (≥25 ha) vineyards in England as case studies to compare model output with mapped conditions, and through discussions with vineyard managers of the respective sites regarding soil properties. Results from three of these 13 validation exercises are presented in Section 5.5. Validation of climatic variables were not undertaken within the scope of this thesis as the 5 x 5 km gridded and freely available datasets used had previously been subjected to independent testing and validation (Perry & Hollis 2005). However, 2015 April air temperatures were recorded in one east Sussex vineyard using a series of 15 temperature sensors (see Section 5.7 and Figure 5.13) and were used to illustrate the effect of slope and cold air accumulation on vineyard radiation frost risks, and to help validate a WRF model downscaling exercise – from 9 x 9 to 3 x 3 to 1 x 1 km grids. Results from this exercise were not integrated into the viticulture suitability model, but are presented in Section 5.6.1 because it is anticipated they will inform future viticulture suitability model development, i.e. the integration of higher spatial resolution recent meteorological variables. Additionally, as part of the same exercise, a single case of a spring air frost at a vineyard in Suffolk, was used to corroborate the 3 x 3 km grid WRF model output for ground and air frost occurrence (Section 5.6 and Figure 5.1.5).

To place modelled climatic suitability for viticulture in England and Wales in the context of existing vineyards and other cool-climate wine producing regions of Europe this thesis chapter also presents results of an analogue modelling exercise – Section 5.6. The recent (2004–2013) bioclimatic (GST, GDD, and HI) mesoscale (9 x 9 km) values for five of the largest (≥25 ha) established vineyards in England (Section 5.6.1), and for other cool-climate viticulture regions in north-eastern Europe (Champagne, Mosel-Saar-Ruwer, Franken, Neuchatel and Eastern Denmark (Zealand) – Section 5.6.2) were deduced from WRF model simulated climatologies using ArcGIS v10.3 (see Section 2.3.6 for methods). Subsequently, an analogue between bioclimatic values (2004–2013) of the five vineyards in England and similar or higher values in other biophysically suitable areas are presented (Section 5.6.1). Likewise bioclimatic values from other cool-climate viticulture regions of north-eastern Europe could be compared with modelled values in biophysically suitable areas of England. The aim of this approach is to present, for the first time, recent (2004–2013) bioclimatic values for viticulture in England and Wales, to comparatively illustrate bioclimatic suitability for viticulture, and to provide an indication of cultivar suitability and adaptive capacity by identifying cultivars grown in vineyards and areas with similar bioclimatic values.

Modelling viticulture suitability in England and Wales provides an indication of spatial risk and opportunities for production. However, where physical and climatic potential for viticulture is apparent, it is without a commercial context. That is to say the economic case for viticulture is not present in the suitability model. To illustrate opportunities for conversion from one crop to another, in this chapter, sugar beet producing areas are explicitly examined for viticulture suitability, complemented with an evaluation of rudimentary economic viability of both crops (Section 5.8).

When the three elements of this chapter (the viticulture suitability model, the climate and cultivar analogue, and the basic economic assessment) are collectively considered it provides a first detailed model of spatial risk for those considering investing in English and Welsh viticulture. Furthermore it delivers the modelling structure, initial validation, and geographic assessment required to underpin a tool that will help identify suitable vineyard locations.

5.1. Soil dataset evaluation

To develop a biophysical model of viticulture suitability in England and Wales a soil database representative of vineyard conditions was required (Section 2.4.4). Three soil datasets were acquired and examined for model applicability: the Harmonised World Soil Database (HWSD) v1.2 (FAO 2015), the Countryside Survey (CS) of Soils – 2007 (Countryside Survey 2015), and the National Soilscapes Map of England and Wales (LandIS 2015). All three datasets were imported in to ArcGIS v10.3 and overlain with English and Welsh vineyard locations, ahead of a visual model assessment of soil properties for known vineyards and subsequent discussions with vineyard managers regarding the representativeness of the datasets. A Boolean method of imposing strict pH ranges (5.5–8) and soil texture descriptors to the suitability model was employed using data from the Countryside Survey (Figure 5.1) and HWSD (Figure 5.2) respectively. This approach immediately resulted in several well established vineyards in England being excluded from the suitability analysis as the HWSD and CS soil values for the vineyards were outside of those deemed 'suitable' for viticulture – see Sections 1.2.3 and 2.4.4. However, subsequent communication with those vineyards established that some of the data values applied from either datasets were not actually representative of their vineyard soils. Furthermore, of the 10 producers contacted all had engaged in aspects of soil amelioration and careful root-stock selection to mitigate soil variables that could be considered 'unfavourable'. For example, three of the vineyards contacted were growing vines on soils with a pH of 8.2 – 8.4, theoretically unsuitable (Section 1.2.3), but growers had mitigated the risk by growing on vine root-stocks that were alkaline tolerant. Another three had successfully established vineyards (for over 15 years) on 'heavy' clay soils, not considered free draining, but had found little problem with water logging or vine growth, attributed by one producer to both a sloping site and the implementation of land drains. As noted by Skelton (2014), vineyards in England and Wales have been established on a wide range of soil 'types' and amelioration activities can mitigate potentially negative soil characteristics.

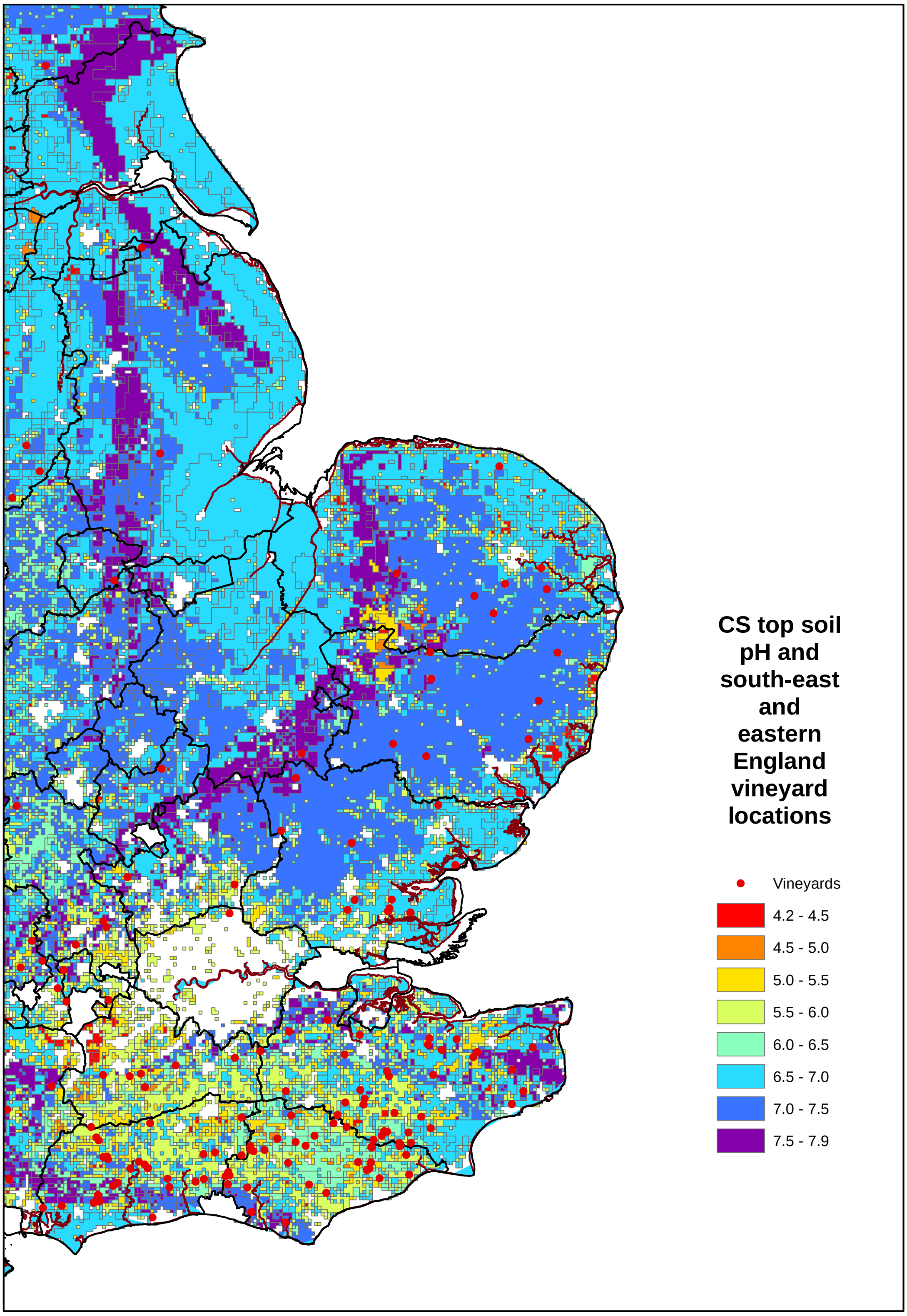


Figure 5.1: Countryside Survey (2007) topsoil pH for south-east and eastern England, and vineyard locations

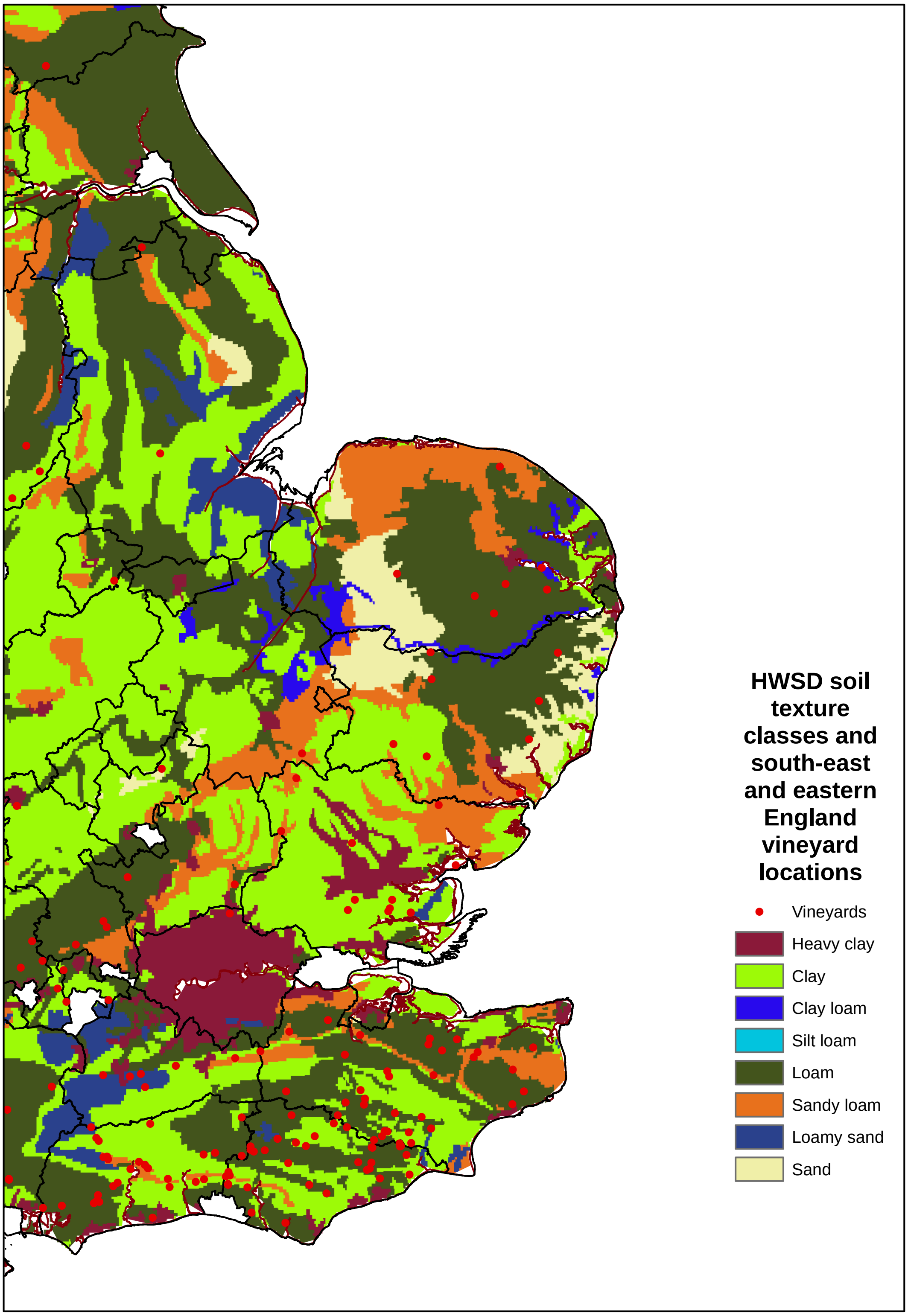


Figure 5.2: HWSD (FAO 2015) soil texture classes for south-east and eastern England, and vineyard locations

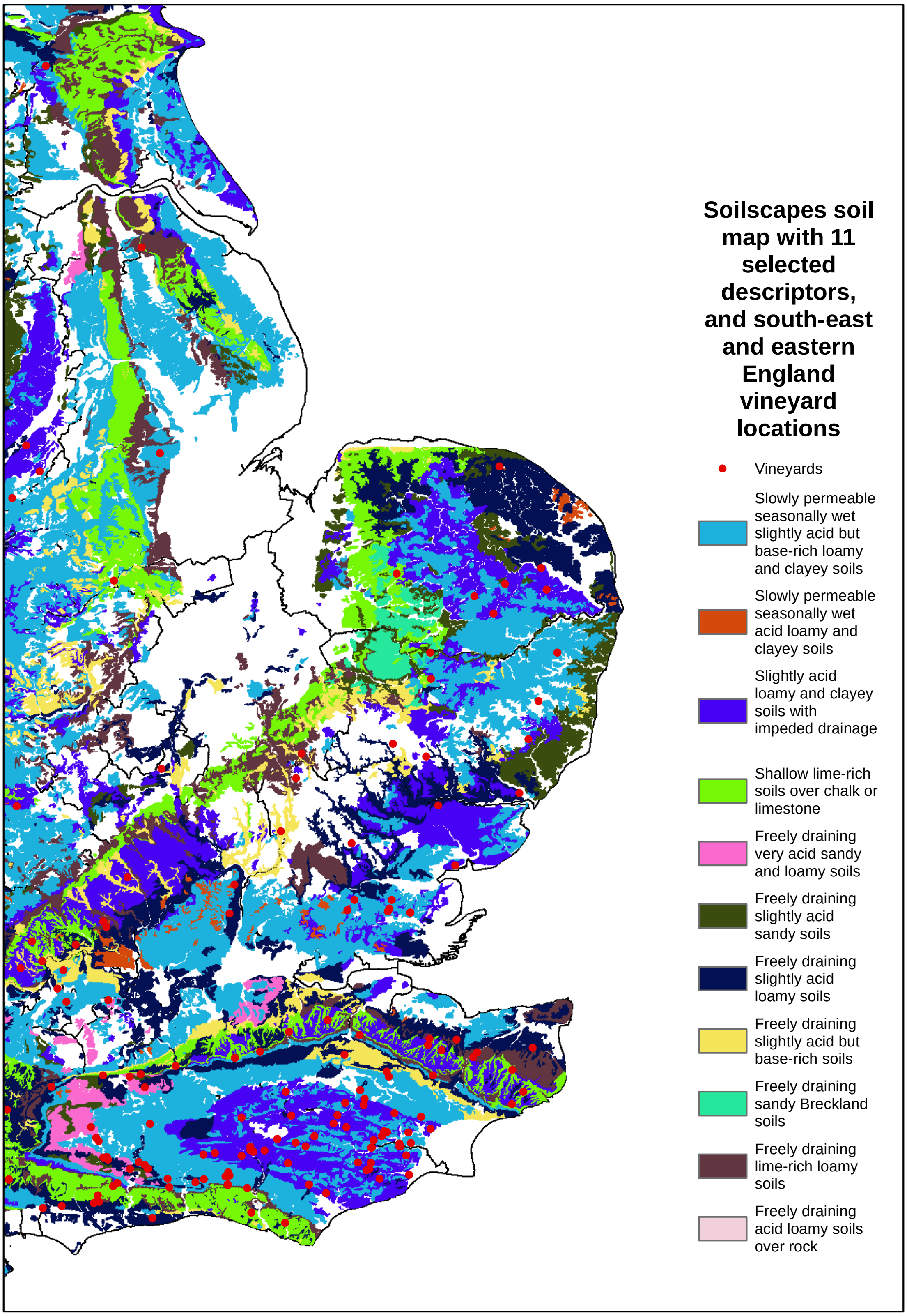


Figure 5.3: Soilscapes (LandIS 2015) soil descriptors for south-east and eastern England, and vineyard locations

Following this initial exploration of the appropriateness of the three soil datasets two were found to be unrepresentative of conditions in existing vineyards, and subsequently the SoilScapes set (Figure 5.3) was employed for use in the suitability model. It was found to usefully describe soils of established vineyards and provide a broad soil descriptor from which suitability analysis could be performed (see Section 2.3).

5.2. Biophysical suitability results

Following model development criteria set out in Section 2.4.5, 17% of land area in England and Wales (15,316,232 ha (Office for National Statistics 2013)) was classified through the model as biophysically suitable for viticulture (Figure 2.2), i.e. excluding climatic suitability, equating to 2,616,920 ha. The model threshold for biophysical suitability is any 50 x 50 m grid cell that contained soil and land cover and elevation and aspect and slope parameters identified in Sections 1.2.3 and 2.2.4, and listed in Table 2.2 as being suitable for viticulture. Where a grid cell does not meet any of these requirements it was excluded from the model (Figure 2.2). Mean model fuzzy biophysical suitability was 0.4 (0 = not suitable; 1 = highly suitable) with a range of 0.09–0.99. Limiting soil suitability in the model to areas that were classified as having freely draining soils, or shallow lime-rich soils over chalk or limestone reduced land suitability to 6.5% (1,002,885 ha) and 1.6% (252,554 ha) respectively. When the biophysical model was restricted to areas currently classified as 'Arable or Horticulture' (CEH, 2007) (Figure 2.2), just over half of the land area remained, suggesting that 1,435,867 ha of land dedicated to arable or horticulture production has potential for conversion to viticulture. Of this 549,270 ha was on soil classified as freely draining, and 179,852 ha on shallow lime-rich soils over chalk or limestone. Hampshire alone was shown to have 27,384 ha of suitable land on shallow lime-rich soils over chalk or limestone, slightly less than the Champagne viticultural area (33,500 ha), which is also predominantly over chalk (Johnson & Robinson 2001). Norfolk and Lincolnshire combined had a slightly larger area – 38,382 ha of biophysically suitable land on shallow lime-rich soils over chalk or limestone.

Results by Unitary Authority (UA), presented in Table 5.1, show that when all suitable land use categories are included in the model Devon has the largest area of biophysically suitable land (206,776 ha), followed by North Yorkshire (162,393 ha). However respectively these two UAs only account for 3.6% and 0.3% of existing English and Welsh vineyard (≥ 1ha) area, raising the possibility that these UAs are limited by factors other than biophysical suitability.

Table 5.1: Top 20 biophysically suitable Unitary Authorities (UA) by area (ha), their proportion of land suitability, and their mean fuzzy value

Rank order	**Unitary Authority**	**Suitable hectarage**	**% of UA land area**	**Unitary Authority**	**Mean suitability**
1	Devon	206,776	31.2	Norfolk	0.54
2	North Yorkshire	162,393	14.8	Essex	0.52
3	Cornwall	118,502	32.8	Suffolk	0.52
4	Norfolk	117,231	21.3	Kent	0.47
5	Hampshire	110,172	29.5	North Yorkshire	0.45
6	Wiltshire	108,692	33.4	Lincolnshire	0.45
7	Cumbria	108,288	15.1	Dorset	0.44
8	Lincolnshire	98,095	16.0	Hampshire	0.42
9	Northumberland	95,947	18.9	Cornwall	0.41
10	Shropshire	94,240	29.5	Cumbria	0.41
11	Kent	86,842	23.9	Herefordshire	0.39
12	Dorset	86,270	33.5	Oxfordshire	0.38
13	Oxfordshire	82,299	31.6	Devon	0.37
14	Herefordshire	76,440	35.1	Gloucestershire	0.37
15	Essex	75,049	20.3	Wiltshire	0.36
16	Staffordshire	71,692	27.3	Shropshire	0.36
17	Suffolk	70,119	18.2	Northumberland	0.35
18	Gloucestershire	69,272	25.6	Northamptonshire	0.35
19	Leicestershire	66,084	31.7	Leicestershire	0.33
20	Northamptonshire	65,370	27.6	Staffordshire	0.32

As well as depicting volume of biophysically suitable land area in England and Wales, through employment of a Fuzzy Logic methodology (Section 2.4.5) grid cells (50 x 50 m) were classified according to Fuzzy value. Such a classification enabled areas of higher or lower suitability to be identified. Figure 5.4 illustrates the spatial distribution and classification of biophysical viticulture suitability, from the model, across England and Wales (Figure 5.4A) and at a regional level (Unitary Authority – Kent), including existing vineyards (Figure 5.4B). It also demonstrates model application at a much higher resolution local scale (Figure 5.4C), the value of which is subsequently demonstrated in the model verification and analysis of 13 individual vineyards ≥25 ha (Section 5.5). Figure 5.4 illustrates the value of such a model in identifying viticulture potential at different scales; at higher resolution (Figure 5.4C) site specific parameters can be examined, whereas in Figure 5.4A and B, regional suitability can be analysed and quantified. This scaling enables the model to be applied for different purposes, for example vineyard site assessments or to inform regional land use policy.

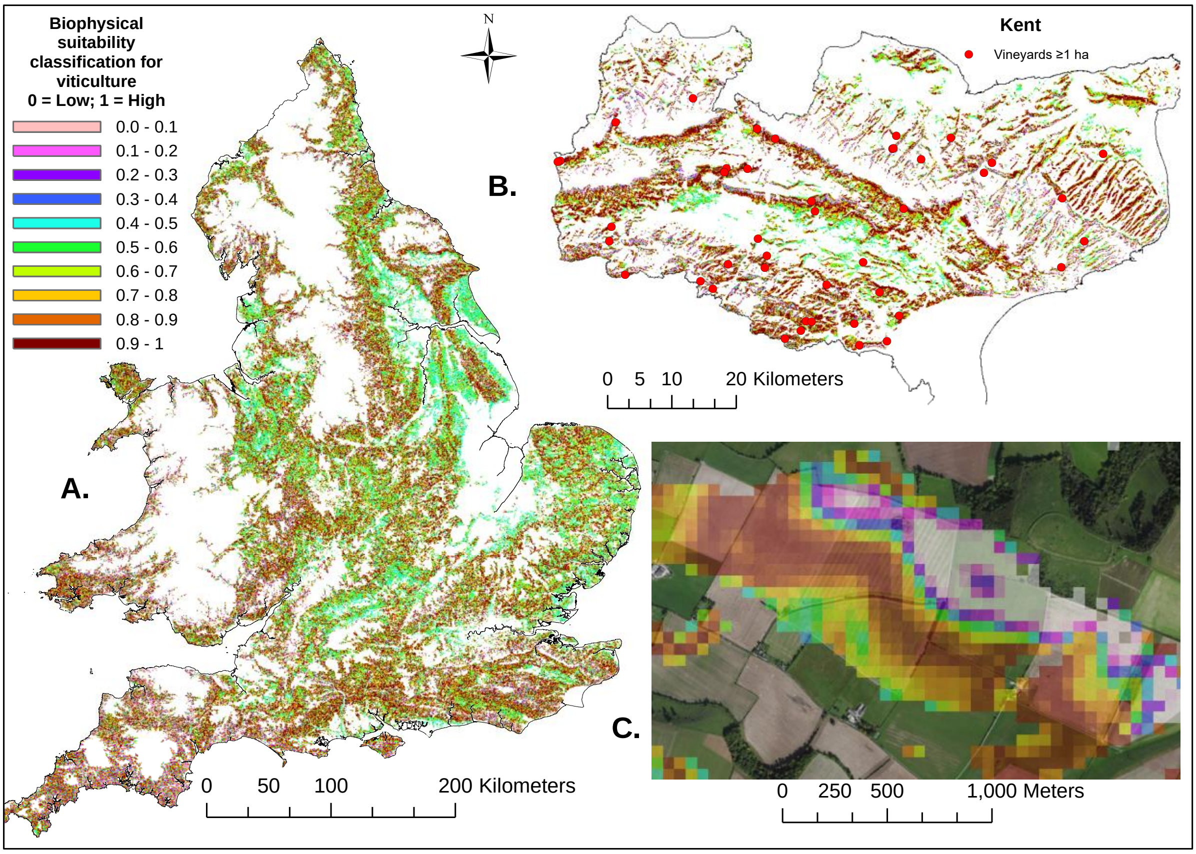


Figure 5.4: Biophysical suitability at national (A), Unitary Authority (Kent) (B), and local (C) scales.

At a Unitary Authority scale, when all suitable land use categories are included, Norfolk, with the fourth highest area of suitable land (117,231 ha), also has the highest mean fuzzy suitability value, 0.54 (Table 5.1), but only contains 1% of vineyard (≥ 1ha) area (as at 2013) (Table 3.1). Essex and Suffolk with mean fuzzy suitability values of 0.52, contain 5.3 and 1.6% of vineyard area (≥ 1ha) respectively. On the other hand Kent, with 16.6% of existing (2013) vineyard area (≥ 1ha) has a lower mean fuzzy value of 0.47. Whilst not yet including climatic variables these results suggest scope for spatial adaptation and expansion of the English and Welsh viticulture sector to biophysically suitable areas outside of the dominant Kent, Sussex (East and West), Hampshire and Surrey viticultural regions (Table3.1). Currently, it may be the case that biophysically suitable land in East Anglia is utilised for other crops, such as sugar beet, for economic reasons.

Detailed analysis of biophysical suitability across each of the existing 367 vineyards (≥ 1ha) in England and Wales was not undertaken within this thesis. However, using the visually prescribed approximate centre of these vineyards as a rudimentary guide (see Section 2.4.1), when overlain with the biophysical model, it was possible to show that the central points of only 183 of the 367 vineyards (≥ 1ha) corresponded with model suitability. That is to say, ~50% of existing vineyards (≥ 1ha) were positioned on land that was not deemed, by the model, to be suitable for viticulture. Of the vineyards that were within the model suitability range, their mean fuzzy membership value was 0.51. These results suggest room for improvement in the biophysical positioning of vineyards in England and Wales.

336 of the 367 vineyards fell within the prescribed 150 m maximum elevation height for vineyard suitability, with a mean elevation of the approximate centres of all 367 vineyards being 66.7 m. Only 231 of the 367 vineyards had approximate centres (50 x 50 m grid) within the prescribed suitable 90–270^{o} aspect. Whilst the approximate centres of vineyards are not necessarily representative of entire vineyard sites this finding, along with elevation, is indicative of why so many vineyards fell outside of the suitability model. The approximate centres of 344 out of the 367 vineyards fell within model suitability for slope (1–15%), with 15 being <1% and the remainder between 15–24%.

The top five soil 'types' of existing vineyards were classified as: 'Slightly acid loamy and clayey soils with impeded drainage' – 92 (25%), 'Freely draining slightly acid loamy soils' – 85 (23%), 'Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils' – 70 (19%), 'Shallow lime-rich soils over chalk or limestone' – 32 (9%), 'Freely draining lime-rich loamy soil's – 19 (5%). A further five vineyards were positioned on soils classified as being 'Slowly permeable seasonally wet acid loamy and clayey soils'. These results suggest that of the approximate centres of the 367 vineyards identified and analysed, 45% are positioned on soils classified by the SoilScapes (LandIS 2015) data as having impeded drainage or being slowly permeable and seasonally wet, factors that are not deemed 'ideal' for viticulture due to their negative association with disease pressures and impact on vine health (Lanyon et al. 2004).

Mean land cover classifications of vineyard centres was: 'Arable and Horticulture' – 152 (41%), 'Improved grassland' – 137 (38%), 'Rough grassland' – 23 (6%), and 'Neutral grassland' – 4 (1%), indicating that the majority of vineyards were positioned on land either previously used for crop production or potentially for hay or ley farming. The remainder were positioned on land that could have been used for silage, hay or pasture or that was deemed low-productivity grass or semi-natural sites (Centre for Ecology and Hydrology 2007).

Modelled biophysical suitability was calculated throughout 13 vineyards ≥25 ha. A mean fuzzy suitability of 0.6, with a range of individual vineyard mean values from 0.34 to 0.74 was found. Two vineyards had maximum cell values of 0.99 indicating very high suitability. An analysis of biophysically suitable land with >0.74 fuzzy suitability values across England and Wales resulted in a further 1,592,749 ha of land being identified, i.e. land with a higher value rating than the mean of the 13 largest vineyards in England and Wales. Perhaps of greater significance to this thesis was that 284,110 ha were in the counties of East and West Sussex, Kent, Surrey, Hampshire and Wiltshire, where the majority of the 13 large vineyards were located, as this indicates existing climatic suitability and opportunities for intra-regional expansion. Elevation ranged from three to 124 m across the 13 sites with the average of all 13 vineyard means being 50 m, again within the 'optimal' criteria of the model. Mean aspect averaged across all 13 vineyards was 158º (south-south-east) and slope was 5.6% with a range of 0.08 – 15.5%, just outside the model suitability limit. The most dominant soil type was 'Shallow lime-rich soils over chalk or limestone' followed by 'Freely draining slightly acid loamy soils'. Eleven of the 13 vineyards were on soil types classified as free draining or over chalk or limestone, whilst two were on 'Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils' or 'Slightly acid loamy and clayey soils with impeded drainage'. Ten of the 13 vineyards were predominantly established on land classified as Arable or Horticulture under the LCM (2007), two were on land classified as improved grassland and one on rough grassland.

Whilst the assessment of biophysical characteristics in existing vineyards provides a benchmark of physical factors that contribute to the current state of viticulture in England and Wales, it is only when complemented with viticulturally relevant climatic variables that suitability and potential for expansion can be fully clarified. Biophysical suitability alone does however allow for an assessment of site suitability and identifies areas that may become suitable under future climate scenarios.

Biophysical model verification is addressed in Section 5.5, and was undertaken prior to the incorporation of climatic parameters to develop the model further.

5.3. Climatic suitability results

In Section 4.6 GST was found to positively correlate with yields (2004–2013) (Table 4.1), and June rainfall had a statistically significant negative relationship with wine yield (Table 4.1). In Section 3.2, Table 3.5, low yielding years were attributed by producers to April and May frost events and high levels of rainfall during the growing season. Low sunlight levels were also attributed as a causal factor in low yielding years (Table 3.5). These analysis were used to choose the parameters used in this section to determine climatic suitability and they were subsequently integrated into the viticulture suitability model as described in Section 2.4.5 and shown in Figure 2.5.

The overall distributions of 1981–2010 mean GST, growing season rainfall, June rainfall, April and May air frosts spring frost and growing season bright sunshine within England and Wales, derived from the

UKCP09 5 x 5 km gridded dataset (Section 2.1.1), were calculated and mapped using ArcGIS v10.3. Results are presented in Figures 5.5A, B, C, D, and E respectively.

Although a single grid cell with the highest mean 1981–2010 GST (14.8°C) was found located in Hampshire, the counties with the highest average GST means were Essex and the Isle of Wight, both with 1981–2010 means of 13.9°C. These were followed by Cambridgeshire (13.8°C), West Sussex, East Sussex and Kent, all highly populated with vineyards (see Figure 3.2), and each with mean GSTs of 13.6°C, along with Suffolk, which only currently hosts 17 vineyards. Figure 5.5A shows, in general, lower GSTs on higher land (North Wales, the Pennines, and Lake District in Cumbria), and higher GSTs in south-central, south-east and eastern England, particularly on the south coast. However, the Severn estuary and southern coastal areas of Dorset can also be seen to have GSTs in the 13.5–14.5°C range, similar to those observed in south-central, south-east and eastern England.

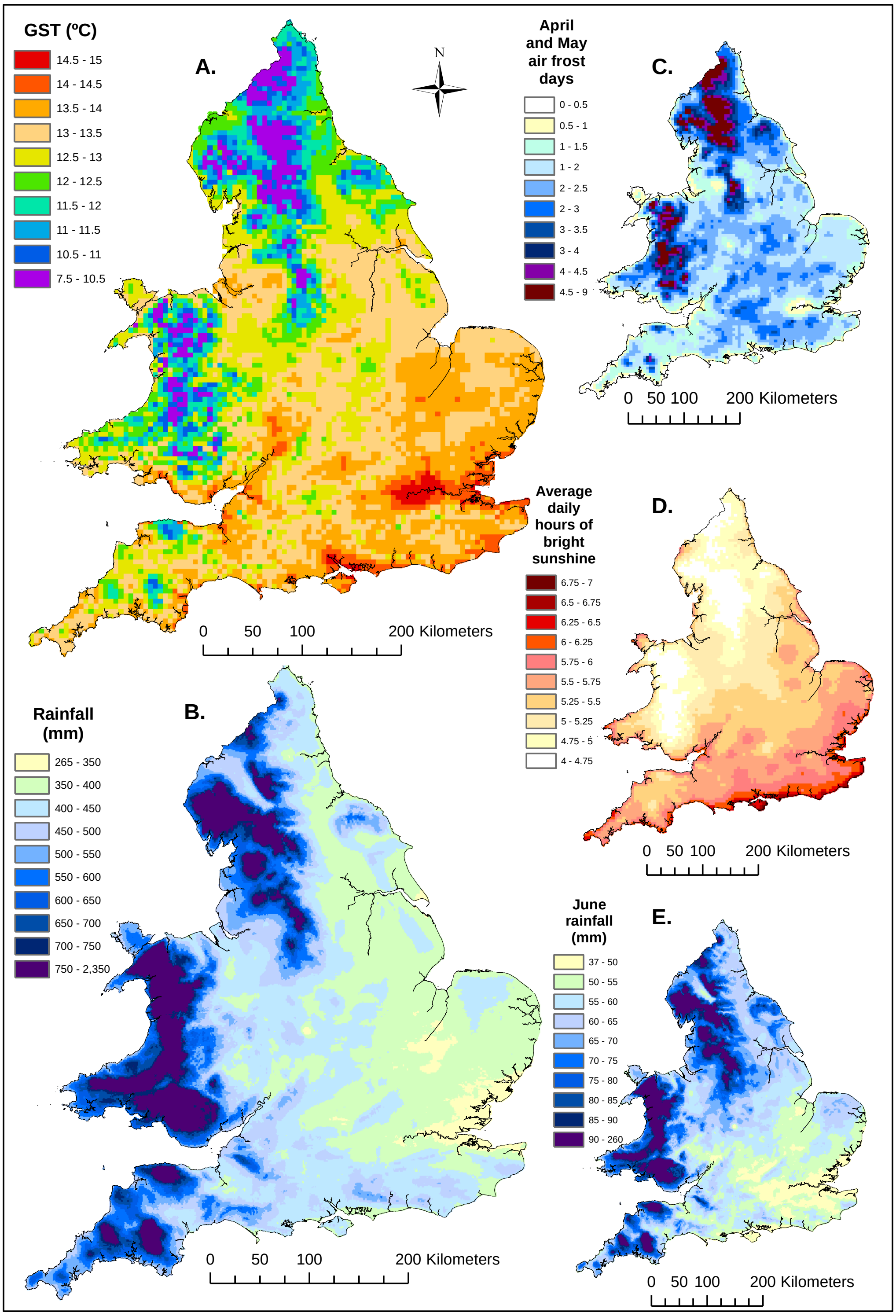


Figure 5.5: 1981–2010 mean viticulture climate conditions in England and Wales. A – GST (ºC) (5 x 5 km); B – Growing season rainfall (mm) (1 x 1 km); C – April and May air frost days (5 x 5 km); D – Growing season hours of bright sunlight (5 x 5 km); and E – June rainfall (mm) (1 x 1 km). Data sources: CEH 2014 (Rainfall) and Met Office 2015a (Temperature, Frost and Sunshine)

Throughout the growing season (April – October) the county with the lowest average mean rainfall was Essex (346 mm), followed by Cambridgeshire (356 mm), and Suffolk (362 mm). During the month of June the Unitary Authority with the lowest mean rainfall value within areas designated as biophysically suitable for viticulture was the Isle of Wight (47 mm), followed by the Isle of Scilly (49 mm), Kent (49 mm) and Surrey (50 mm). Figure 5.5B illustrates a growing season west – east configuration of higher to lower levels of rainfall, with areas in the east of England showing particularly lower levels. This configuration alters slightly for June rainfall (Figure 5.2E) where the south-east, central and southern areas of East Anglia are drier.

Figure 5.5C illustrates lower April and May air frost occurrence in coastal areas of England and Wales and in urban conurbations such as London. Higher elevations (Dartmoor, the Welsh mountains, and the Pennines and Moors of northern England, experience higher (4.5 – 9 days) air frost occurrence. The majority of East Anglia experienced (1981–2010), on average, between 1 and 2 days of air frost in April and May, whilst the viticulturally dominant areas of south-central and south-east England had slightly higher levels of 2–3 days. Areas in Dorset, Cornwall, the Severn Estuary, and Anglesey can also be seen to have experienced lower levels of air frost during the critical period of April and May, when air frosts can impact both grapevine yield and berry quality (Trought et al. 1999).

Section 1.1.1 of this thesis identifies the critical role of sunshine during the growing season for grape-vine phenology and grape berry phenolic, anthocyanin and other quality characteristic developments. Figure 5.5D illustrates high levels of growing-season mean daily hours of bright sunshine along the south-coast, particularly in south-central and south-east England, with decreasing sunshine levels north and westward. Southerly areas within Dorset, Hampshire, West and East Sussex, and Kent have an average of >6 hours per day during the growing season. Suffolk and Essex also have large areas with similar levels of sunshine to those found in south-east England.

Overlaying Figures 5.5A, B, C, D, and E with locations of vineyards (≥1 ha) (Section 2.4.4), enabled an analysis of historic (1981–2010) growing season conditions in locations where vineyards presently exist. Whilst this 30-year time-period is not entirely representative of 'conditions' during the post-2004 period, when vineyard numbers have increased dramatically (see Figure 3.1), presenting these conditions in bands and calculating the number of vineyards that fall within each climatic band allows for an assessment of the climatic spatial variability in which vineyards are presently (2013) located. Results, presented in Table 5.2, indicate the potential for spatial optimisation of viticulture to areas with higher degrees of climatic suitability.

Table 5.2: Percentage of English and Welsh vineyard locations (from 367 ≥1 ha) within imposed 1981–2010 mean climatic bands

Vineyards (%)	**GST (°C)**	**Vineyards (%)**	**Daily mean hours of bright sunshine**	**Vineyards (%)**	**April and May Air frost days**	**Vineyards (%)**	**Growing season total rainfall (mm)**	**Vineyards (%)**	**June rainfall (mm)**
10	>14	4	>6.25	3	<0.5	4	<350	16	<50
40	13.5 – 14	21	6 – 6.25	3	0.5 - 1	21	350 - 400	34	50 - 55
35	13 – 13.5	26	5.75 – 6	13	1 – 1.5	39	400 - 450	27	55 - 60
12	12.5 – 13	27	5.5 – 5.75	38	1.5 - 2	23	450 - 500	13	60 - 65
2	12 – 12.5	14	5.25 – 5.5	35	2 – 2.5	6	500 - 550	5	65 - 70
1	<12	8	<5.25	8	>2.5	7	>550	5	>70

These results demonstrate that the majority (85%) of vineyards (≥1 ha) in England and Wales are positioned in locations (within 5 x 5 km grids) with a 30-year (1981–2010) mean GST above the 13°C climate/maturity threshold for cool-climate viticulture (Jones 2006). However only 10% are positioned in regions with a mean GST >14°C, the observationally driven climate/maturity threshold for Chardonnay and Pinot Noir (Jones 2006), these being the dominant grape cultivars in England and Wales (see Figure 3.3). Only 4% of vineyards were located in areas with the highest level of sunshine hours, found predominantly along the south-eastern coastal areas of England (Figure 5.5D), with the majority experiencing 5.5–6 hours per day on average. All vineyards were positioned within grid-cells that indicated spring air frost risk, and whilst 5 x 5 km grid-scale is not necessarily representative of site specific inherent risk, these results suggest that without risk mitigation activities or site positioning that allows adequate cold air drainage (see Section 5.6 for a case study), all sites are historically exposed to a degree of threat. 1981–2010 mean rainfall throughout the growing season and in the critical month of June (Section 4.6) varied widely across locations with the majority of vineyards (≥1 ha) experiencing 400–450 mm during the growing season and 50–55 mm in June. Whilst 'idealistic' growing season rainfall will depend largely on soil characteristics and other growing-season climatic variables, it is evidenced, through Section 4.6 of this thesis that June rainfall can affect flowering and grapevine yields. For both these variables, and critically for the month of June, there were vineyards positioned in areas with lower rainfall, demonstrating potential for improved climatic positioning.

Inter-annual variability of GST and growing season rainfall in England and Wales was identified as a risk to wine yield in Sections 3.2 and 4.6. Inter-annual variability is depicted in this section through SD. However, as acknowledged in Section 2.4.5 the use of SD does not indicate the relative magnitude of the standard deviation and the Coefficient of Variation (CV) would illustrate the relative variability more clearly. Thus in section 7.3 it is recommended that further refinement of the suitability model incorporate CV to better compare results. Figure 5.6 illustrates the standard deviation (SD) of these two climatic variables for the 1981–2010 period. GST inter-annual variability is more apparent through central England, areas in East Anglia and southern Hampshire. In general, proximity to the coast will reduce the SD because sea surface temperature doesn't vary so much year to year. The further inland, the less influence the sea has and then temperature can vary more according to sunshine and wind direction anomalies. Inter-annual variability in growing-season rainfall is more apparent across higher elevation land in England and Wales, and interestingly areas within East and West Sussex, and Hampshire can be seen to have a standard deviation of 110–140 mm, higher than the majority of east Anglia and Essex which generally have an inter-annual variability of 55–90 mm of rainfall during the growing season, indicating greater consistency. Areas in east Wales, the Severn estuary, and Dorset can be seen to have much greater levels of growing-season rainfall 'stability'.

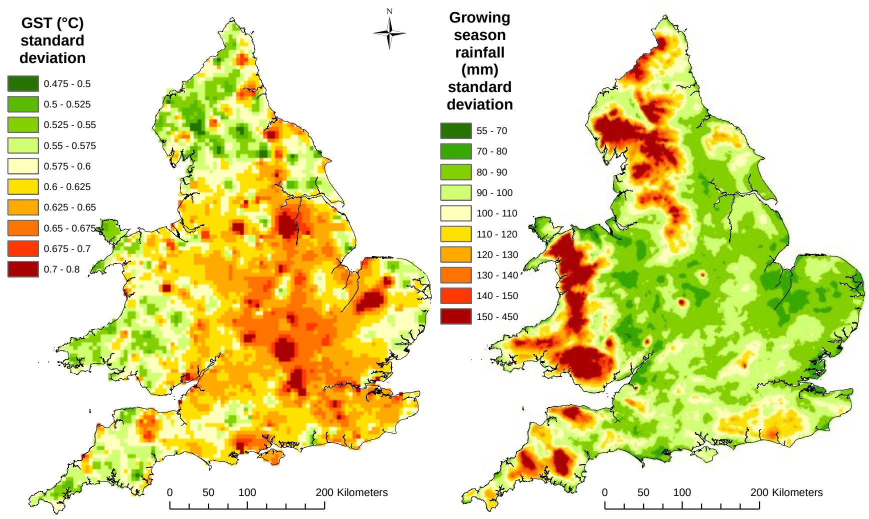


Figure 5.6: 1981–2010 GST (°C) (5 x 5 km) and growing season rainfall (mm) (1 x 1 km) inter-annual variability (expressed as SD) across England and Wales. Data sources: Met Office 2015a (GST) and CEH 2014 (Rainfall).

When inter-annual variability over a 30-year period is analysed at vineyard level all vineyards ≥ 1ha are located in areas with a GST SD above 0.53°C, and growing season rainfall SD above 73 mm. As illustrated in Table 5.3 there is potential for vineyards to be positioned in areas with lower levels of inter-annual variability than most currently are. The relationship between 30-year mean inter-annual GST and growing season rainfall variability and English and Welsh wine-yields remains statistically unquantified, however lower levels of inter-annual variability indicate greater growing season climatic stability which in turn, when all else is equal, is conducive to better yield consistency.

Table 5.3: 1981–2010 inter-annual variability (expressed as SD) of GST and growing season rainfall in 367 English and Welsh vineyard (≥1 ha) locations.

Vineyard (%)	GST (°C) SD	Vineyards (%)	Rainfall (mm) SD
11	<0.575	5	<80
15	0.575 – 0.6	28	80 – 90
32	0.6 – 0.625	26	90 – 100
30	0.625 – 0.65	19	100 – 110
11	0.65 – 0.675	17	110 – 120
1	>0.675	5	>120

Climatic suitability for viticulture in England and Wales is not dependent on any one single variable examined in this thesis section, rather it is the combination of factors, identified through Chapters 3 and 4, that more completely illustrate climatic suitability. When 1981–2010 mean GST, GST SD, April and May air frost days, growing season bright sunlight hours, growing season rainfall, growing season rainfall SD, and June rainfall values are individually fuzzified (see Table 2.3), and then combined (Fuzzy Overlay), the resulting climatic suitability model can be visualised to help identify spatial suitability. Figure 5.7 is the result of this process for England and Wales and is presented for areas deemed biophysically suitable for viticulture (Section 5.2). White areas in Figure 5.7 are not biophysically suitable.

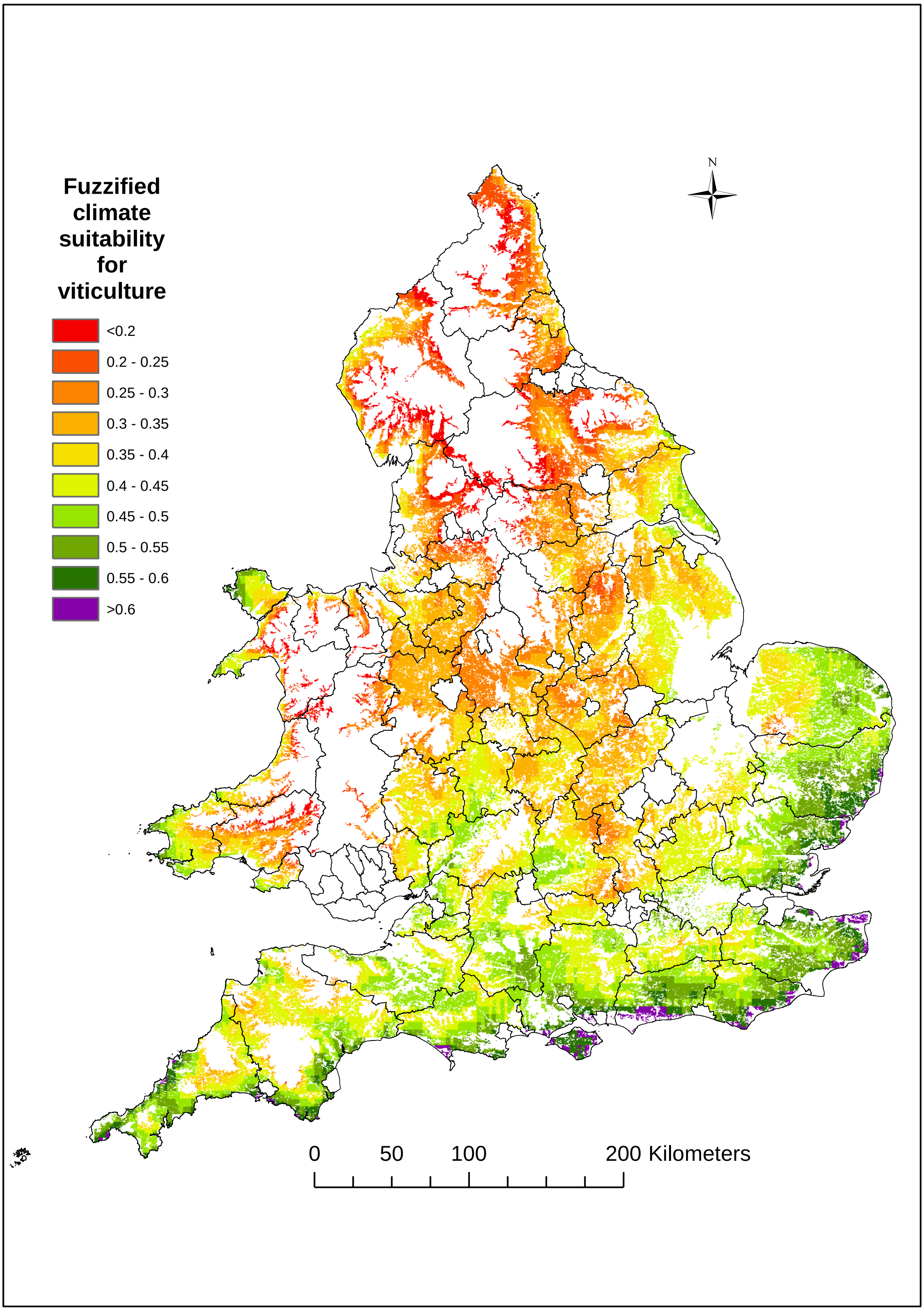


Figure 5.7: Fuzzified 1981–2010 mean climatic suitability for viticulture in England and Wales (50 x 50 m) imposed on biophysically suitable areas.

The highest maximum cell-value for combined climatic suitability was found in West Sussex, but at UA scale the Isle of Wight had the highest mean fuzzy climatic suitability (see Table 5.4), followed by West Sussex and Suffolk. These results suggest an apparent correlation between climatic suitability and the distribution of viticulture in the south-east of England, but also indicate a high degree of mean climatic suitability in Suffolk, which has eight vineyards (> 1 ha) equating to only 1.6% of vineyard area (ha) in England and Wales. Whilst biophysical suitability in North Yorkshire is high it can be seen from these results that its potential has been historically limited by its low climatic suitability. Conversely Norfolk, Suffolk and Essex indicate both relatively high mean biophysically suitability values and area (Table 5.1), and relatively high combined climatic suitability (Table 5.4). Within these Eastern counties it can also be seen (Figure 5.3) that there is less historic GST and growing season rainfall inter-annual variability than in the south-east and south-central areas which currently dominate production. This suggests these areas have greater temperature and rainfall stability from one season to the next.

Table 5.4: Top five counties by climate suitability (Mean fuzzy = the average fuzzy suitability values of 50 x 50 m grid cells in the county; Max fuzzy = the highest fuzzy suitability value of a grid cell in the county)

County	Climate suitability (Mean fuzzy)	County	Climate suitability (Max fuzzy)
Isle of Wight	0.59	West Sussex	0.75
West Sussex	0.52	Kent	0.69
Suffolk	0.51	East Sussex	0.66
East Sussex	0.50	Essex	0.65
Kent	0.50	Isle of Wight	0.65

5.3.1. Wind data integration

Wind in vineyards can negatively affect suitability (see Section 1.1.1) and was commented on by producers as a production risk in England and Wales (Section 3.2). Mean daily wind data from the UKCP09 5 x 5 km gridded dataset (Met Office 2015a) was calculated for the growing season, fuzzified (linear) and integrated into the climatic suitability model resulting in reduced suitability along a few coastal areas of southern and eastern England but not materially affecting climatic suitability distribution. However the UKCP09 interpolated wind data was for wind speed at 10 m above ground level. As such its representativeness of vineyard conditions was not deemed to be reliable enough to integrate within the model, and it was subsequently removed. Modelled wind speed at vine height (1-2 m) would be useful to further refine the suitability model, but in its absence elevation was applied as a restricting factor (<150 m, with a fuzzy optimum of 52.5 m, see Table 2.2). This restriction will in part account for higher model values for areas less likely to be exposed to winds.

5.3.2 Rain days

Within Sections 4.1, 4.2, 4.5, 4.6, and 5.3 relationships between climatic parameters and suitability for viticulture relevant to rainfall have concentrated on monthly or growing-season rainfall totals. However, it should also be noted that the number of rain days could have a different effect on both yields and viticulture suitability. Heavy rainfall over a short period of time was not explicitly mentioned by producers as a climate change threat (see Table 3.4) but extreme weather was. There is very little research into the effects of extreme rainfall on viticulture but it can be noted that during June 2012 rainfall, attributed in part to low yields in 2012 (Table 3.5 and Section 4.6), was both the highest total (138 mm) and had the highest number of rain days 14.4 (≥1 mm) during the 2004–2013 period. To more accurately determine the relationship between rain days and yield, daily rainfall totals would be required. Unfortunately this was not available from the Met Office (2014b) or CEH-GEAR (2014) monthly data employed in this study.

5.4. Combined viticulture suitability results

The viticulturally relevant climatic analysis of spatial variability, presented in Section 5.3, merely indicated opportunities for spatial adaptation to areas of greater suitability, but does not take into consideration land availability within those areas. For example whilst areas with the highest level of sunshine are seemingly underpopulated with vineyards, Figure 5.5D illustrates that these areas are confined to a narrow strip of land along the southern coast of England, a strip in which land may not be available, or which may be climatically unsuitable for other reasons, such as potential wind exposure. The integration of the biophysical suitability model with the climatic suitability model and subsequent fuzzification facilitates a better understanding of land availability and overall suitability (Section 5.4).

Combining viticulture biophysical and climatic models for England and Wales through an overlay fuzzification process (see Section 2.4.5) results in a comprehensive viticulture suitability model – as presented at national scale in Figure 5.8. From this it is possible to assess collective suitability by Unitary Authority (limited to counties to exclude small borough pockets of suitability) and gain an understanding of the amount of potential viticultural land under different model fuzzified classifications.

The combined biophysical and climatic viticulture suitability model (Figure 5.8) illustrates, in general, higher fuzzified spatial suitability in southern and eastern England, than that observed through a sole analysis of biophysical suitability, as was presented in Figure 5.4. East Anglia, areas of south-east and south-central England, areas within Cornwall, South-west Wales and Anglesey can visually be seen to have areas of high suitability. These visual observations are further clarified when results by county are examined in Table 5.5 which shows the mean value of all cells within counties, the highest (maximum) suitability score within counties, and the total (summed) of all cells within counties, for the top 10 counties in England and Wales.

Table 5.5: Mean, maximum and summed fuzzy suitability for viticulture ranked by County.

County	Mean suitability	County	Maximum suitability	County	Summed suitability
Isle of Wight	0.457	Kent	0.818	Norfolk	194276
Suffolk	0.451	East Sussex	0.805	Devon	147161
West Sussex	0.440	Isle of Wight	0.800	Hampshire	136290
Essex	0.438	West Sussex	0.800	Essex	130377
Vale of Glamorgan	0.432	Dorset	0.799	Kent	128564
East Sussex	0.423	Cornwall	0.780	Lincolnshire	128232
Norfolk	0.416	Devon	0.776	North Yorkshire	127623
Kent	0.412	Pembrokeshire	0.755	Suffolk	125546
Anglesey	0.390	Hampshire	0.754	Cornwall	116559
Surrey	0.381	Suffolk	0.748	Dorset	105472

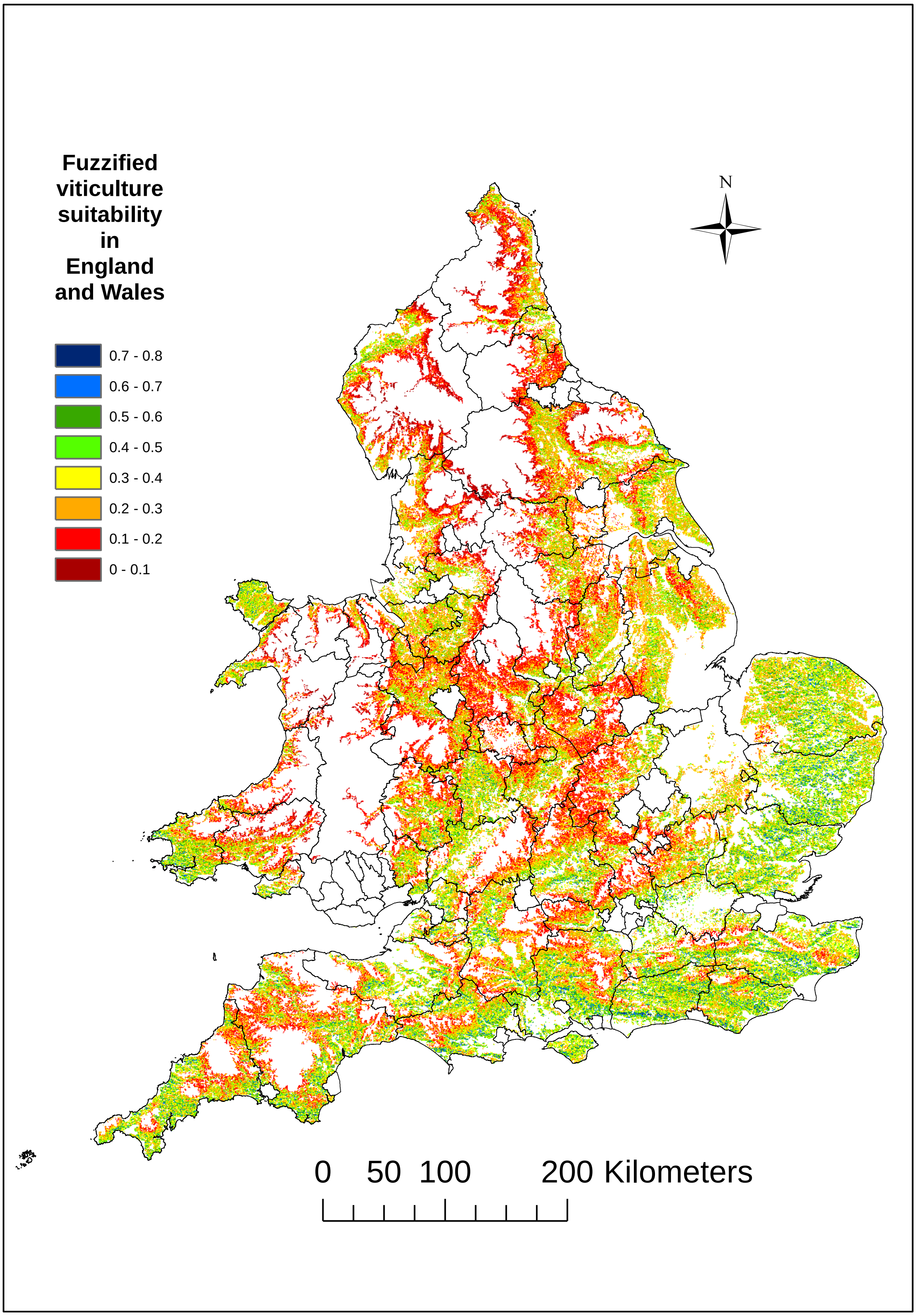


Figure 5.8: Fuzzified viticulture suitability model for England and Wales based on biophysical appropriateness (50 x 50 m) and mean 1981–2010 climate parameters (5 x 5 km).

In Wales, the Vale of Glamorgan and Anglesey 'scored' particularly well, perhaps surprising as these areas only currently have 6.3 and 2.6 ha of vineyards respectively (See Figure 3.2 and Table 3.1). Within counties the highest value grid cell was found in Kent, with pockets of areas in the south-west of England also scoring highly. Again taking into account area, Norfolk topped suitability. Although county-wide assessments of viticulture suitability do not elucidate 'pockets' of land with high suitability within larger areas, this assessment again illustrates opportunities for spatial adaptation and sector growth in areas with higher modelled viticulture suitability, and concurrently areas that indicate more favourable climatic suitability for viticulture.

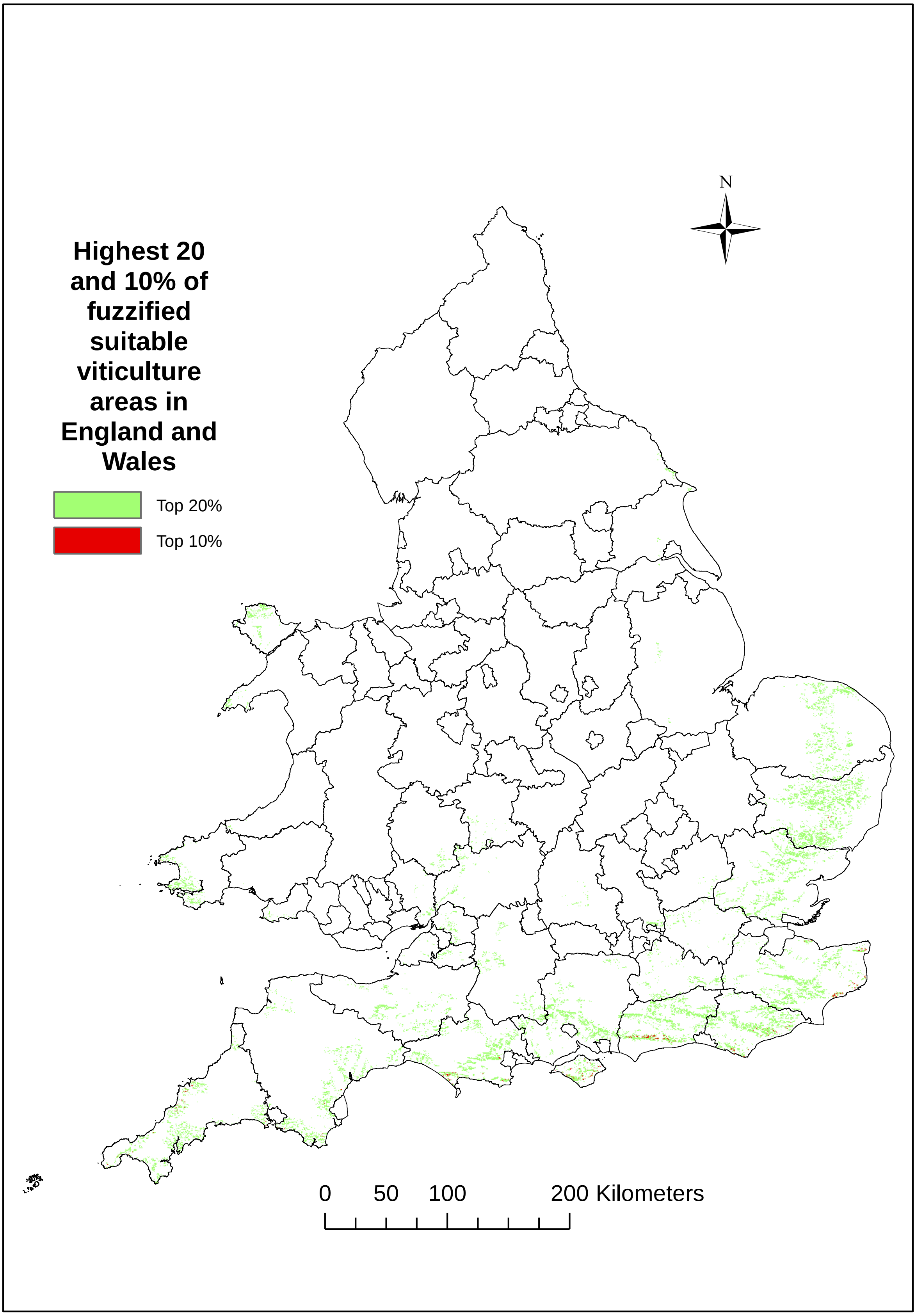


Figure 5.9: Viticulture suitability (50 x 50 m) in England and Wales limited to the highest 20 and 10% of fuzzified classifications.

Limiting the fuzzy suitability model to present the top 10 and 20% of land suitability area in England and Wales (Figure 5.9) results in 33,700 ha (10 and 20% combined), 0.2% of all land in England and Wales and 1.3% of biophysically suitable land being suitable. Within the top 20% Suffolk has the largest volume of land (4,560 ha), followed by West Sussex (3,933 ha), and Kent (3,538 ha).

When the model was further restricted to show the top 5% of suitable land according to the fuzzy model the results stretched across 25 unitary Authorities with West Sussex having the largest area. Results are presented in Table 5.6.

Table 5.6: Top 5% of classified viticulture land by Unitary Authority in England and Wales. (B – Borough)

Unitary Authority	Area (ha)
West Sussex	911
East Sussex	503
Kent	468
Suffolk	343
Cornwall	341
Dorset	308
Isle of Wight	292
Devon	151
Hampshire	91
Essex	88
Pembrokeshire	73
Wiltshire	21
Vale of Glamorgan	19
Medway (B)	14
North Yorkshire County	9
City of Plymouth (B)	8
City of Portsmouth (B)	7
Isle of Anglesey	6
Brighton and Hove (B)	5
Norfolk	4
Poole (B)	3
Torbay (B)	3
Somerset	1
Thurrock (B)	1
Swansea	1

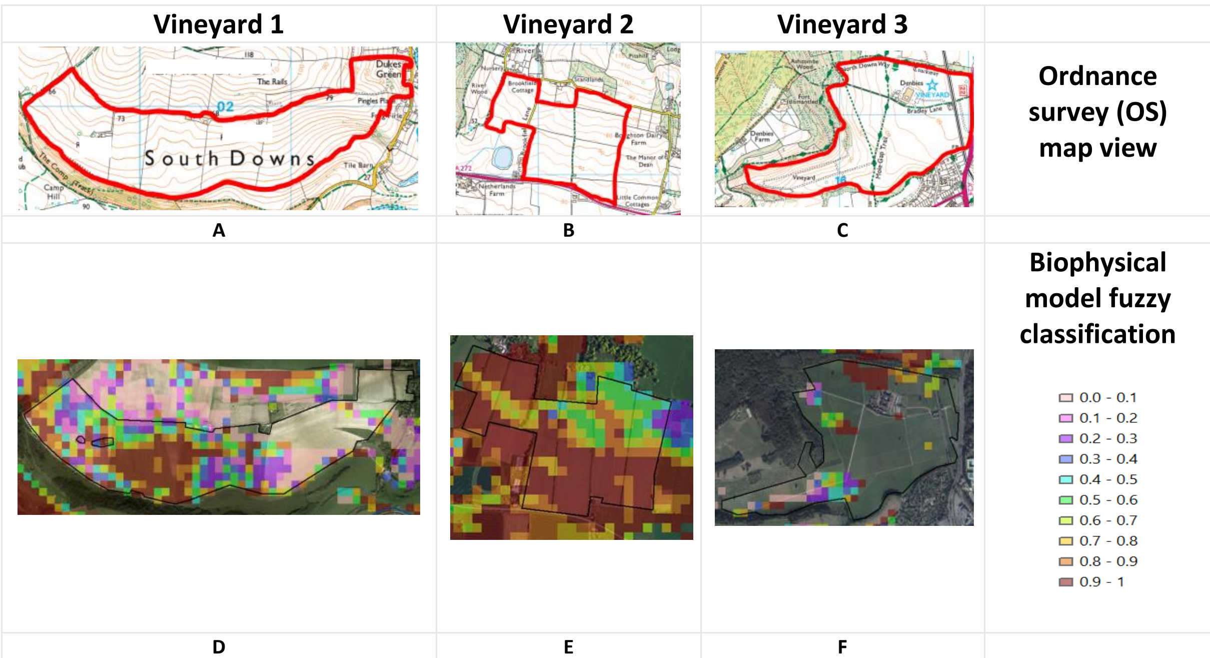
5.5. Biophysical suitability model validation

Following extensive biophysical suitability model construction the topographical characteristics of 13 large (≥25 ha) vineyards were assessed to help validate the model. A comparison was made between model gridded (50 x 50 m) values and Ordnance Survey (Edina 2015) contoured physical maps of the vineyard sites. Figure 5.10 shows output for three of the 13 vineyards assessed. Soil characteristics

(Figures 5.10P, Q, and R) were assessed through communication with vineyard managers and were found, in relation to the SoilScapes descriptors used, to correspond to those observed onsite. Topographical values from the model were visually compared with Ordnance Survey (Figures 5.10A, B, and C) maps to determine a 'sensible' representation of the model values against contoured properties, illustrated through the maps.

Vineyard 1, in Figure 5.10D can be seen to contain an area in the east that does not fall within the suitability model. This was found, through closer examination of the vineyard site, to accurately reflect a steep 'zone' within the site (>25%) which was unplanted. Elevation and aspect (Figure 5.10G and J) corresponded to those observed in Figure 5.10A, with parts of the north-eastern vineyard being excluded from the model as aspect ranged outside of the 90–270° deemed suitable for viticulture (Section 2.4.4). Generally, the vineyard can be seen to have an aspect ranging from south-west to south-east.

Vineyard 2 can be seen from Figure 5.10E to have a high degree of suitability, corresponding to a favourable landscape evidenced through Figure 5.10B. Vineyard 3 can be seen to encompass large areas that fall outside of model suitability. An observation from the OS map in Figure 5.10C is that much of the land on which the vineyard is located is facing east-north-east i.e. outside of the 90–270° delineated model suitability. These important observations both provide model corroboration and also indicate that the model is constrained to 'idealistic' scenarios of viticulture suitability, i.e. it excludes biophysical features on which vineyards can be established, but which are not considered 'ideal' for viticulture.



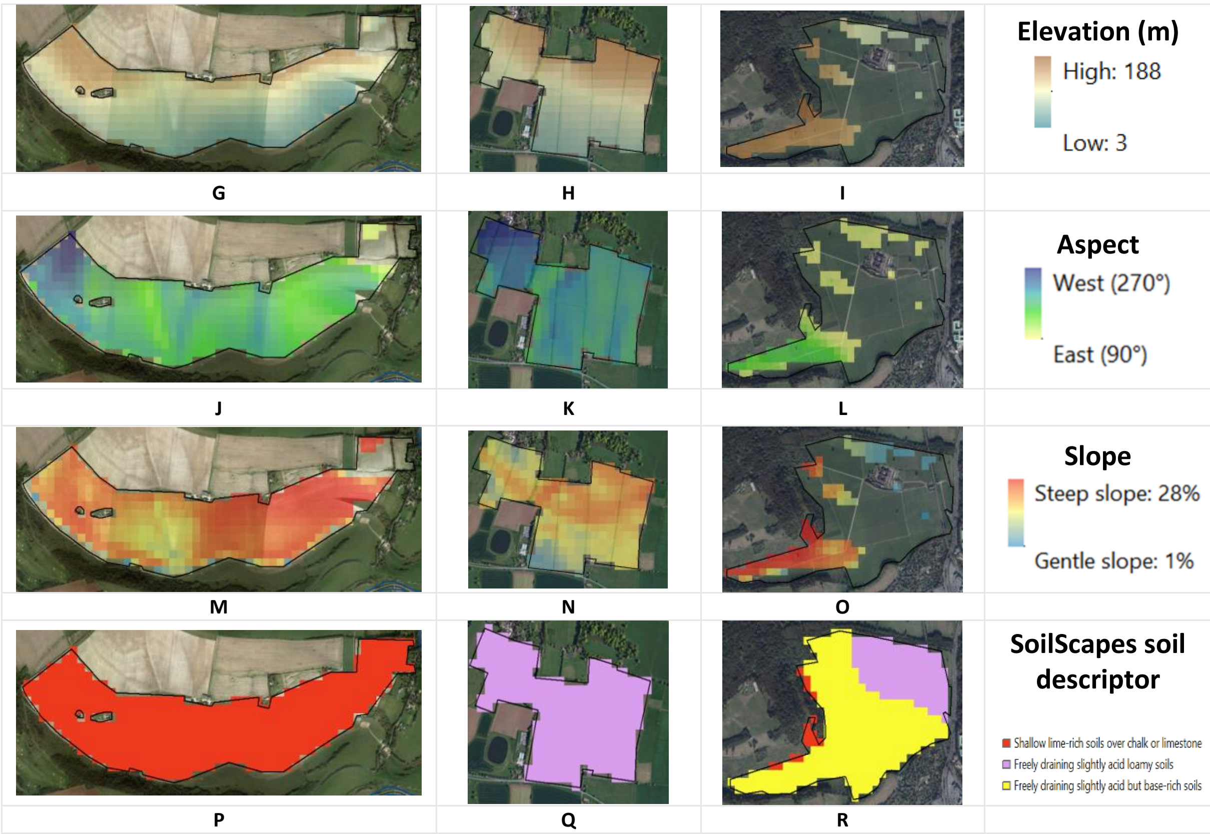


Figure 5.10: OS maps (Figures A, B, and C) for 3 of the 13 (≥25 ha) vineyards employed for model validation

Model biophysical suitability values (D, E, and F) at 50 x 50 m resolution overlain on earth imagery

Topographic values (G, H, I, J, K, L, M, N, and O) at 50 x 50 m resolution overlain on earth imagery

Soil descriptors (P, Q, and R) at 50 x 50 m resolution overlain on earth imagery

5.6. Bioclimatic analogue study

For those considering investing in viticulture in England or Wales the suitability model presented in Sections 5.1–5.4 provides direction regarding spatial suitability and opportunities for vineyard establishment, at national, regional and local scales. However, results in these sections, and those presented in Section 4.6, lack comparison with other cool-climate wine producing regions, both internally, i.e. within England and Wales, and internationally. This thesis section employs bioclimatic index values (2004–2013 mean), generated using the WRF model, to compare 9 x 9 km grid-cells in which large English vineyards (≥25 ha) are positioned with values across England and Wales (Section 5.6.1) and other cool-climate regions in north-western Europe (Section 5.6.2). The WRF model was selected for this application in order to produce a recent decadal dataset, beyond the 2010 limit of the UKCP09 data. It was also selected because the Huglin Index and Growing Degree Day bioclimatic indices require daily data for their calculation (see Table 2.1), which was not available from the UKCP09 datasets.

Furthermore, application of the WRF model as described in Section 2.1.3, enabled an initial assessment of the reliability of model output for analysis of localised historic weather data, with the ultimate goal being the model use for commercial viticulture suitability assessments.

5.6.1. Bioclimatic and analogue analysis of England

Figure 5.11 shows the thermal ranges of the mean 2004–2013 HI, GDD, and GST bioclimatic indices (see Table 2.1 for formulas), and spatial variability across England and Wales. The spatial configurations remain similar between bioclimatic indices and to those observed in Figure 5.5a, with warmer temperatures being observed in the south-east and eastern England. However, the HI resulted in some south-eastern coastal areas having lower bioclimatic values, a configuration not observed through the other bioclimatic index results. Potential reasons for this phenomena are not explored further in this thesis but could relate to issues of WRF model alignment into ArcGIS, referred to in Section 2.3.6, i.e. that the coastal values being observed are skewed by mis-alignment with sea surface temperatures. They may also be a function of the HI algorithm (Table 2.1) that emphasises maximum temperatures over minimum temperatures, suggesting that these south-eastern coastal areas may have lower maximum temperatures than areas with higher HI values. Further investigation is required into this phenomena, and is recommended in Section 7.3.

GDD and HI values are not incorporated into the viticulture suitability model presented in this thesis, but through future validation and downscaling (to 1 x 1 km resolution), it is envisaged that these will be made available to model end-users because both have been widely used as thermal indicators of regional comparativeness and cultivar suitability (Section 1.2.2.).

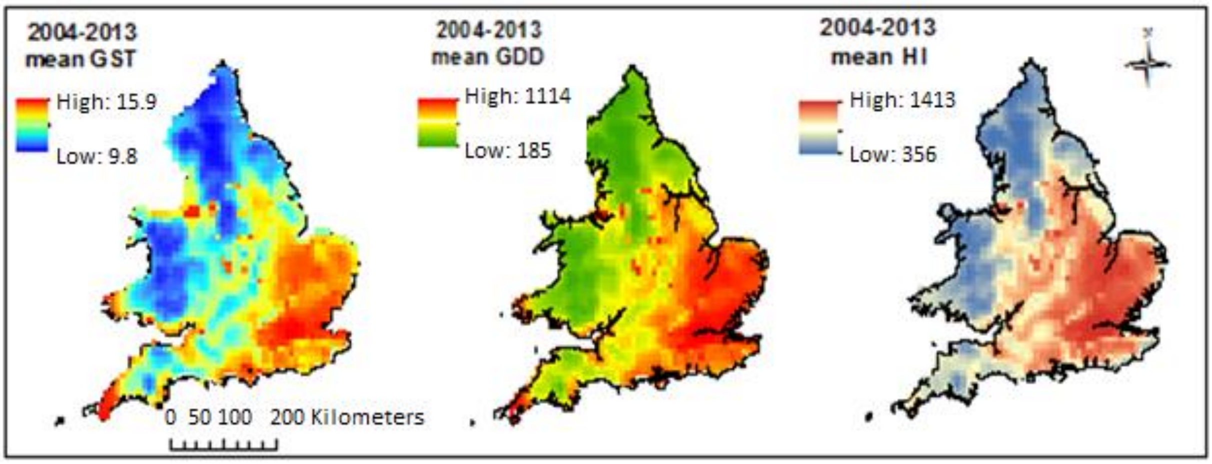


Figure 5.11: 2004–2013 mean GST, GDD and HI values (9 x 9 km) for England and Wales (Source: WRF model)

Selecting the five largest vineyards in England and Wales, all dominated by Chardonnay, Pinot Noir, and Pinot Meunier cultivars for sparkling wine production, their 2004–2013 mean GST was calculated from the WRF model (9 x 9 km) grid values. The same or higher GST values as those found in the five vineyards were then searched for across biophysically suitable land in England and Wales. The result was a mean GST averaged across all five vineyard sites of 14.2°C and 204,727 ha of biophysically suitable land with the same or higher 2004–2013 mean GST. Whilst the spatial resolution of the WRF model is only indicative of vineyard environments these findings suggest a considerable area of land in England and Wales that could, all else being equal or better, be suitable for cultivation of Chardonnay, Pinot noir, and Pinot meunier. To further illustrate potential for the production of these three cultivars the average values of the climatic and biophysical parameters assessed in this work for the five vineyards were calculated and then land sought that bettered each mean value. 16,651 ha of land was identified that had higher biophysical and climatic suitability values than the mean for the five largest vineyards growing Chardonnay, Pinot noir and Pinot meunier. The vast majority of this land (11,885 ha) was found in Kent, Essex and Suffolk. These results indicate significant potential for sector growth or adaptation to land with higher levels of suitability than currently occupied by the largest vineyards in England and Wales.

5.6.2. GST and cultivar analogue within European cool-climate regions

Developing the analogue method of viticulture suitability assessment further the WRF model 9 x 9 km domain mean 2004–2013 GST was overlain onto a map of European vineyard areas that were derived from the CORINE Land Cover (CLC) 2012 inventory (Figure 5.12).

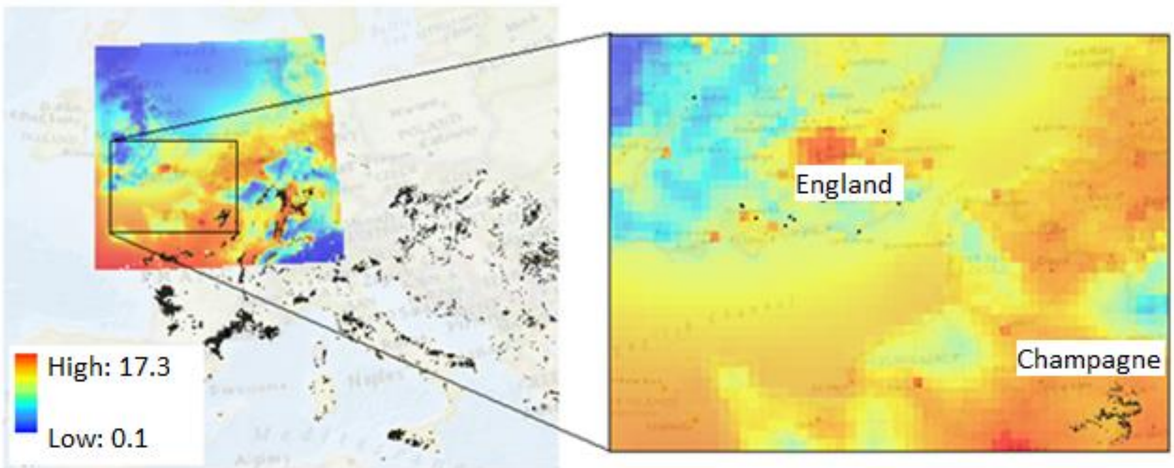


Figure 5.12: WRF domain 2004–2013 (9 x 9 km) mean GST values (°C) and European viticultural areas (black areas/dots) derived from the CLC 2012 inventory.

To provide a bioclimatic comparison between other 'cool-climate' regions in Europe and the 13 vineyards in England of ≥25 ha, mean GST values (2004–2013) for grid-cells which contained vineyards in Champagne, Mosel-Saar-Ruwer, Franken, Neuchatel and Eastern Denmark (Zealand) were extracted and averaged for each wine producing area (vineyards stretched across more than one 9 x 9 km grid cell). Results presented in Table 5.7 show GST values and the dominant cultivars grown in each region (Johnson & Robinson 2001).

Table 5.7: 2004–2013 mean GST values (Source: WRF model) and dominant cultivars in six European 'cool-climate' viticulture areas (Source: Johnson & Robinson 2001).

	Neuchatel	**England**	**Eastern Denmark (Zealand)**	**Mosel-Saar-Ruwer**	**Franken**	**Champagne**
GST (°C)	13.73	14.01	14.02	14.05	14.55	15.01
Dominant cultivars	Chasselas Pinot noir	Chardonnay Pinot noir Pinot meunier	Rondo Regent Leon Millot	Riesling Müller-Thurgau Elbling	Silvaner Müller-Thurgau	Chardonnay Pinot noir Pinot - meunier

These results suggest that the 13 largest vineyards in England have had a 2004–2013 mean GST 1°C lower than that of the Champagne region, which also is dominated by Chardonnay and Pinot noir production for sparkling wine. Relevant to Figure 1.4, large vineyards in both England and Champagne have been operating within the climate-maturity groupings observed by Jones (2006), although in England Figure 1.4 suggests viticulture is practiced at the very bottom end of climate-maturity thresholds for these cultivars, albeit in the middle of the 'cool-climate grouping. Perhaps of greater interest is the observation that the modelled 2004–2013 GST suggests that the large vineyards in England have had a similar GST to that modelled for Eastern Denmark and Mosel-Saar-Ruwer (MSR) in Germany. However, these are dominated by different cultivars, including Müller-Thurgau in MSR, which until 2004 was the dominant cultivar in England and Wales (see Figure 3.3), and Rondo and Regent in Eastern Denmark which were also traditionally grown in England (Skelton 2010). These observations do not account for climatic variables other than GST or seasonal distribution thereof, modelled over a 9 x 9 km grids resolution. However, they do initially indicate potential for cultivar adaptation within these regions, and perhaps confirm the marginal nature of climate in large English vineyards for Chardonnay, Pinot noir, and Pinot meunier, relative to other 'cool-climate' regions. Additionally, they indicate the importance of careful siting of vineyards in England and Wales (where Chardonnay and Pinot noir are to be grown) in climatically suitable areas.

5.7. WRF model validation

To help assess WRF model performance and to facilitate future viticulture suitability model development (incorporating WRF model derived weather variables at 1 x 1 km resolution) a case-study of in-vineyard temperature variability relative to 9 x 9, 3 x 3 and 1 x 1 km modelled thermal values (WRF model output) was undertaken for a single vineyard in East Sussex. Specifically, this was for 2015 April air frost occurrence. 15 temperature sensors were installed at the vineyard – shown in Figure 5.13, by the author in February 2015 as part of the ADVICLIM project (ADVICLIM 2015). Temperature data (min, max and mean) recorded by these sensors every hour captured air frost (90 cm above ground) occurrence in April 2015 and allowed for a comparison with WRF modelled April air frost occurrence.

Figure 5.13: Positioning of temperature sensors installed at an East Sussex vineyard. Sensor names relate to cultivars in which they were positioned.

Temperature sensor data from the vineyard confirmed that there were six air frost events (April 2015) recorded at the lowest vineyard point (34 m – Riesling row 42), two recorded by the sensor halfway up the vineyard (43 m – Ortega row 37), and one recorded by the highest positioned temperature sensor (60 m – PM row 59). Sensor elevations, derived from the OSDTM50 integrated into the biophysical suitability model (see Table 2.2), were found to match, almost identically (+/-1 m) those recorded on OS contour maps of the vineyard. These results are relevant in two ways. They indicate how, under radiation frost conditions, cold air flows downslope and how it can accumulate in vineyard areas where little cold air drainage exists, increasing frost damage risk in those areas. Hence the optimum elevation (52.5 m) and slope (5%) integrated into the suitability model allows for cold air drainage, where no barriers to such exist. These findings also help validate the WRF model output for April air frost events in 2015. Here, Figure 5.14 indicates that in the grid cells that cover the vineyard, at 9 x 9 km one event is modelled, at 3 x 3 km resolution two are recorded and at 1 x 1 km resolution three events are recorded. An average of results from the three sensors referred to previously gives a mean of 3.5 frost events, suggesting good WRF model representativeness of local occurrence.

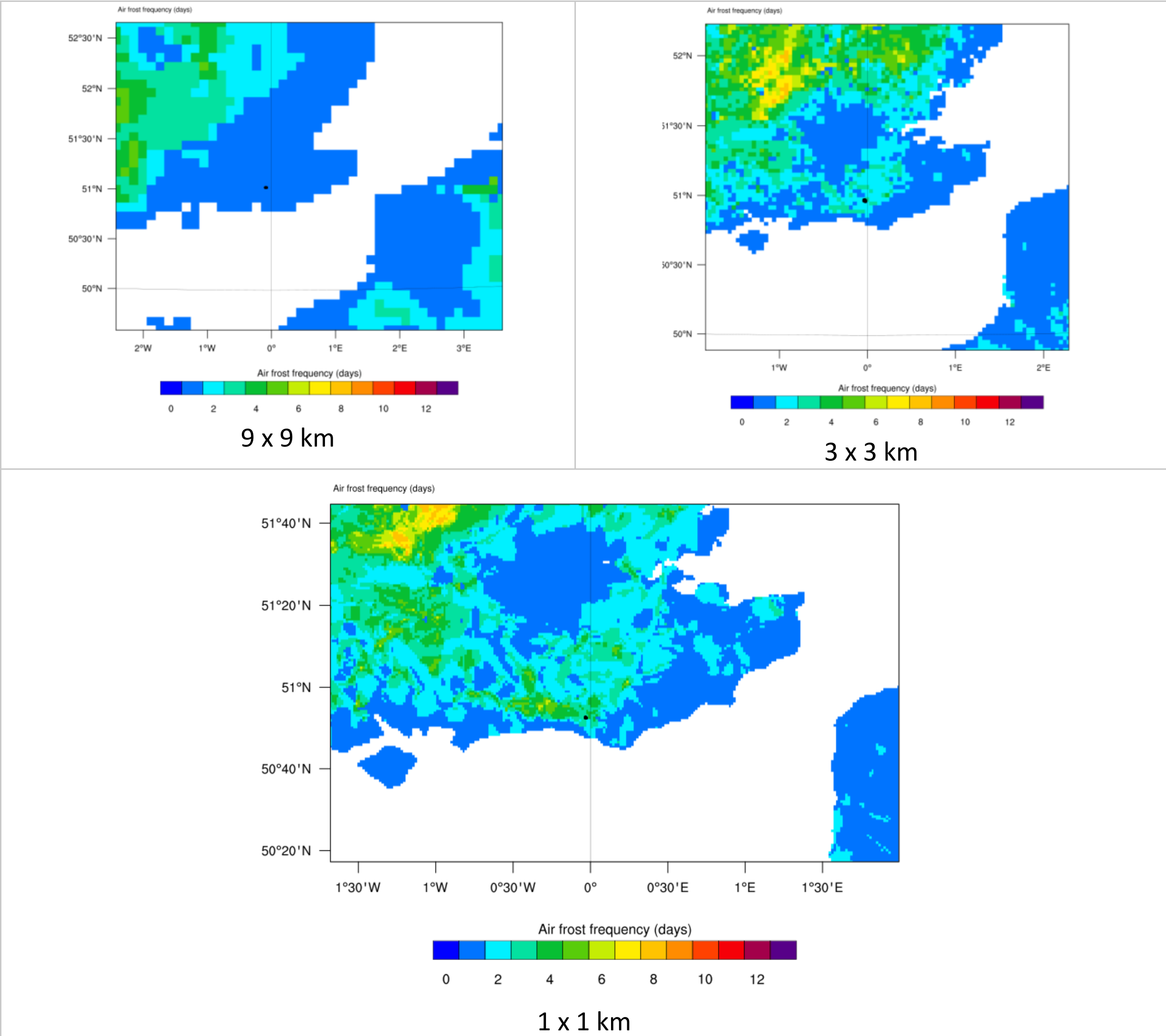


Figure 5.14: Downscaled WRF model output for April 2015 air frosts at 9 x 9, 3 x 3 and 1 x 1 km resolution. ● indicates the location of the sample vineyard. Data source: WRF Model.

Using the same WRF model data, dynamically downscaled to a 3 x 3 km resolution grid, a single frost event was captured in a vineyard in Suffolk. The model here was used to validate an observation made by a grower. Figure 5.15, from the WRF model, shows air (T2 (2 m)), ground (TSK) and dew point (TD (2 m)) temperature on the 4th May 2014 for a 3 x 3 km grid where the vineyard was situated. The ground temperature (TSK) (-3^{o}C) shown on the graph concurred with what the vineyard owner had observed. He had experienced vine damage following the event and estimated to have lost about 25% of his crop as a result. This crop loss suggests that the ground frost had risen to the bud height on the vines, and at T2 (2 m above ground) a minimum temperature of 0^{o}C was simulated.

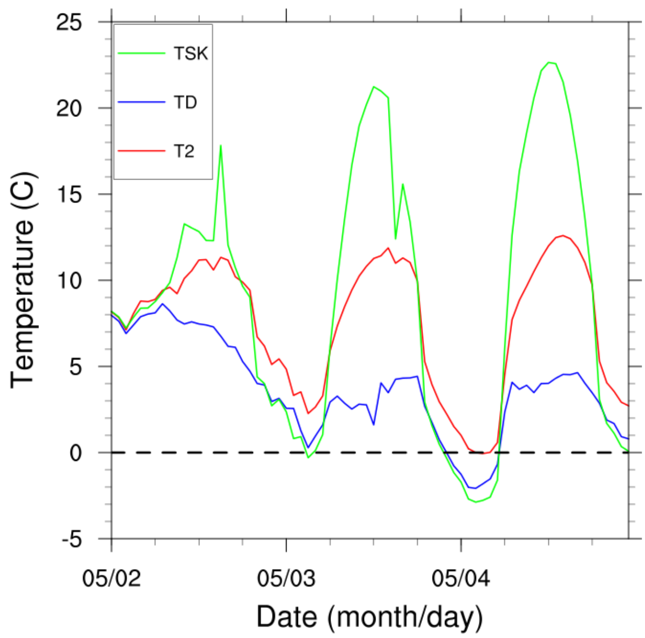


Figure 5.15: Air temperature (T2), Skin (ground surface) temperature (TSK) and dew point temperature (TD) for 2nd to 4th May 2014 in a 3 x 3 km grid cell encompassing a Suffolk vineyard. Data source: WRF Model

These two initial examples of WRF model spring air and ground frost validation provide corroborate assessments of frost risk in vineyards (Hammersmith 2014). They also provide a platform from which to further refine and embed, in the future, WRF model output into the viticulture suitability model presented in this chapter. At present, utilising 1981–2010 data on a 5 x 5 km grid provides good indication of spatial and temporal variability in viticulturally relevant climatic variables, but having the ability to present more recent and higher resolution data would significantly enhance model applications.

5.8. Potential conversion to viticulture: an economic perspective

Results presented in Sections 5.1–5.5 relate to biophysical and climatic suitability for viticulture in England and Wales and tools to help identify suitable areas. Whilst spatial suitability is critical to the viability of viticulture, those considering investing in viticulture in England and Wales also require an economic perspective. This is particularly the case where land use conversion is considered. As identified in Section 5.1 the majority of vineyards in England and Wales are established on land previously designated as 'Arable or Horticulture' under the Land Cover Map 2007 (Centre for Ecology and Hydrology 2007). Section 5.4 illustrates significant high quality and climatically suitable land that could potentially be made available for viticulture in England and Wales. However, decisions regarding conversion potential from one crop to another require economic analysis. A complete fiscal analysis of English and Welsh viticulture falls outside of the scope of this thesis but here a rudimentary case study is presented to illustrate comparisons between the economics of viticulture and sugar beet production. Sugar beet was selected as a comparator because sugar beet in England is predominantly grown in East Anglia (Figure 5.16), a region identified through the suitability model (Sections 5.1–5.5) as having high viticulture potential, and also because sugar beet production in England is challenged by an impending removal of EU subsidy and exposure to the global sugar commodity market, perhaps providing an opportunity for conversion to more ‘in-vogue’ crops such as wine grapes (*Vitis vinifera* L.). It should be acknowledged, however, that sugar beet has an important current role in farm rotations.

Analysis of existing sugar beet production locations (kindly provided by British Sugar Plc.) overlain onto the biophysical suitability model (Figure 5.16) shows that there are 513 sugar beet growers (14% of growers who supply British Sugar), on land that is, at least in part (only point-locations of sugar beet farms were incorporated within the map), deemed suitable for viticulture. The range (Fuzzy mean) of suitability for these growers is from 0.26 – 0.84. This suggests that at least bio-physically there are opportunities for conversion. Figures 5.5, 5.7 and 5.16 indicate that the positioning of many sugar beet farms in East Anglia are within similar climatic conditions to current viticulture locations in south-east and south-central England. Furthermore, several sugar beet farms are located close to existing vineyards in East Anglia (see Figure 5.16).

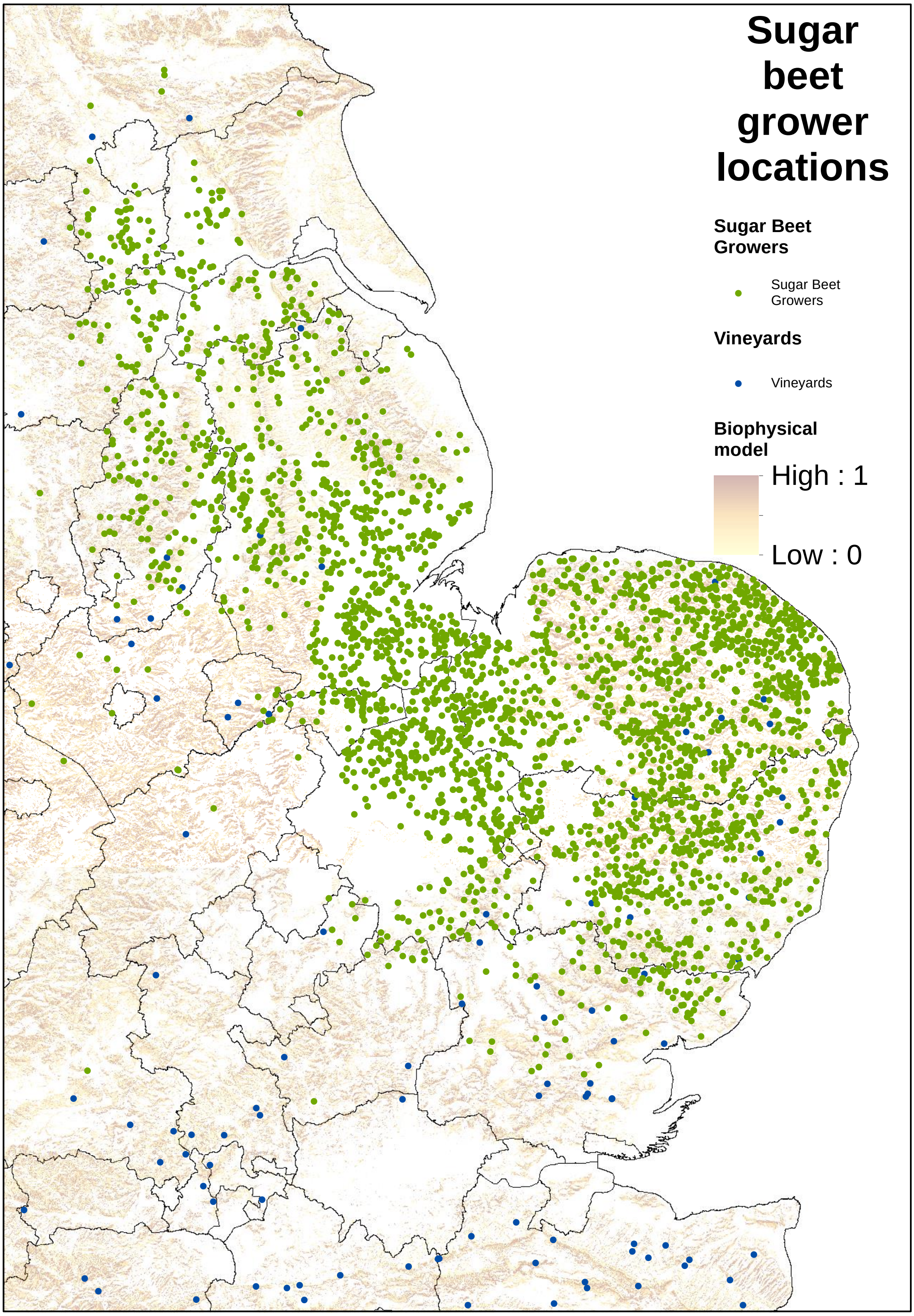


Figure 5.16: Sugar Beet growers (green) (Source: British Sugar) and vineyard (≥1 ha) (blue) (Source: Skelton 2015) locations overlain on the biophysical viticulture suitability map (50 x 50 m).

Return on investment for viticulture is largely dependent on market forces over a period of time, grape quality, and yield. There is not yet a body of evidence regarding wine production and investment economics for English and Welsh wine production, but in general a suitable vineyard site, in a favourable year can yield 10 t/ha (4 t/acre). Whereas poorer vineyards are achieving less than 3 t/ha (1.2 t/acre), an average yield for an established vineyard in England, growing Chardonnay, Pinot noir and Pinot meunier, is considered to be around 6 t/ha (2.4 t/acre) (Skelton 2014).

If the crop is sold, the current market value for sparkling grape varietals (Chardonnay, Pinot noir, Pinot meunier) is around £2,300 per tonne but fluctuates depending on cultivar demand, quality (sugar and acid levels), and supply and demand. Vineyard establishment costs are estimated to be £25,000/ha with annual running costs of between £7,000 and £8,000 / ha per year (Skelton 2014), excluding picking labour costs. Net return per ha is estimated to range between £342 and £5,967 per ha (Skelton 2014).

Sugar beet is a commodity based crop that traditionally, in Britain, has a negotiated and established value per tonne (National Farmers Union 2016). In 2015 yields per ha were 59.5 tonnes (low production), 70 tonnes (average production), and 80.5 tonnes / ha (high production) (Redman 2015). Once operational costs were taken into consideration gross margins per hectare were estimated to range between £334 and £765. These were lower than 2014 (£548 – £1,054) and still lower than 2013 (£935 – £1,569) (Redman 2015). The 2016/17 value has been set at £20.30/tonne, estimated to be close to cost of production (Řezbová et al. 2015). Further to these observed declines in profitability, annual commodity prices for sugar (global) indicate declining value over the last six years (National Farmers Union 2016). In comparison to mean estimated returns on viticulture, sugar beet production is, as a three year average, 72% lower. Where vineyards are established in suitable locations and within favourable climatic conditions returns in viticulture could be 588% higher than the 3 year mean of the range of returns presented for sugar beet.

Future market trends/demand for grapes or sugar beet cannot be estimated within the scope of this thesis. Furthermore, this analysis only illustrates low, medium and high yield financial returns for both crops, not for a single year and not to illustrate the degree of yield variability over-time. Further analysis of such a nature would be required for a full fiscal study of the sectors investment security. However, from these rudimentary figures it could be concluded that return on investment is potentially higher for viticulture than sugar beet. Furthermore wine production could extend margins and profitability further.

5.9. Discussion

In this chapter multi-criteria decision analysis (MCDA) was applied, combined with fuzzy logic, and geographic information systems (GIS), to assess and present spatial suitability for viticulture in England and Wales. Areas that are biophysically suitable, which benefit from more favourable mean climatic conditions, and which are more stable through lower exposure to inter-annual weather variability, were sought through the modelling process. Additionally, a climate analogue approach was also used to map areas in England and Wales with similar historic growing-season temperature conditions to those found in larger commercially established vineyard regions, and to provide comparators of seasonally averaged conditions (2004–2013) with other cool-climate wine producing regions in France, Germany, Switzerland and Denmark. When an evaluation of viticulture potential is extended to cultivar suitability at broader temporal and spatial scales bioclimatic indices can provide an indication of climate-cultivar suitability (Jones et al. 2006). Using three commonly applied bioclimatic indices: GST, GDD, and the HI, the results provide a first coarse bio-climatic benchmark in England and Wales and enable model suitability to be aligned with the *Vitis vinifera* L. cultivars grown in selected regions and vineyards.

Finally, to provide an example of potential for conversion to viticulture from a commodity based crop to viticulture the rudimentary economics of investment returns for sugar beet and wine grapes were evaluated.

Model validation against 13 large vineyards in England suggest a good biophysical correlation with observed and mapped vineyard properties – providing confidence that the biophysical model is representative of existing vineyard environments. It should be noted, however, that the biophysical model resolution was restricted to 50 x 50 m with values being representative of the centres of each grid cell. As such there is potential for variability across grid cells that could render differences in suitability within a cell environment. Notwithstanding apparent model alignment with reality, it is recognised that the SoilScapes (2015) dataset and descriptors employed within it are broad and that higher resolution and accurate soil data layers for individual soil properties (Section 1.2.3) would be of additional value to such a model.

17% (~2.5 million ha) of land area in England and Wales was found to be biophysically suitable for viticulture, with over 1 million ha on free draining soils and >250,000 ha of this on chalk or limestone – similar to soils found in the Champagne region of France (Johnson & Robinson 2001). Biophysical model results demonstrated that large areas of suitable land are present in England, particularly in Devon, North Yorkshire, Norfolk, Essex and Suffolk, where presently relatively few vineyards exist (see Figure 3.2). This suggests that biophysical factors are not limiting to viticulture in these areas. Conversely it suggests that it may be weather phenomena, climate, or other factors that are limiting to viticulture in these areas. Here it is worth noting that the present configuration of viticulture in England and Wales has not developed as a result of a nationwide suitability assessment, and the lack of such an assessment, until now, may partly explain why some seemingly suitable areas have not been exploited. It should also be recognised that this type of land – crop suitability assessment has only been undertaken in limited form for other crops (Braimoh et al. 2004), as decisions are often undertaken by individual growers/developers. However, land suitability for 'new' crops such as miscanthus (for bio-energy) or infrastructure applications have benefitted from such an in-depth analysis (Lovett et al. 2014; Charabi & Gastli 2011).

Subsequent evaluation of historic (1981–2010) GST, spring air frosts, seasonal and June rainfall, and growing season daily average of bright sunshine hours revealed spatial variability that confirmed limiting climatic factors in some areas, but indicated opportunities for viticulture in others. Essex and the Isle of Wight (with relatively few current vineyards) were found to be 0.3°C (GST) warmer than Sussex and Kent, where most vineyards are presently established (Figure 3.2). Suffolk was found to have the same historic mean GST (13.6°C) as Sussex and Kent but only eight vineyards. The south coast of Dorset and the River Severn estuary were also evidenced as having areas with a similar mean GST to those found in south-east England. East Anglia in general exhibited lower levels of spring air frosts than those observed in the viticulturally dominant areas of south-central and south-eastern England, and was also drier (particularly Essex and south Suffolk) in general during the growing season. The volume of June rainfall, critical to flowering (Section 4.6), was lower in Kent, Surrey and the Isle of Wight. Inter-annual variability in GST and seasonal rainfall volumes was found, as expected, to be spatially variable across England and Wales. GST was more stable (1981–2010) in East Anglia, most of south-west England and west Wales than in south-central England. Seasonal rainfall totals were also found to be more stable in East Anglia and more variable in south-central England.

These observations of climatic variability indicate opportunities for spatial adaptation or expansion of viticulture beyond areas traditionally established. In particular Essex, Suffolk and areas within south Norfolk that have been shown to be biophysically suitable, express high degrees of climatic suitability and greater levels of stability from season to season, than areas currently populated with vineyards. The lack of viticulture practiced in these counties is therefore somewhat surprising but could be explained through a prior lack of nationwide suitability analysis, inertia regarding establishment of vineyards in the south-east, and potentially a skills shortage within East-Anglia. At present the only education provision in viticulture and wine production is provided in Sussex at Plumpton College. One meteorological variable that could be limiting to viticulture is wind (Section 1.1.1), and it has been suggested that wind exposure, specifically cold easterly winds, reduces viability for viticulture in East Anglia (Skelton 2014). Whilst wind data is not incorporated into the suitability model, site aspect and elevation are. Where suitable topographic factors (optimal southerly facing sites and elevations of 20–80 m) are identified, exposure to easterly winds and dominant south-westerly winds should be minimised.

Fuzzified and combined biophysical and climatic suitability for viticulture in England and Wales results in more favourable values being found in south and south-eastern coastal areas, Suffolk, Essex, Kent, East and West Sussex, Hampshire and the Isle of Wight. Highest (top 5%) land values were found in West Sussex. When the model is restricted to the top 20% suitability classification, 33,700 ha of land is identified. This is almost the same area (ha) as the Champagne region in France (33,500 ha). Whilst indicating that it doesn't require anywhere near 100% of suitable land in England and Wales to match the Champagne area, this hectarage still represents a large area to remove from production of other crops which could be considered more valuable or important to issues of food security.

These results don't just indicate spatial opportunities for viticulture expansion, but opportunities for expansion to significant volumes of land deemed by the model to have higher degrees of suitability than many established vineyard locations. Such opportunities could help improve sector resilience to weather and climate risks and maximise potential for viticulture in England and Wales. Currently only 50% of existing vineyards in England and Wales were classified as suitable by the biophysical suitability model. From an analysis of the approximate centres of vineyards it can be suggested that this is due to vineyards falling outside of 'suitable' elevations and aspects. However, 45% of existing vineyards were also found to be positioned on soils with impeded drainage and only 50% of vineyards were positioned in areas with GST's above 13.5^{o}C and 10% above 14^{o}C. Along with observations of poor spatial positioning mapped historic (1981–2010) climatic variables, relevant to viticulture, also demonstrated the sub-optimal positioning of many vineyards. Existing site positioning could therefore be considered sub-optimal in many cases, with significant 'room for improvement'. Interestingly, larger commercial vineyards were observed to all fall within model suitability with optimal aspect, slope and elevation ranges, and to have been established on 'favourable' soil types.

The analogue approach employed in Section 5.6 further demonstrates opportunities for viticulture in areas similar to or with a higher suitability classification than existing large vineyards – which incidentally account for a large volume of international wine awards (English Wine Producers 2016a). Yet, when cultivars in other cool-climate viticulture regions, shown to have a similar 2004–2013 GST, were examined it was observed that those dominating production in England (Chardonnay and Pinot noir) were being cultivated at the very margins of suitability. Here it should be re-stated that this analogue approach is independent of precipitation or other meteorological variables which have also been shown (Section 4.6) to affect wine yields in England and Wales.

For those considering investing in viticulture in England and Wales, decisions can be supported through the model developed in this thesis chapter. Yet such decisions are highly likely to also have an economic dimension. Using just one commodity based crop as a case-study, it has been shown in Section 5.8 that, where vineyard sites are appropriately selected, there is currently potential for a higher return on investment with viticulture than sugar beet.

These findings demonstrate the importance of spatial optimisation of viticulture in England and Wales, to exploit areas with high potential and greater climatic stability. Modelling and mapping viticulture suitability enables the presentation of opportunities for spatial adaptation, sector growth, and increased resilience to weather and climate risks for viticulture, which in-turn could help to increase and deliver more consistent wine yields in England and Wales. When complemented with climate analogues and indicators of cultivar suitability the model is a powerful tool for supporting local and regional land economy assessments. Additionally, it will be of benefit to those involved in relevant policy sectors.

The volume of land identified as being biophysically suitable in England and Wales (Section 5.2) far outweighs that which is considered climatically suitable (Section 5.3). However, under climate change scenarios this land could increase in overall suitability. Chapter 6 presents an analysis of potential suitability in England and Wales under future climate change scenarios to move from observations of existing suitability to future potential.

Chapter 6

From viticulture suitability to wine quality potential: a pattern scaling approach to modelling future vintages in England and Champagne

Weather risks and climate opportunities for viticulture in England and Wales have been presented and analysed in Chapters 3 and 4. Results from these chapters were subsequently used to inform a spatial suitability model for viticulture in England and Wales (Chapter 5), developed to help increase the viticulture sector's resilience to weather variability and threats, and to optimise the positioning of viticulture in areas with more favourable weather and climate conditions, and biophysical features. Spatial adaptation and expansion opportunities were complemented by a case-study of crop conversion potential, namely that of sugar beet production to viticulture, which indicated existing favourable economic circumstances for viticulture (Section 5.7). However, notwithstanding important conclusions from these chapters, the weather and climate data presented in these analyses and used to justify viticulture opportunities was historical (1954–2013), i.e. it didn't account for potential impacts of future climate change on viticulture.

The trend that has been attributed to improved viticulture suitability in England and Wales is one of warming in the viticulturally dominant areas of south-central and south-east England (Section 3.2 and Figure 4.1). At a simple level this suggests that continued warming under climate change scenarios may result in a further 'improvement' of conditions, and increasing suitability. Precipitation on the other hand, particularly around flowering, was found to have negatively affected wine yields in England and Wales (Section 4.6), and to have remained a sustained threat during the 1989–2013 period (Figure 4.2). Both these climatic variables were shown to exhibit degrees of inter-annual variability, and for the 2004–2013 period, GST was shown to have a statistically significant relationship with yield (Section 4.6) indicating a vulnerability of viticulture to weather variability. Yet, future growing season temperatures (GST or monthly mean), precipitation totals, and inter-annual variability thereof, under a range of climate change scenarios for England and Wales, and their possible future impact on viticulture suitability, have not been examined in the existing literature. The very phenomenon (climate change) that was deemed by producers (Section 3.2) to have contributed to recent sector growth, may provide enhanced opportunities, or conversely may limit viticulture suitability on future timescales. Producers' perspectives of climate change threats have been analysed for historic relevance (Chapters 3 and 4) but threats and opportunities regarding future impacts have not been assessed against climate change scenarios. Future climate change analysis exists for more established wine producing regions of the world (Webb et al. 2008; Jones & Webb 2010; Santos et al. 2012a; Tóth & Végvári 2015) and a better understanding of likely impacts on viticulture in England and Wales will arm those already involved in, or considering investing in the wine production sector with knowledge to help inform strategic decisions. Currently, the sector is exposed to potential future risks that could undermine investment.

Wine style and specifically wine quality of a particular style is what regions are often recognised for (Lough et al. 1983; Tesic et al. 2001; Jones 2006; Briche et al. 2014). In some locations restrictive rules govern cultivar establishment, viticulture practices and wine 'type'. One such region is Champagne in France (Figure 6.1), where Chardonnay, Pinot noir and Pinot meunier dominate the landscape (they form the key cultivars used in the production of Champagne). Were the climatic conditions in Champagne to change beyond those of 'accepted' vintage variability, it is likely that wine style or/and quality could be affected. Champagne presents a good case-study of weather and climate impacts on wine quality as only in the 'finest' years is a vintage declared by Champagne houses, often recognised through vintage ratings – see Section 2.5.2 and Table 2.4. Where a vintage is declared it can be assumed that the meteorological conditions that contributed to it were favourable. This phenomenon presents an opportunity to examine how, under climate change scenarios, the conditions that lead to these vintage years may change. Specifically, how likely they are to be repeated and, perhaps even more relevant to this thesis, what the temporal outlook for the likelihood of those conditions occurring in England and Wales is; after all the two dominant cultivars grown in England (Chardonnay and Pinot noir – see Figure 3.3) are the same as those in the Champagne region (Comité Champagne 2016). In this Chapter, therefore, this thesis shifts its attention from purely one of historic and present viticulture suitability in England and Wales, to both future suitability and future wine quality prospects. An assessment of both provides a more complete picture of the future effects of climate change on the emerging wine sector in England and Wales, and helps to better identify future threats and opportunities for England, Wales and the Champagne region.

The methodologies used to derive historic (1991–2010) and future scenarios of growing season conditions in England and Champagne are described in Sections 2.5.3 and 2.5.6. The pattern scaled approach, used in this chapter to derive future climate projections for south-east England and Champagne, has been employed in a viticulture-climate change study previously – Webb et al. (2013), using seasonal projections derived from old IPCC scenarios (Section 2.5.4) from the Special Report on Emission Scenarios (SRES) (Nakićenović & Swart 2000). Studies of potential future climate change impacts on viticulture in Europe by Fraga et al. (2013a) and Tóth & Végvári (2016) also employed SRESs.

Neither had a specific focus on England and Wales and results from Tóth & Végvári (2016) suggested that even by 2050 only a small area of south-central England could be suitable for viticulture. Their findings, however, failed to acknowledge the present spatial distribution of vineyards in England and Wales – see Figure 3.2. No work covering England and Wales, regarding viticulture, has been performed using the latest RCPs (Intergovernmental Panel on Climate Change 2013). Results in this chapter are based on historic observed data (growing season monthly temperature (°C) means, and precipitation totals (mm)) from CRU TS 3.23 for 1990, 1996, 2002, 2006, 2012, and 1991–2010, and future pattern scaled scenarios for 2021–2040 and 2041–2060, generated using ClimGen (see Section 2.5.6). Figure 6.1 shows the CRU TS 2.23 0.5 x 0.5° grid structure covering north-east France and south-east England, with the grid cells encompassing the majority of the Champagne region and the viticulturally dominant and highly suitable (see Figure 5.9) viticultural areas in south-east England, indicated with a red outline.

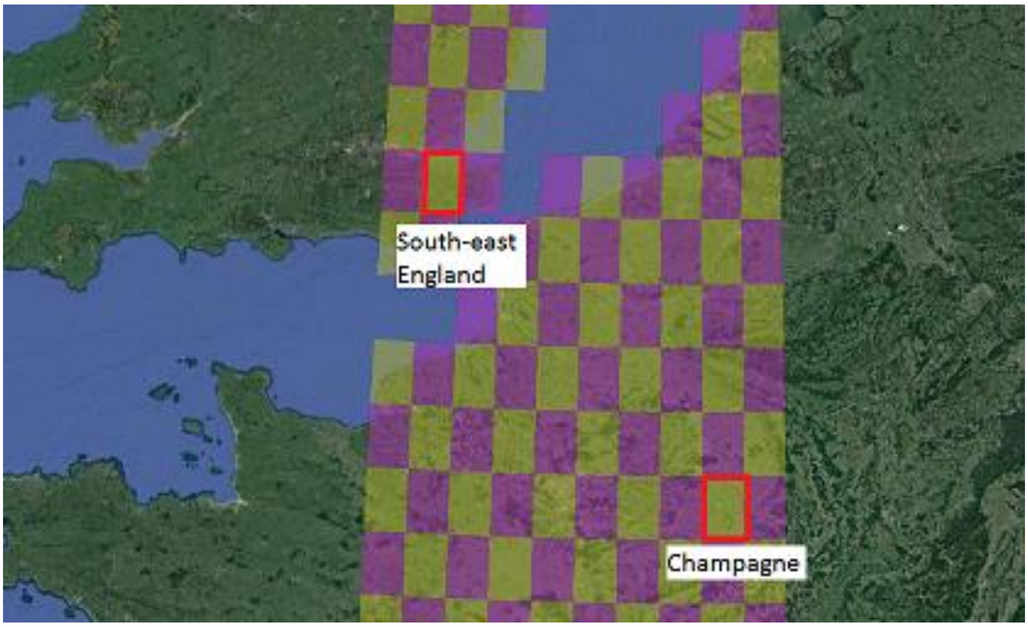


Figure 6.1: CRU TS 3.23 0.5 x 0.5° grids for the Champagne region and south-east England, highlighted with a red outline.

Growing season (April – October) monthly mean temperatures and precipitation totals for both the Champagne region and south-east England were extracted from ClimGen for the grid cells highlighted in red (Figure 6.1).

Unlike Champagne, for which there are recognised 'high quality' vintages (Table 2.4), there are no vintage rating guides for England and Wales. However, an analysis of growing-season monthly temperature and precipitation variables that occurred during 'high quality' Champagne vintage years, indicates seasonal conditions that could be deemed favourable for high quality production, and which could be searched for under modelled future climate scenarios to assess likelihood of re-occurrence. Furthermore, such an analysis could be made for south-east England to compare future scenarios that may lead to high quality wine production opportunities.

6.1. Monthly temperature and precipitation structure during high quality Champagne vintages

Historic monthly mean temperature and precipitation data extracted from CRU TS 3.23 (see Section 2.5.6) grid cells covering the Champagne region for 1990, 1996, and 2002 are presented in Table 6.1. These three years were selected for analysis following an assessment of 'expert' ratings for historic Champagne vintages (see Section 2.5.2 and Table 2.4) – they were all rated highly.

Table 6.1: 1990, 1996, and 2002 growing season mean monthly temperatures (°C) and precipitation totals (mm) for the Champagne region, from CRU TS 3.23

	April	May	June	July	August	September	October	GST / Total
1990 Mean temperature	8.3	14.9	15.3	18.5	20.1	13.8	12.7	14.8
1990 Precipitation	51.4	16.6	76.8	29.9	37.2	35.3	67.9	315
1996 Mean temperature	10.1	11.2	16.9	17.8	17.9	13.1	11	14
1996 Precipitation	6.6	88.9	22.2	33.3	93.4	40.6	47.9	333
2002 Mean temperature	10	13	17.6	17.9	18.4	14.5	10.8	14.6
2002 Precipitation	18.8	68.3	60.2	68.6	80.5	38.6	58.6	394

Meteorological conditions during the 3 years varied and the data shows both precipitation and GST differences. GST ranged from 14 – 14.8°C and precipitation from 315 – 394 mm. It is not immediately obvious from the data what meteorological variables or patterns contributed to the high quality vintages, but when GST and growing season precipitation volumes during 1990, 1996, and 2002 are compared to the other 17 years (Figure 6.2) for which vintage ratings were available (Section 2.5.2 and Table 2.4), it can be observed that these three years were all cooler and drier, except for 1991 and 2004, discussed below.

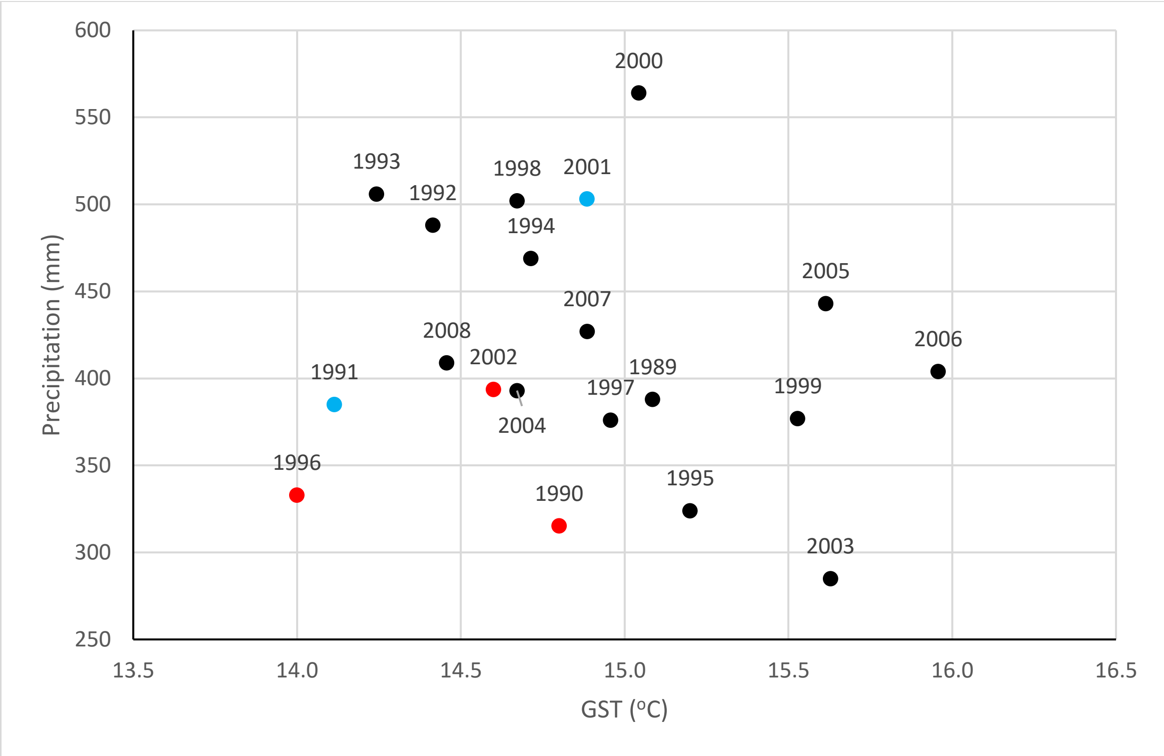


Figure 6.2: 1989–2008 Champagne vintage GST (°C) and precipitation (mm) from CRU TS 3.23 depicting markedly high quality (●), and low quality years (●).

Complementary commentary provided by two of the sources of vintage information: Berry Bros. & Rudd (2015) and Decanter (2015), on reasons behind the high quality vintage ratings, facilitates this investigative process. 1990 was noted as having had some frost damage in April, cool conditions during the latter part of spring that prolonged flowering, and a long, hot and dry summer to which the vintage success was attributed. Light rain that fell in September was deemed to have aided the ripening process by preventing any drought stress. The spring frost damage did not prevent the yield being the 3rd largest on record. The season resulted in wines with excellent alcohol and acidity levels (Berry Bros. & Rudd 2015; Decanter 2015). 1996 was deemed the best vintage since 1990, but it too suffered from frosts in early May, following a warm April. Early June was considered perfectly warm and sunny with flowering starting in mid-June. August was noted for being cool and experiencing periods of heavy rain but the first weeks of September were sunny with low night temperatures and drying winds. Picking started in mid-September, although some growers and wineries waited as late as October – indicating the extended ripening potential of the season. The quality of 2002 was attributed to a cold preceding winter (reducing disease overwintering), a mild late spring, perfect conditions at the important time of flowering (mid-June), a warm but not hot mid-summer, some rain in August and early September but a series of dry and sunny days from the 10th September that aided maturation. The balance of sugar and acidity were regarded as excellent (Berry Bros. & Rudd 2015; Decanter 2015).

For all three vintages dry and generally sunny conditions from flowering through maturation were deemed favourable. Some precipitation in September during 1990 and 2002 was thought to have helped vintage quality but the precipitation in September 1996 was not commented on, potentially because precipitation in August (93.4 mm) had already reduced any drought risk. In all three years between 35 and 40.5 mm of rain fell during September. In contrast, in two 'low quality' Champagne years, 1991 and 2001 (Table 6.2), precipitation during maturation was higher (70.1 and 114.9 mm respectively). During maturation, moderately dry and stable atmospheric conditions are considered favourable for high-quality wines (Jones & Davis 2000a; Nemani et al. 2001; Ramos et al. 2008). Commentary on both the 1991 and 2001 Champagne vintages indicates that high levels of precipitation during maturation contributed to disease pressures that reduced vintage quality (see also Section 1.1.1). GST was similar in both high and low quality vintage years (Tables 6.1 and 6.2), suggesting that GST is not a reliable predictor of quality by itself. Rather it is the combination of temperatures and precipitation, and particularly the seasonal structure of both that has a greater effect. 1991 and 1996 both had similar GST's, 14.1 and 14^{o}C respectively, but during flowering in June mean temperatures were 14^{o}C in the lower quality vintage (1991) and 16.9^{o}C in the higher quality vintage of 1996. In the same month rainfall in 1991 was 84.8 mm, but in 1996 only 22.2 mm. This confirms how critical the flowering period is to quality (see Section 1.1.1 and results in Section 4.6).

In Figure 6.2 it is noticeable that 2004 had very similar growing season conditions to the high quality vintage of 2002. An examination of Table 2.4 in Section 2.5.2 shows that four out of six sources of vintage ratings have already awarded it a high rating. However, as only data for four of the six sources was available it was not included for further analysis but it is relevant to note that one of the sources: Berry Bros. & Rudd (2015), commented that 2004 was a vintage which combined quality and quantity and which has a good chance, over time, of being recognised as an excellent vintage.

Table 6.2: 1991 and 2001 growing season mean monthly temperatures (^{o}C) and precipitation totals (mm) for the Champagne region, from CRU TS 3.23.

	April	May	June	July	August	September	October	GST / Total precipitation
1991 Mean temperature	8.5	10.6	14	19	19.6	16.8	10.3	14.1
1991 Precipitation	52.4	26.3	84.8	90.1	9.6	70.7	51.6	386
2001 Mean temperature	8.2	14.9	16	18.8	19.4	12.8	14.1	14.9
2001 Precipitation	112.9	38.4	39.6	90.6	45.8	114.9	59.8	502

6.2. Monthly temperature and precipitation structure during high and low yielding English and Welsh wine vintages

Historic monthly mean temperature and precipitation data extracted from the CRU TS 3.23 grid- cells covering south-east England for 2006 and 2012 are presented in Table 6.3. Conditions attributed by producers (Section 3.2) for the highest yielding year of 2006 (33.9 hL/ha) were a warm spring followed by good or 'optimum' temperature and weather conditions at flowering and fruit set. The absence of spring frosts was also given as a reason. Conditions that lead to the lowest yielding year on record, 2012 (6 hL/ha), were primarily attributed to wet and cold weather during flowering and fruit set and a wet and cold growing season. Table 6.3 shows the warmer and drier conditions in June 2006, and the growing season in general, compared to 2012. High precipitation (80.5 mm) in June 2012 are evidenced, compared to 37.5 mm in 2006. The GST for 2006 in south-east England (15.3^{o}C) is higher than those observed in the high quality vintage Champagne years (Table 6.1) but here no comparison with wine quality is being made as quality vintage ratings for English wines do not openly exist, unlike in Champagne.

Table 6.3: 2006 and 2012 growing season mean monthly temperatures (^{o}C) and precipitation totals (mm) for South-East England, from CRU TS 3.23

	April	May	June	July	August	September	October	GST / Total
2006 Mean temperature	8.9	12.7	16	20.5	17.3	17.6	14.1	15.3
2006 Precipitation	28.1	97.5	37.5	19.8	100.2	48.6	79.1	411
2012 Mean temperature	7.7	12.8	14.7	16.5	17.8	14.2	11.1	13.5
2012 Precipitation	106.1	12.4	80.5	74	37.9	25.5	133.4	470

6.3. CRU TS v. 2.23 data reliability

CRU TS 3.23 is used in ClimGen as the observed baseline (1961–1990) to which the pattern-scaled changes are added (see Section 2.5.6). The performance of ClimGen and outputs for the present-day therefore do not require validation but the CRU TS v 2.23 data itself, for Champagne and south-east England, requires assessing to determine its reliability. The GSTs for 2006 (15.3^{o}C – Table 6.3) and 2012 (13.5^{o}C – see Table 6.3) extracted from CRU TS 3.23 correspond well to the GSTs (15.2 and 13.2^{o}C) extracted from the Met Office regional data for south-central and south-east England (Met Office 2014b) which were used in Chapter 4 of this thesis. The slightly higher values in the CRU TS 2.23 data are a likely result of two slightly different spatial areas being examined. It can be seen in Figure 4.3 (2006 and 2012) (Section 4.3) that the area of south-east England from which the CRU TS 3.23 data is extracted is warmer than the majority of south-central and south-east England. Although a like-for-like comparison is not possible due to the differing spatial parameters (Met Office regionally averaged data for south-east and south-central England vs three CRU TS 3.23 grid cells) the results indicate good CRU TS 3.23 data agreement with observational Met Office data (2014b).

6.4. Ensemble climate change projections for the Champagne region and south-east England (2021–2040, and 2041–2060)

Analysis of historic mean monthly temperatures and precipitation presented in Sections 6.1–6.2 presents a portrait of growing season conditions conducive to high and low quality wine production (Champagne), and high and low yields (dominated by the same cultivars; Chardonnay and Pinot noir) in south-east and south-central England during the last ~25 years. One of the core aims of this thesis chapter is to analyse how climate change may affect these conditions in future years and hypothesise about potential impacts on wine quality in both south-east England and the Champagne region (Figure 6.1 depicts the spatial domains assessed for historic and future climatic conditions).

Growing season average temperature (GST)

Outputs from a pattern scaled modelling process (see Section 2.5.6) for two RCPs (2.6 and 8.5) for future projected GST for the Champagne region and south-east England, and for two time periods (2021–2040, and 2041–2060) are presented in Figure 6.3. Only two of four RCPs, within the ClimGen range, are examined to present both ‘best-case’ and worst-case’ scenarios of projected change. The values presented are the means of 12 climate models (Table 2.5), with the range of model values under each RCP illustrated with vertical bars.

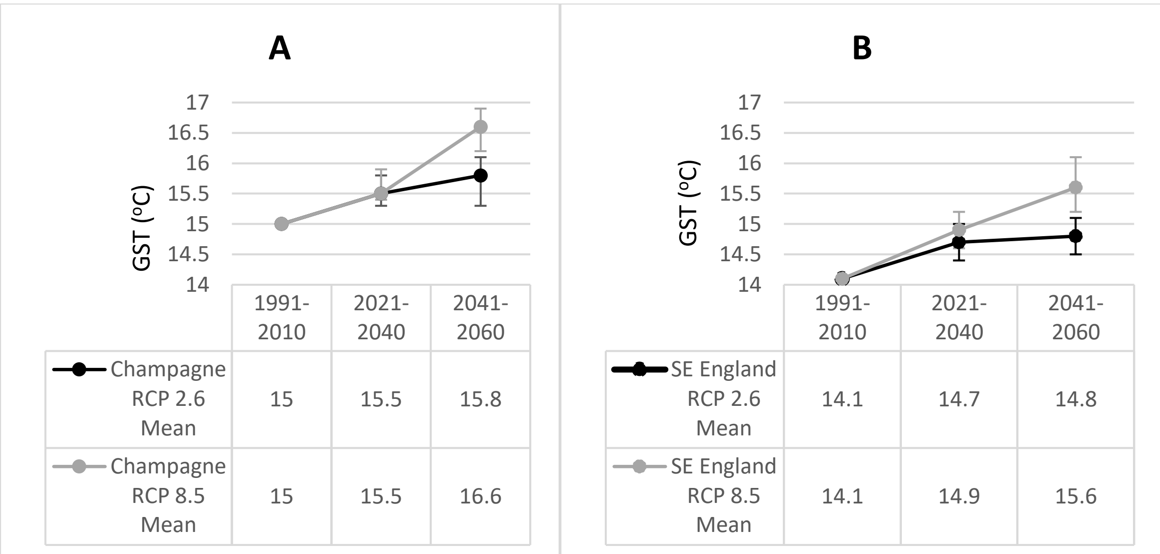


Figure 6.3: Champagne (A) and south-east England (B) GST observed baseline (1991–2010) from CRU TS 3.23 and mean GST (°C) projections under RCP2.6 and 8.5 for 2021–2040 and 2041–2060 with the range of model (x12) results, derived from ClimGen, as vertical bars.

Under RCP2.6 ensemble mean GSTs in Champagne are projected to rise to 15.5°C in 2021–2040, 0.5°C above the observed 1991–2010 baseline, and 0.7–1.5°C above those observed during the high quality years of 1990, 1996, and 2002. This rise is projected to be followed by even higher average mean temperatures in 2041–2060, of 1–1.8°C above the high quality vintages of 1990, 1996 and 2002. RCP8.5, when applied to modelled future GST projections for the Champagne region, indicates a similar short term (2021–2040) rise to that projected by RCP2.6, but greater GST increases in 2041–2060 – up to 16.6°C are projected. For both scenarios, short (2021–2040) and longer-term (2041–2060) projections of the ensemble means indicate a range of 1–2.6°C above the mean (14.5°C) observed in high quality vintage years, and 0.5–1.6°C above the 1991–2010 baseline period.

Growing season temperature changes of such a magnitude are likely to affect both phenology and wine quality. Under RCP2.6 Chardonnay and Pinot noir would remain, until post 2041–2060, within the climate maturity groupings observed by Jones (2006) (Section 1.1.1 and Figure 1.4). However, under RCP8.5, within the next ~40 years Pinot noir would be subjected to GSTs of 0.6°C above its historic climate – maturity grouping threshold (16°C), according to the ensemble model mean. Chardonnay would be almost at its threshold limit of 17°C under the 'worst-case' model scenario. The adaptive capacity of these cultivars remains unquantified but such temperatures may threaten the viability of the Champagne region, where the dominant cultivars of Chardonnay and Pinot noir to be relied on, post 2050.

GST in the south-east of England, under RCP2.6 is projected, according to the ensemble mean, to rise to 14.7°C by 2021–2040. This is 0.6°C above the 1991–2010 mean for south-eastern England. In the longer term (2041–2060) a projected GST of 14.8°C would place the cultivars of Chardonnay and Pinot noir within the temperature maturity groupings found by Jones (2006) (see Figure 1.4 in Section 1.1.1). Interestingly the projected GSTs for south-east England under RCP2.6 for 2021–2040 (14.7°C) is only 0.2°C above those found in high quality champagne vintages (1990, 1996, and 2002). However, under RCP 8.5 GSTs in south-east England, by 2041–2060, are almost equal to projections for the Champagne region for 2021–2040 (15.5°C), representing a ~1°C difference.

Results presented in Figure 6.3 show the mean and spread of an ensemble of 12 climate models under 2 RCPs, as vertical bars. Model uncertainty is presented in Table 6.4 where low, median, high output and the ensemble standard deviation (SD) are presented under both RCPs for south-east England and the Champagne region. In all cases the SD amongst models ranges between 0.15 and 0.28 but is higher for the 2041–2060 time period in both regions reflecting decreasing agreement amongst models. Under

RCP 8.5 there is marginally greater uncertainty (SD = 0.04) amongst models for south-east England than the Champagne region.

Table 6.4: Model low, median, high and standard deviation (SD) GST projections under RCP 2.6 and 8.5 for south-east England and the Champagne region.

	South-east England GST (°C)				Champagne GST (°C)			
	Low	Median	High	SD	Low	Median	High	SD
2021-2040 RCP2.6	14.4	14.7	15	0.18	15.3	15.5	15.8	0.16
2041-2060 RCP2.6	14.5	14.8	15.1	0.2	15.3	15.8	16.1	0.27
2021-2040 RCP8.5	14.6	14.8	15.2	0.19	15.4	15.6	15.9	0.15
2041-2060 RCP8.5	15.2	15.6	16.1	0.28	16.2	16.7	16.9	0.24

These projected shifts in temperatures relate to a historically recognised and commonly accepted Northern Hemisphere growing season period of April – October (Jones 2006; Fraga et al. 2013a; Hall & Jones 2010; Webb et al. 2013). Under such warming conditions it is likely that the growing season would lengthen, both starting earlier and ending later. This is likely to induce shifts in the temporal occurrence of phenology stages, and may, as observed elsewhere (Jones & Davis 2000a; Jones et al. 2005; Tomasi et al. 2011; Webb et al. 2011; Molitor et al. 2014), drive shortening phenophases. Associated phenological changes may affect quality as the balance between sugars, acidity and phenolic composition of berries will likely be affected (see Section 1.1.1). Furthermore such changes could increase early season frost risk caused by earlier bud burst (Mosedale et al. 2015) and or late season frost risk where harvest dates are delayed (Molitor et al. 2014).

Growing season precipitation

Both yields in south-east and south-central England and wine quality in Champagne have been shown in Chapter 4, Section 4.6, and in this chapter to be significantly affected by growing season precipitation, particularly during flowering and maturation.

At a monthly timescale, projected precipitation (mm) changes under both RCPs for 2021–2040 and 2041–2060 are presented in Figure 6.5 for both regions.

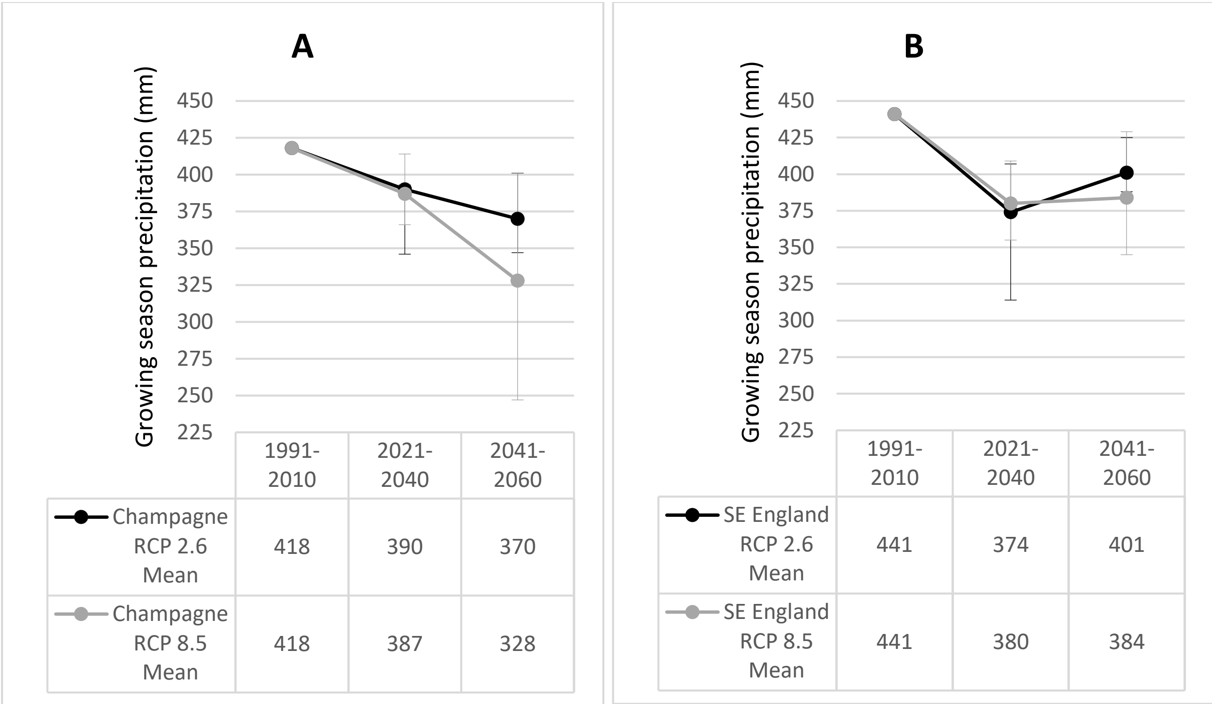


Figure 6.4: Champagne (A) and south-east England (B) growing season precipitation (mm) baseline (1991–2010) from CRU TS 3.23, and mean precipitation projections under RCP2.6 and 8.5 for 2021–2040 and 2041–2060, with the range of model (x12) results derived from ClimGen as vertical bars.

Projections of future growing season (April – October) precipitation vary between the two regions and two time periods. During the baseline period (1991–2010) south-east England had 5.5% (23 mm) more precipitation than the Champagne region. By 2021–2040 the Champagne region is projected (by the ensemble mean) to have ~7% less precipitation than 1991–2010 under both RCP 2.6 and 8.5. By 2041–2060 this is projected to have reduced 11% under RCP 2.6 and 22% under RCP 8.5. One model (ncar_ccsm4), under RCP 8.5, projected a 40% drop in precipitation (247 mm) for the Champagne region by 2041–2060). A ~15% reduction in growing season precipitation between 1991–2010 and 2021–2040 in south-east England is projected by the model ensemble mean for both RCP 2.6 and 8.5, a greater reduction than projected for the Champagne region. These projections indicate that by 2021–2040 the south-east of England and the Champagne region will have similar growing season precipitation levels, 374 – 390 mm. However, whilst longer term (2041–2060) projections for the Champagne region show a continued reduction in precipitation during the growing season, model mean projections for south-east England show an increase between 2021–2040 and 2041–2060 under RCP2.6 of 7%, and under RCP 8.5 of 1%. For 2021–2040, under RCP 2.6, the SD of model projections was 31.8 (Table 6.5), and under RCP 8.5 was 18.6 indicating greater uncertainty regarding precipitation projections for this ‘short-term’ period in south-east England, than in the Champagne region (SD of 15.1 and 17.8 respectively). By 2041–2060 the projected increase in precipitation, from 2021–2040, in south-east England under both RCPs remains below the 1991–2010 baseline, and could be attributed to decadal variability in rainfall. The projected increase was not observed in all models. Under RCP 8.5 model SD for 2041–2060 was 28.4 (Table 6.5) indicating less agreement than RCP 2.6 (SD – 13.8) for the same period. This model mean projected increase between 2021–2040 and 2041–2060 is perhaps indicative of a more vigorous water cycle under warming conditions, or could be a function of the pattern-scaling approach where 20-year periods are used. 20-year mean projections may mask this variability. However, it warrants further research using a greater number of GCMs, and/or comparative regional climate change studies using different downscaling approaches, i.e. dynamic or statistical. These are recommended in Section 7.3.

The projection of an overall decrease in precipitation in south-east England between 1991–2010 and 2021–2040 was also observed by Murphy et al. (2009) in the UKCP09 report. Here they found a projected 18% reduction in summer precipitation by 2050 (against a 1961–1990 mean) under a median emissions scenario. A decrease in precipitation to 2021–2040 in the south-east of England may aid productivity and quality as high precipitation has been associated with low yields and quality (Section 4.6), but the longer term impact, and the greater projected decrease for the Champagne region, may threaten productivity and quality through lack of water availability, without significant adaptation activity.

Table 6.5 again shows the uncertainty within the 12 models for precipitation over south-east England and Champagne (RCP2.6 and 8.5) for the two time-periods considered.

Table 6.5: Model low, median, high and standard deviation (SD) growing season precipitation (mm) projections under RCP 2.6 and 8.5 for south-east England and the Champagne region.

	South-east England precipitation (mm)				Champagne precipitation (mm)			
	Low	**Median**	**High**	**SD**	**Low**	**Median**	**High**	**SD**
2021-2040 RCP2.6	314	378	407	31.8	371	388	412	15.1
2041-2060 RCP2.6	388	395	425	13.8	342	370	397	19
2021-2040 RCP8.5	355	375	409	18.6	366	385	414	17.8
2041-2060 RCP8.5	345	380	429	28.4	247	338	401	59.7

Under RCP 2.6 the model SD is higher for south-east England than Champagne in the period 2021–2040, indicating greater uncertainty within the model ensemble. Under RCP 8.5 the SD for 2041–2060 is 59.7 for the Champagne region indicating the highest degree of uncertainty for this region.

The impacts of projected changes to precipitation will depend partly on its temporal distribution during the growing season, discussed below. The reduction in precipitation projected for Champagne (relative to 1991–2010), under RCP 8.5 by 2041–2060 suggests that Champagne will experience similar growing season precipitation totals to those observed during the high quality Champagne vintages of 1990 and 1996. South-east England is projected to move closer to the precipitation totals of 2006 (411 mm), a high quality vintage year under both RCPs, and to those in 2002 (394 mm) in Champagne, another high quality vintage year.

It has been demonstrated through this thesis that high temporal resolution data helps better explain impacts of weather and climate conditions on yield and quality. The following closer examination of monthly projected changes for only 2041–2060 (centred on 2050) is likely to be of greater interest to those involved in viticulture now, or considering viticulture investment as the life-span of a vine is commonly regarded to be <50 years (Gladstones 1992). Figure 6.5 presents the projected monthly distribution of precipitation, derived from the ensemble model mean under both RCP 2.6 and 8.5 for 2041–2060.

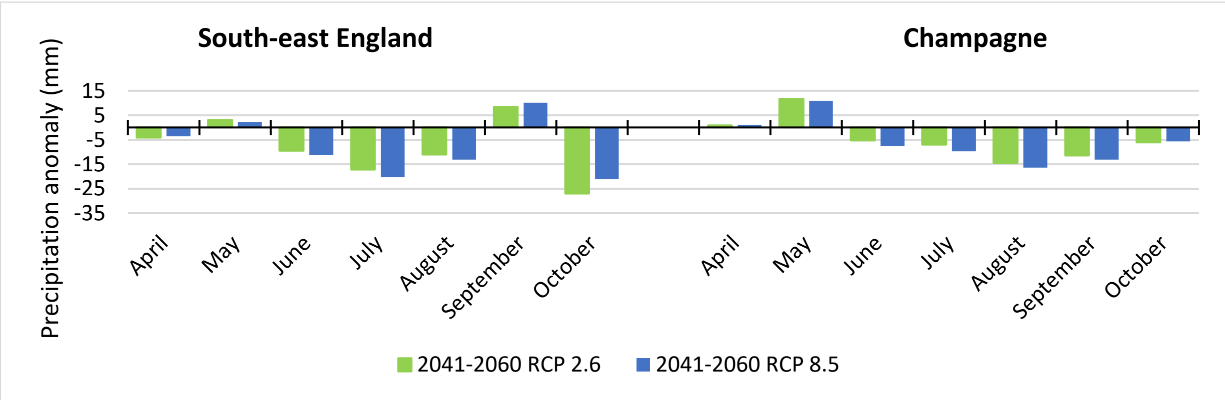


Figure 6.5: South-east England and Champagne 2041–2060 projected monthly precipitation (mm) anomalies from an observed 1991–2010 baseline (= 0) under RCP 2.6 and 8.5 scenarios. Showing mean projections from 12 climate models (Table 2.5).

Important seasonal shifts of precipitation distribution between 1991–2010 and 2041–2060 can be observed in Figure 6.5 for both the south-east of England and the Champagne region. Figure 6.5 indicates a projected decrease in precipitation during the growing season in both areas under both RCPs, a decrease that can also be deduced from Figure 6.4. However, Figure 6.5 also illustrates a projected change to slightly higher totals in the bud-burst and harvest months of May and September in south-east England, and lower totals in the remaining growing-season months. The projections for June are particularly interesting as previously high levels of precipitation in June have been shown to correspond to low yields (Section 4.6) as rainfall can negatively affect flowering. The precipitation total in June in the low yielding year of 2012 in south-east England was ~80 mm (see Table 6.3). Here in Figure 6.5 lower levels of precipitation are projected for June in both the south-east of England and the Champagne regions, indicating lower risks to flowering, where flowering occurs in June. This projected decrease in June precipitation is consistent with previous studies of seasonal temperature and precipitation projections for south-east England. The UKCP09 report study, Murphy et al. (2009) indicated drier (-18% at 50% probability under a median emissions scenario), and warmer summers and wetter winters.

By 2050 growing season temperature increases may have advanced phenology to the point that the critical period of flowering occurs before June. However, Figure 6.5 also indicates a small increase in May precipitation volumes. This shift towards higher earlier summer precipitation levels poses a potential threat to both English and Champagne wine yields and quality. Critically, results suggest that the small volumes of September precipitation that were deemed to have aided the high quality vintage years of 1990, 1996, and 2002 are projected to decrease significantly by 2041–2060 in the Champagne region. Lower precipitation during maturation may lead to drought stress on vines and affect grape berry and wine quality. Significantly higher precipitation in May may also affect flowering, and thus grapevine yield.

The 12 model spread of results for monthly precipitation by 2041–2060 is presented in Figure 6.6 for south-east England. A large spread indicates lower model agreement. From Figure 6.6 it can be seen that projected precipitation is lowest in 2041–2060 than 1991–2010 in all models for all months, under both RCPs, except for May and September. Whilst there is strong model agreement regarding projections for May there is less agreement for September, indicated by the greater model spread.

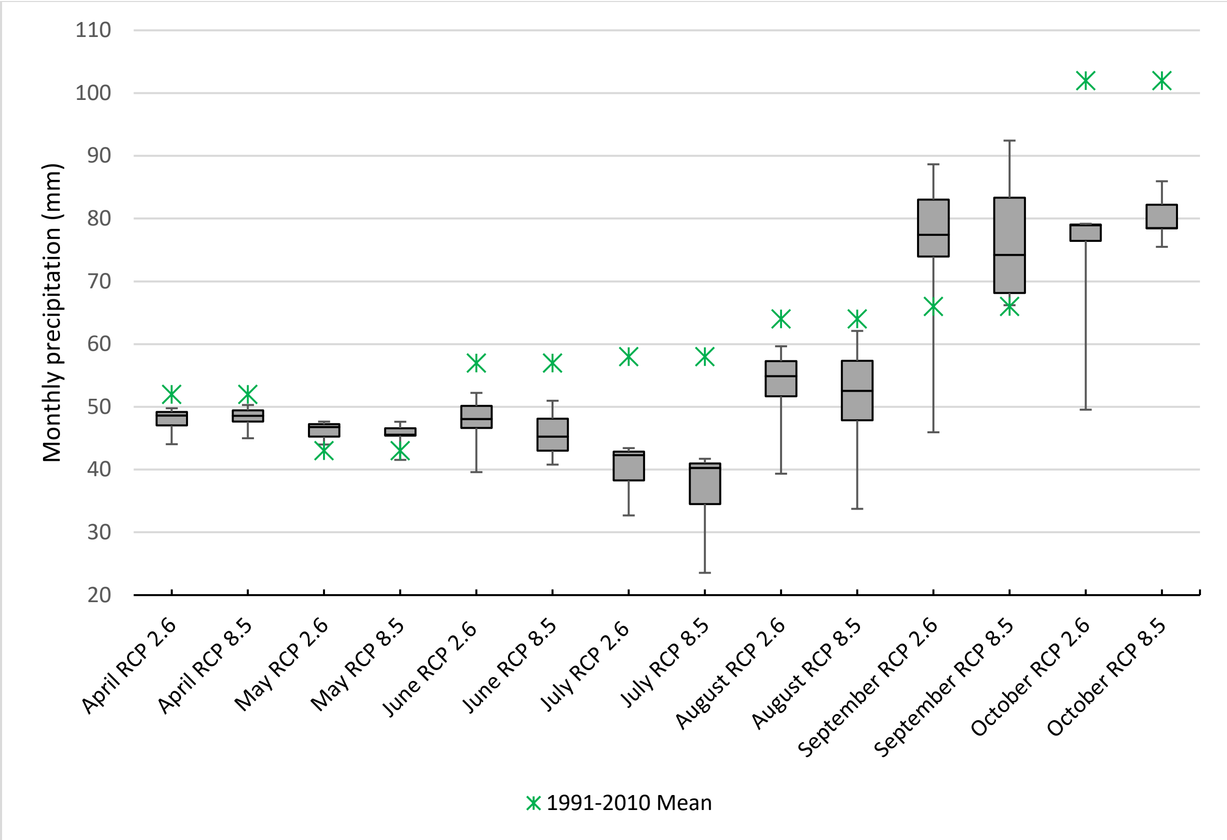


Figure 6.6: South-east England projected growing season monthly precipitation (mm). Dispersion of 12 climate model results under RCP2.6 and 8.5, for 2041–2060, and an observed 1991–2010 baseline.

Model spread for precipitation in Champagne is presented in Figure 6.7. In general there is a wider model spread under RCP 8.5, and greater model uncertainty regarding changes to the summer months of July and August under both RCPs. In all months except May and September, under both RCPs, there is strong model consensus that precipitation totals will fall below the 1991–2010 mean. When Figures 6.6 and 6.7 are compared it is evident that there is less model agreement in general for projections for the Champagne region than south-east England. This result was also reflected in the SD results presented in Table 6.5.

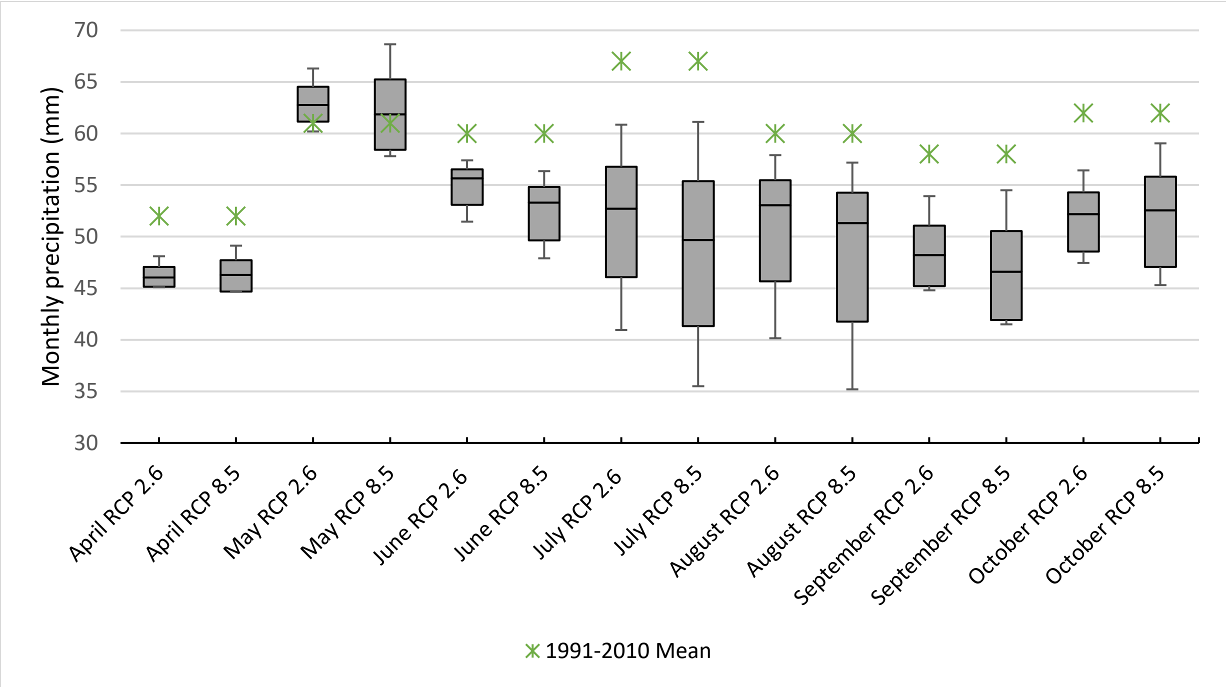


Figure 6.7: Champagne projected growing season monthly precipitation (mm). Dispersion of 12 climate model results under RCP2.6 and 8.5, for 2041–2060, and an observed1991–2010 baseline.

At a growing season monthly scale projected changes to mean temperature, as an average of all 12 climate models (Table 2.5), for 2041–2060 under RCP2.6 and 8.5, are presented in Figure 6.8.

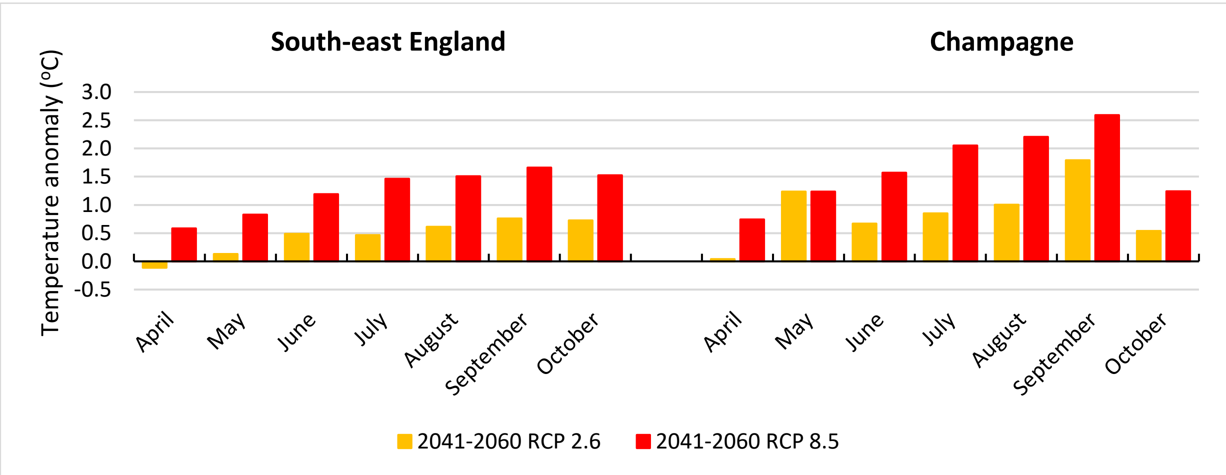


Figure 6.8: South-east England and Champagne 2041–2060 projected monthly mean temperature (°C) anomalies from a 1991–2010 observed baseline (= 0) under RCP 2.6 and 8.5. Showing mean projections from 12 climate models

Differences in the projected monthly distribution of mean temperatures (2041–2060) exist between the two RCPs for Champagne and south-east England, with RCP 8.5 projecting much greater temperature rises as expected. These projections show increases of over 2°C in July, August and September in the Champagne region under RCP 8.5, and 1.5°C over the baseline in July, August, September and October in south-east England. South-east England and Champagne are projected to see an increase in temperatures in all months under both RCPs, except for a small projected decrease in April 2041–2060 in south-east England. These temperature increases, under RCP 8.5, when combined with a reduction in precipitation, particularly in the Champagne region, could significantly threaten productivity without adaptation practices such as irrigation. Figures 6.9 and 6.10 show model range for growing season months under both RCPs in both regions.

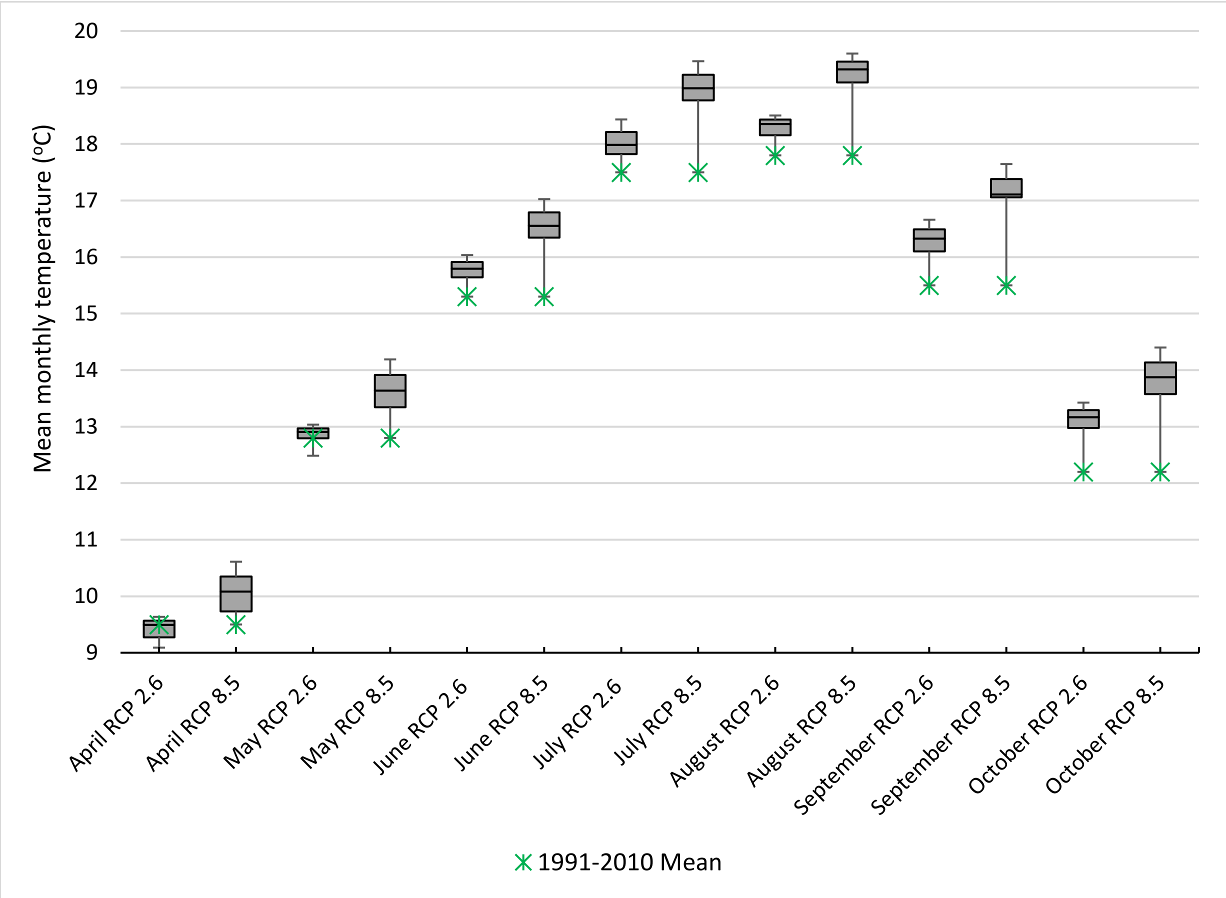


Figure 6.9: South-east England projected growing season mean monthly temperature (°C). Dispersion of 12 climate model results under RCP2.6 and 8.5, for 2041–2060, and an observed 1991–2010 baseline.

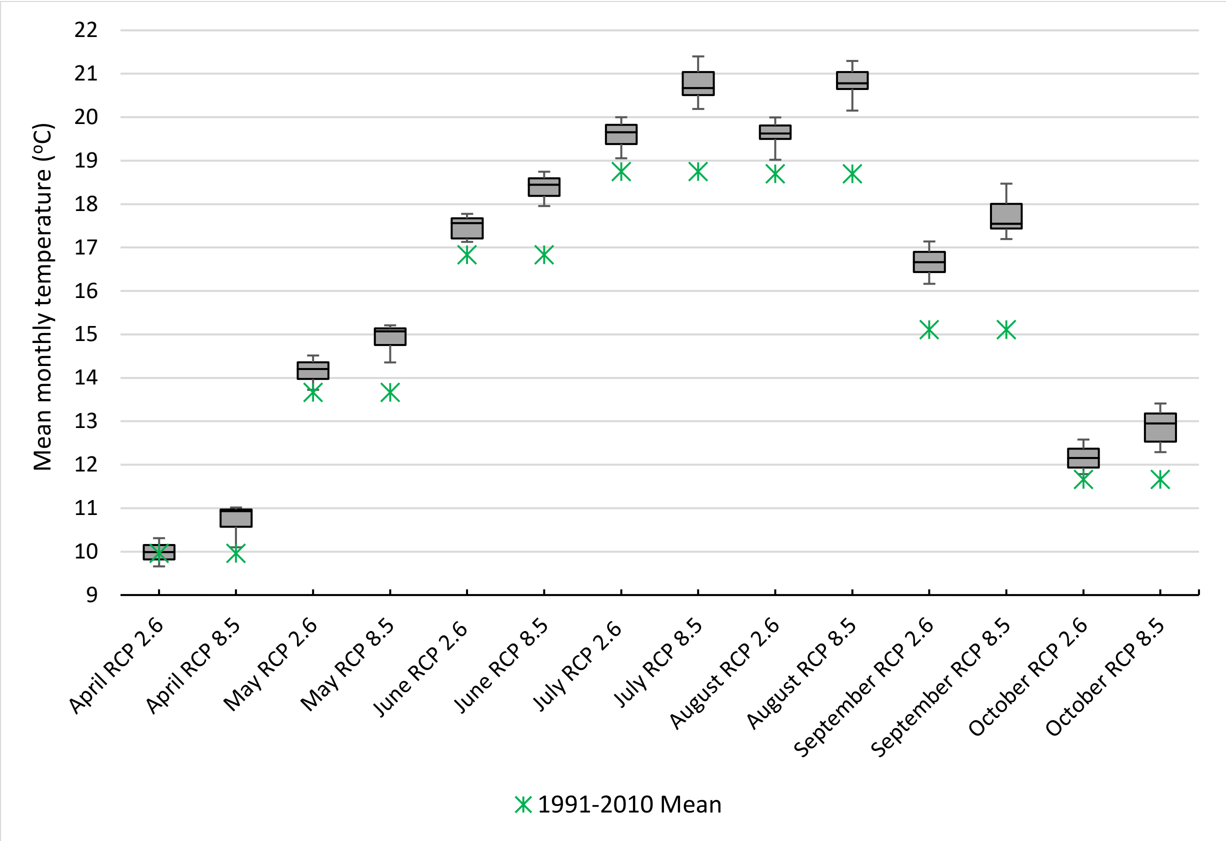


Figure 6.10: Champagne projected growing season mean monthly temperature (°C). Dispersion of 12 climate model results under RCP2.6 and 8.5, for 2041–2060, and an observed 1991–2020 baseline.

For both regions, under both RCPs there is model agreement that by 2041–2060 growing season monthly temperatures will be above those of 1991–2010.

Combined, these results for the projected monthly distribution of precipitation and temperature indicate, for south-east England, a decrease in precipitation during the growing season by 2050 and an increase of more than 1°C in temperature. . Such conditions could lead to higher quality and higher yields, in the absence of acute events such as spring frosts. However, earlier phenophases could place flowering into the month of May and harvest in the month of September, months that are projected to have higher precipitation totals than the 1991–2010 mean. Significantly, it could be deduced from these modelled projections (Figures 6.4 and 6.5) that the changing seasonal distribution of precipitation, combined with warmer growing season temperatures could alter water availability and impact yields where insufficient water is available to grapevines, particularly during maturation (August – September). This would seemingly be a greater risk to the Champagne region where previous high quality vintages (see Section 6.5) have relied on 'beneficial' precipitation during maturation to relieve potential water stress in the grapevines. From a temperature perspective alone the Champagne region would have a

GST consistent with those found in regions growing Sauvignon blanc, Semillon and Cabernet Franc, according to the climate maturity groupings indicated by Jones (2006) in Figure 1.4.

6.5. Likely repetition of high quality Champagne vintages and analogue growing season temperature and precipitation conditions in south-east England

One of the main aims of this chapter is to illustrate the likely repetition of growing season conditions that have previously led to high quality Champagne vintages (see Section 6.1). Initially, looking solely at projected future growing season monthly temperature in the Champagne region, Figure 6.11 shows the spread of model results for all years (2041–2060) for the growing season monthly mean temperatures under RCP 2.6 and 8.5 compared with the observed 1990, 1996, and 2002 high quality Champagne vintage temperatures. The high quality vintage of 1990 was attributed to a 'long, hot and dry summer' despite early season frosts (Section 6.1). Results in Figure 6.11 suggest that although under both RCPs median model projections (2041–2060) are for higher mean temperatures in April, June, July and September than in 1990, the median model projected temperatures in May, August, and October are lower than in 1990, except August under RCP 8.5. However, earlier season higher temperatures would likely mean that harvest would have been completed before October and hence the relevance of October conditions during such future periods may be limited. Overall the projected median results for both RCPs are for warmer growing season conditions than those observed in 1990. Median model projected temperatures in all months, except April and June (under RCP 2.6), for the 2041–2060 periods are higher than they were during the 1996 and 2002 high quality vintage years. Under RCP 8.5 the median projections for August and September are 2.5 – 4.5^{o}C respectively, above those in 1996. This projected hotter ripening to harvest period would likely reduce berry acidity and increase sugar levels and potential alcohol beyond those found in high quality vintage years. Shorter phenophases and earlier ripening would alter berry composition (Section 1.1.1), and make repetition of the 1996 and 2002 vintages very unlikely. However, the spread of monthly mean temperature projections across all models and for all years (2041–2060) indicates that there is potential for monthly mean temperature 'conditions' observed in 2002 in particular to be repeated. Perhaps more so than conditions in 1990 or 1996, based on the greater number of months that 2002 temperatures fall within the spread, i.e. in all months except September under RCP 8.5. Here, the model spread illustrates the role of inter-annual variability in potentially presenting opportunities for seasonal (2002) temperature repetitions during 2041–2060.

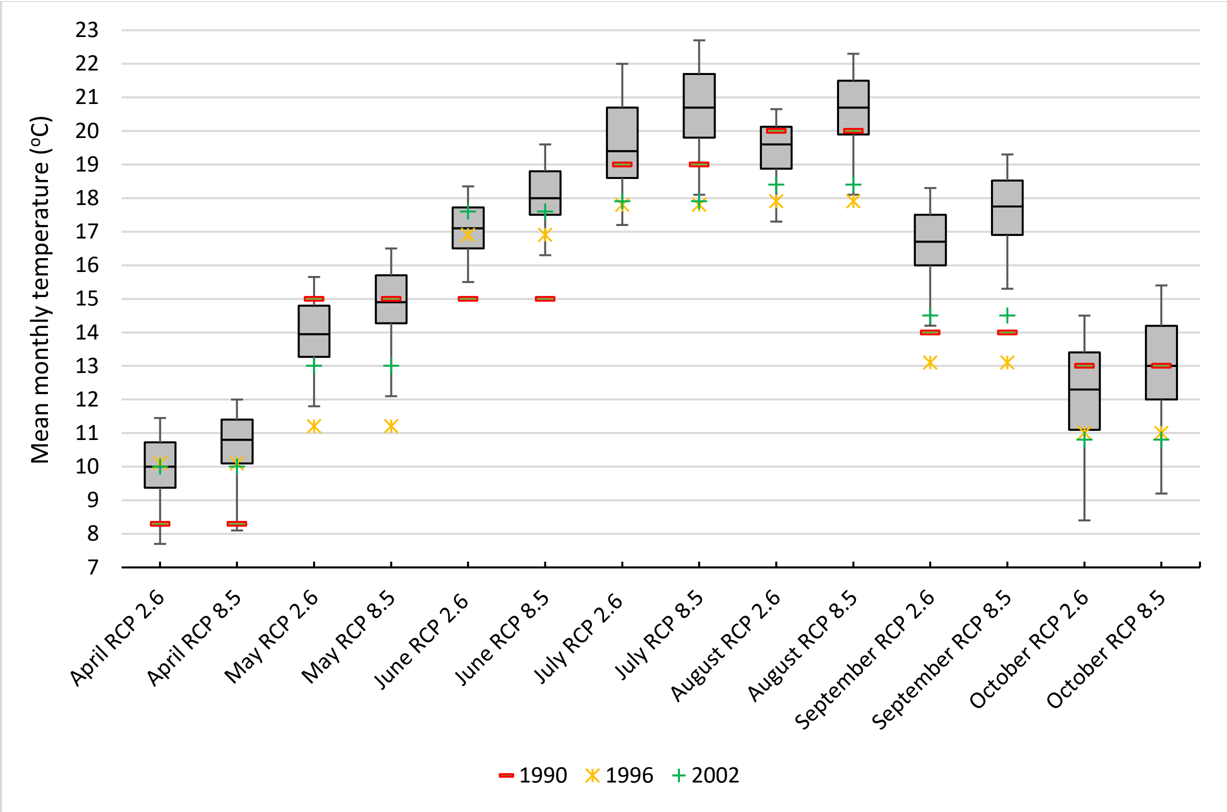


Figure 6.11: Champagne projected growing season mean monthly temperature (°C). Dispersion of 12 climate model results under RCP2.6 and 8.5, for all years (2041–2060), and observed 1990, 1996, and 2002 monthly temperatures. Source: ClimGen and CRU TS 3.23.

The observed growing season precipitation totals for the high quality Champagne years of 1990, 1996, and 2002 are shown in Figures 6.12, compared with the spread of model output under RCP2.5 and 8.6 for 2041–2060. Median projected monthly precipitation totals are different to the patterns observed in all three high quality vintage years. Future projections do however suggest the potential for repetition of monthly precipitation totals observed in 1990 as all the 1990 values fall within the model inter-quartile range, except for May where projections across all models and years are for higher precipitation totals. 1996 had lower precipitation in April than is projected for 2041–2060 but higher than projections for August. For the other growing season months 1996 precipitation totals have the potential for repetition during 2041–2060, particularly July, September and October, under both RCPs, where the totals fall within the interquartile model range. Compared to 2002, median projections for all months except April and September are lower in 2041–2060.

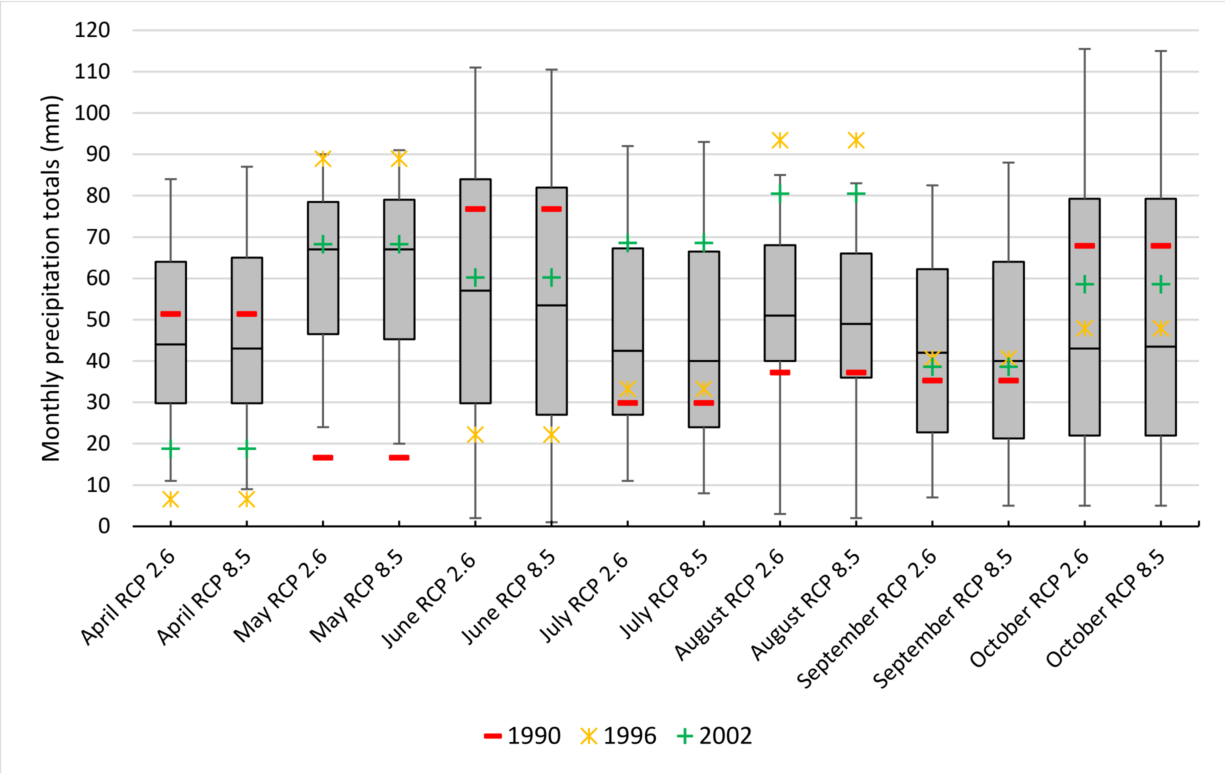


Figure 6.12: Champagne projected growing season monthly precipitation (mm). Dispersion of 12 climate model results under RCP2.6 and 8.5, for all years (2041–2060), and observed 1990, 1996, and 2002 monthly precipitation totals. Source: ClimGen and CRU TS 3.23.

The low precipitation and high temperatures in May 1990 are projected to increase and decrease respectively, particularly under RCP 2.6, perhaps negatively affecting flowering (Figures 11 and 12). Subsequently lower precipitation in June, but higher temperatures, and then higher precipitation and temperatures on average through to September indicate that the seasonal weather patterns that contributed to such a high quality year are unlikely to be repeated. Growing season conditions in 1996 were generally very dry (333 mm), and median projections of all models and years (2041–2060) show higher precipitation in the months of April, June, July and September but drier in May and August under both RCPs. The projected increase in temperature may 'off-set' the projected 2041–2060 median precipitation increase (to 365 mm) but a significantly drier August indicated through the model median (>40 mm), with higher temperatures (1.5–3°C) leading to greater evapotranspiration, could threaten the likely repetition of this vintage quality. Drier future (2041–2060) seasonal conditions than 2002, except in April and September, under the median model results for the period, and warmer temperatures in on average indicate reduced water availability that threatens the likely repetition of this vintage. However, inter-annual variability in both mean monthly temperatures and precipitation totals indicates that there remains the potential for the 2002 vintage to be repeated under RCP 2.6 as all observed conditions in

2002 fall within the model and 20-year spread of results. Under RCP 8.5 only a likely repetition of the 2002 September temperature mean falls below the model spread.

Figure 6.13 shows the same observed mean temperature distribution in the Champagne region for 1990, 1996, and 2002 but this time with projected ensemble model distributions of temperature for south-east England for all years (2041–2060). The aim here is to illustrate potential for high quality vintage conditions observed in the Champagne region occurring in south-east England under future climate change (2041–2060) scenarios. Figure 6.13 also shows the observed growing season monthly temperatures for 2006 and 2012 in south-east England, years identified as being particularly high and low yielding respectively (Figure 4.8 and Table 3.5). Figure 6.13 enables an evaluation of the likely future (2041–2060) repetition of conditions during these years.

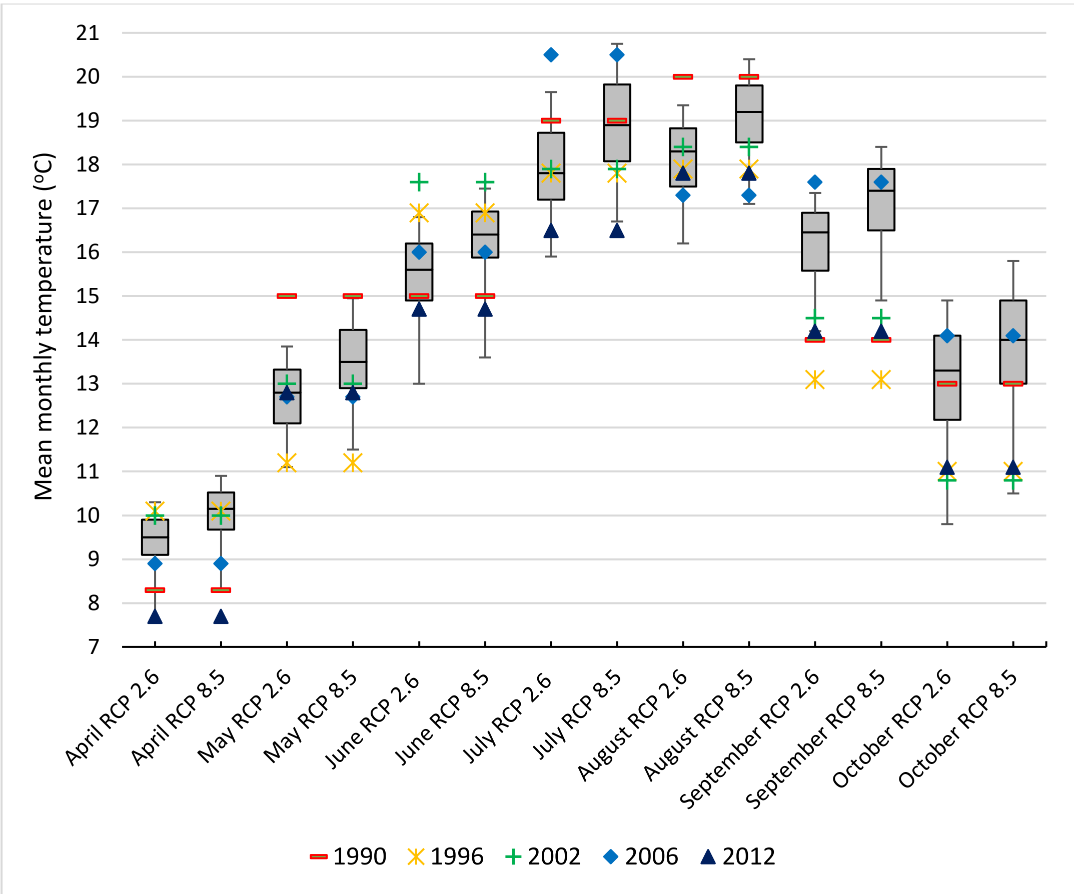


Figure 6.13: South-east England projected growing season mean monthly temperature (°C). Dispersion of 12 climate model results under RCP2.6 and 8.5, for all years (2041–2060), and observed 1990, 1996, 2002 monthly Champagne temperatures, and 2006 and 2012 monthly south-east England temperatures. Source: ClimGen and CRU TS 3.23.

Projected warming during growing seasons in south-east England (Figure 6.9) from 1991–2010 to 2041–2060 places future growing season temperatures closer to those observed during the high quality Champagne vintage years of 1990, 1996, and 2002. On a monthly basis it can be seen in Figure 6.13 that the model spread for all years indicates that this is particularly the case for 1996 and 2002 under both RCPs up until August Post August model ensemble median projections for temperatures are between 2–~4°C higher in 2041–2060 in September than in 1996 and 2002, and between 1–~3°C in October. However, with sufficient precipitation, such conditions indicate good potential for the repetition of high quality vintage years in south-east England. A potential that is higher than in the Champagne region itself. Additionally median temperatures are projected to be much more aligned to those of 2006, a high yield year in south-east England, than 2012, a low yielding year in south-east England. Under the model spread for 2041–2060, potential for repetition of the 1990 Champagne vintage temperature conditions in south-east England is evident in Figure 6.13 in all months except May and September, and August under RCP 2.6. However in May projections are for cooler conditions than in 1990 and in September for warmer conditions. Warmer conditions in September would likely benefit fruit maturation, whilst cooler conditions in May would still be the same or just above (under RCP 8.5) the 1991–2010 mean of 12.8°C (Figure 6.9).

Observed monthly precipitation totals for 1990 fall within the model interquartile spread of all projected years (2041–2060) except for May and June where projections for south-east England are higher and lower respectively (Figure 6.14). In comparison to the Champagne monthly precipitation totals for 1996, future projections for south-east England are generally wetter according to the model ensemble median, except for May and August that are projected to be drier. Projections are also for drier conditions in May, June, July and August (2041–2060) compared with the 2002 Champagne vintage, but potentially wetter in April and similar in September and October. In looking at the range of projected results from all years and models in Figure 6.14 there is potential for the repetition in south-east England of precipitation observed during 1990 and 2002 in Champagne. However, the large spread of precipitation results for south-east England in September and October (2041–2060) indicates lower model agreement about precipitation projections for these months. Conditions at harvest, in September or October, could significantly affect vintage quality through increased disease pressure and poor harvest conditions. Furthermore, when both temperature and precipitation are considered, drier and warmer conditions from post budburst to early ripening (Section 1.1.1), compared with 2002 make its repetition in south-east England less likely

Interestingly 2006, a high yielding year in south-east England, followed a very similar precipitation pattern and monthly totals to those observed in 1996 in the Champagne region (Figure 6.14). Lower median projected precipitation in May and August may mean that repetition of these conditions does not occur exactly but similar temperature projections to those in 2006 for 2041–2060 (Figure 6.13) and a similar precipitation trend through most of the growing season to those projected indicate a greater potential for seasonal conditions of 2006 (for south-east England) and 1996 (for Champagne) being repeated in south-east England than the Champagne region. This is the case under RCP 2.6 and 8.5. The high monthly precipitation totals in 2012, particularly for June, a critical month for flowering (Section 4.6), is not projected for 2041–2060 under the models 20-year spread of results. However, there is potential under the results for May, August and September for wetter conditions which could increase disease pressure and negatively affect maturation.

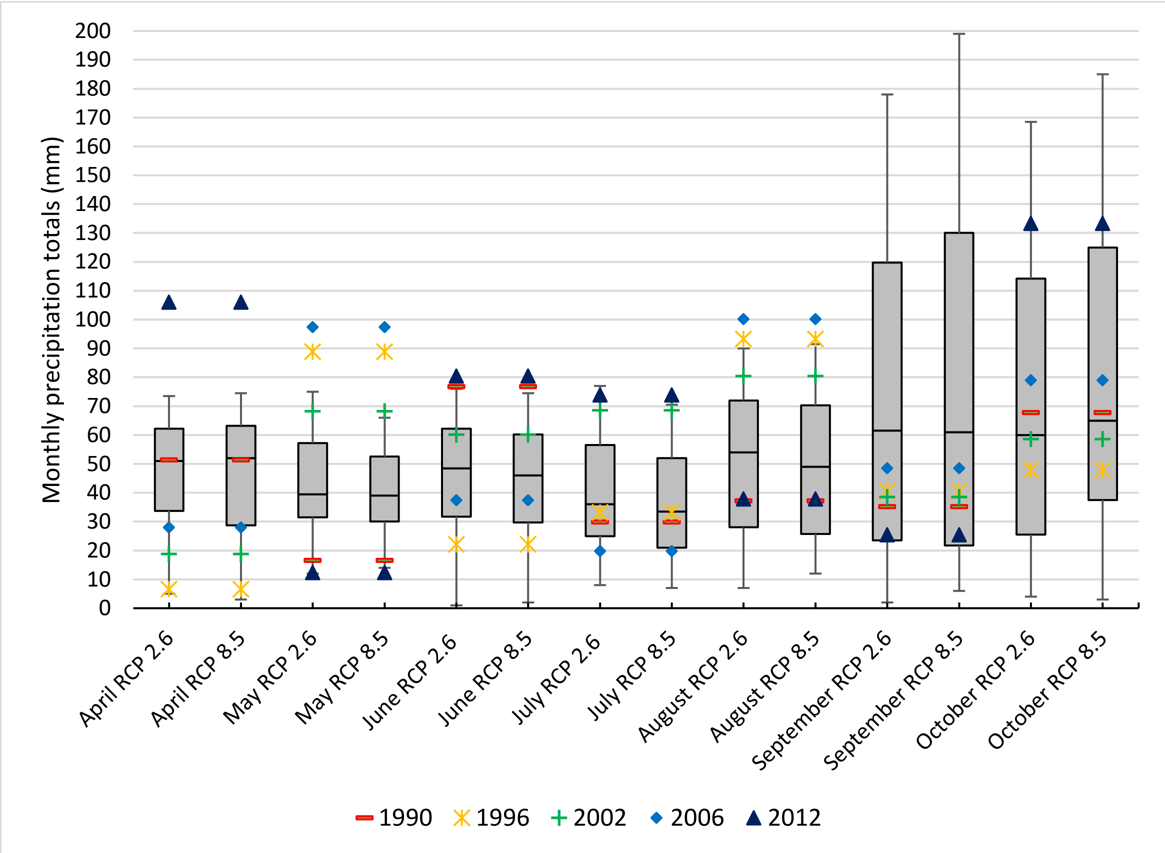


Figure 6.14: South-east England projected growing season monthly precipitation (mm). Dispersion of 12 climate model results under RCP2.6 and 8.5, for all years (2041–2060), and observed 1990, 1996, 2002 monthly Champagne precipitation, and 2006 and 2012 monthly south-east England precipitation. Source: ClimGen and CRU TS 3.23.

These findings suggest that the conditions that lead to high quality vintages are unlikely to be repeated exactly in either south-east England or the Champagne region during 2021–2040. However, using average values for 2041–2060 to illustrate projected change does not elucidate opportunities for seasonal repetition that inter-annual weather variability may present, as demonstrated through the model spreads in Figures 6.11 – 6.14. Instead, it illustrates changes to seasonal patterns that reduce the likelihood of repetition in the case of the Champagne region and takes GSTs (under RCP8.5) beyond those in which current cultivars have been observed to grow (Jones 2006). Conversely for south-east England there looks to be a greater potential for high quality Champagne vintage conditions to be met, and a greater potential that higher yields, as with 2006, are more likely.

6.6. Discussion

English and Welsh wine producers expressed concerns about climate change impacts on wine production in England and Wales (Section 3.1). Chapter 4 presented results of analyses into historic relations between weather variability, climate and productivity of viticulture in England and Wales. Yet producers comments also related to perceptions of future climate change impacts, namely the positive benefits of warming growing season conditions, increased cultivar suitability, and reduced inter-annual variability, and the perceived threats of increased inter-annual variability, extreme weather and increased disease pressures due to warm and wet weather. Other perceptions can be seen in Table 3.3, Section 3.1. Results presented in this chapter do not address all of these perceptions. Instead they seek to present information to help those considering investing in viticulture in England and Wales, or considering forms of adaptation, through analysis of potential impacts of climate change on wine quality and yields. As no data is produced on English wine quality or associated vintage conditions, the Champagne region is used as a proxy, as both south-east England and Champagne grow predominantly the same cultivars (Chardonnay and Pinot noir) to produce sparkling wine, and both have similar biophysical attributes. Furthermore, a comparison between the two regions may be of benefit to those producers considering a move from the Champagne region to England.

Results presented through this chapter only provide an indication of potential future conditions using 12 climate models with values derived using one climate change projection method, pattern scaling, for two RCPs (2.6 and 8.5), and for two time periods (2021–2040 and 2041–2060) for two 0.5 x 0.5° grid cells, one in the Champagne region and one in south-east England. The results cannot demonstrate climatic suitability at higher temporal resolution. The spread of model results, in Tables 6.4 and 6.5 and Figures 6.11 – 6.14 show the range of agreement across models and indicate a range of projected values for monthly temperature and precipitation. These values are generally higher for RCP 8.5 than 2.6, and higher for precipitation than temperature.

Taking all years (2041–2060) and multi-model median values, important growing season conditions in south-east England and the Champagne region can be seen to be likely to alter under future climate change scenarios. Growing season temperatures in both regions are expected to increase with time, potentially taking the Champagne region out of range for Chardonnay and Pinot noir production by 2050, where adaptation practices such as shading are not implemented or available. Projected temperature rises in south-east England indicate increased suitability for these cultivars over the same time period. However, precipitation from 1991–2010 to 2041–2060 is expected to decrease in both regions, with greater reductions in Champagne. Drier harvest conditions may reduce disease pressure and result in more suitable harvest conditions but a precipitation decrease combined with higher temperatures, and therefore likely increased evapotranspiration could result in significant water stress for the cultivars currently grown, without adaptation practices such as irrigation.

The potential for repetition of high quality Champagne vintage conditions is not deemed high for the Champagne region – with warmer growing season conditions and a reduction in precipitation distribution during the season particularly when compared to the high quality 2002 vintage (see Section 6.1 and Figure 6.12). Whilst temperature conditions found during the high quality vintages of 1990, 1996, and 2002 look similar to those projected for south-east England in 2050, mean precipitation projections for south-east England are lower.

Results presented in this chapter explicitly do not take into consideration the adaptive capacity of vineyards or wine-makers in England and Wales, or the Champagne region. To do so would require a quantification of thermal or precipitation buffering provided through various (individual or combined) means of in-situ vineyard or winery practices that mitigate potential changes in meteorological conditions. Such assessments were not the focus of this thesis. Work on adaptive capacity in wine production (Battaglini et al. 2009; Diffenbaugh et al. 2011; Lereboullet et al. 2013; Pickering et al. 2015) has not been relative to specific temperature or precipitation scenarios, in other words adaptation has been discussed theoretically, disconnected from specific modelled changes that may occur for a given location or geographic area. Without first knowing what the future climate change scenarios may be for a specific wine producing region, discussions regarding adaptive capacity remain relatively abstract.

Chapter 7

Conclusions and recommendations

In 1989, Richard Smart was one of the first viticulture scientists to raise the prospect of future climate change impacts on viticulture, specifically risks to appellations in 'old world' regions, potential changes to existing cool-climate regions, and opportunities for new 'new world' regions to emerge. He noted the potential for a global re-distribution of wine grape-growing and recognised the social and economic implications that such shifts could cause (Smart 1989). Whilst large-scale viticulture migration has not been realised to-date, a greater body of evidence has been collected to demonstrate increasing threats to grape-vine phenology, viticulture suitability, and wine quality. This evidence relates especially to temperature increase at global, regional and vineyard scales. The effects of recent temperature rises in viticulture regions have been presented using phenology shifts, harvest dates or wine quality parameters (Jones & Davis 2000a; Tesic et al. 2001; Jones et al. 2005; Garcia de Cortazar-Atauri et al. 2010). Few studies into changing distributions of precipitation and associated viticulture impacts have been undertaken. Future changes have commonly been presented using one or more bioclimatic indices, crop models and climate change models for a range of scenarios (Webb et al. 2008; Hall & Jones 2009; Santos et al. 2010; Fraga et al. 2013a; Webb et al. 2013; Tóth & Végvári 2016). Future climate change projections have not been illustrated in conjunction with potential for adaptive capacity and, as such, modelled changes are generally limited in their representativeness of climate change impacts. Furthermore, as identified in Section 1.2.5 climate change projections for viticulture regions, bar a few exceptions, have been limited in their representation of the inherent uncertainty or biases in climate change models. Where only one or more climate change models have been employed, only one possible result is presented. This limitation is extended where only one or two climate change scenarios are employed. It is recognised, through this work, that studies to demonstrate future climate change impact are strengthened through the use of multi-model projections from which both the mean and the range of uncertainty or agreement can be extracted. Lastly, one of the key critiques of existing climate change and viticulture work relates to the scale of models employed. Whilst *Vitis vinifera* L. is highly sensitive to climatic conditions, where models are used to illustrate potential changes at a low resolution or macroscale the representativeness of impacts at high resolution or mesoscale is questionable.

As recognised by Smart (1989), along with threats posed by changing climatic conditions opportunities will also be presented. Whilst studies to-date have predominantly focused on climate change impacts in the hotter viticulture regions of the world, few have paid attention to emerging 'cool-climate' regions. This thesis has concerned itself with one such region, England and Wales. Previous modelled projections of viticulture suitability have implied that post-2050 southern England may be suitable for viticulture (Tóth & Végvári 2016), but evidence of existing, and rapidly increasing viticulture activity in England and Wales has been overlooked. Although sector growth in England and Wales does not necessarily correlate with viticulture 'suitability' or economic sustainability, a closer examination of historic and future weather and climate risks establishes knowledge from which informed investment decisions can be made. Such was the aim of this thesis.

In Chapter 3 results from a data gathering and generation exercise were presented to quantify recent changes to the viticulture sector in England and Wales. Very little data existed at either vineyard, regional or national scale. Findings in Section 3.1 were expanded on and complemented with a survey of English and Welsh wine producers to better understand their perceptions of climate change and causes behind high and low yielding years (Table 3.5). This initial data gathering and analysis exercise informed subsequent work to quantify historic relations between weather, climate and wine yields in England and Wales (Chapter 4), and helped with the design of a viticulture suitability model (Chapter 5). Chapter 6 looked at future climate change impacts, for both the Champagne region and south-east England to highlight potential impacts on viticulture suitability and wine quality.

7.1. Answers to research questions

7.1.1. Climate change has increased viticulture suitability in England and Wales

True. Rapid recent growth – 148% increase in hectarage during 2004–2013 (Section 3.1, Figure 3.1), of the English and Welsh viticultural sector can in part be attributed to warming temperatures during the growing season (Section 4.1; Figure 4.1) that has placed areas of England and Wales into a GST range (13–15°C), deemed suitable for cool climate viticulture

(Table 1.4; Jones 2006). Climatic conditions have, according to the questionnaire responses of growers/producers, been complemented by structural adaptation of the industry and market demand. Recent growing season temperature in south-east and south-central England is increasingly similar to 1961–1990 GST in the Champagne region. The 1954–2013 upward trend in GST (Section 4.1; Figure 4.1) indicates increasing average thermal conditions suitable for viticulture, supporting producer perceptions of warming growing season trends. While GST, however, has been above the minimum threshold during the 2004–2013 period, wine yield has still varied considerably (6–34 hL/ha). The commonly applied bioclimatic index: GST, was found not to be a reliable indicator of yield. Growing degree days (GDD) and the heliothermal index of Huglin (HI) were examined for spatial variation across England and Wales (Figures 4.3 and 5.11) but not for their relationship to wine yield. The integration of mean daily or monthly data within these bio-climatic indices remains likely to mask shorter term events than can affect vine phenology and yield. The degree of yield variability in this study can in part be explained by the occurrence of air frost and precipitation at key phenological stages.

Critically, the drive to produce English sparkling wine as a result of increasing recognition of both quality and potential, has led to a significant change in dominant cultivars grown. Chardonnay and Pinot noir are considered more 'marginal' cultivars than those they have replaced with respect to the current English and Welsh climate and its variability (Skelton 2014b). It is perhaps their greater sensitivity to England and Wales cool climate conditions that is reflected in a statistically significant relationship, post 2004, between yield and GST (Table 4.1). The evidence is that English sparkling wine production has increased and cultivars have changed, but as a result, the sector is now at greater vulnerability to weather variability. Under climate change there is potential for variability in temperature and precipitation to increase at both intra-annual and inter-annual scales (Maracchi et al. 2005, Beniston et al. 2007, Fraga et al. 2013a), and grape-growers/producers view increasing variability as a threat. A high degree of variability in temperature and precipitation in south-east and south-central England, and in England and Wales (Figures 4.1 and 4.3), has been identified. Critically, substantial changes to the magnitude of inter-annual variability over time (1961–1990 to 1989–2013) were not found, leading to the conclusion that inter-annual growing season variability remains a threat to productivity. At a monthly scale precipitation in south-east and south-central UK during June has been shown to have a statistically significant relationship with yield (Table 4.2) and has been associated by growers/producers to low yielding years (Table 3.5). The variability of precipitation in June has not significantly changed and, therefore, it remains a constant threat to flowering and fruitset, regardless of changes to thermal averages. The increase in interquartile temperature variability in October (Figure 4.7), along with increasing precipitation volumes, suggests that this critical month of the harvest period has recently been more prone to unfavourable conditions. Whilst individual grower and collective industry resilience to the financial implications of weather or climatic variability are not fully explored through this work, the impact on yield represents a climatic risk.

Opportunities for viticulture in England, when examined at a monthly scale, can be seen through rising median, mean and maximum temperature in most growing season months and, in particular, notable temperature increases in the spring months of April and May Figure 4.6). Spring air frost risk and wet flowering and fruitset conditions, however, remain a sustained and critical threat. Harvest period conditions in the south-east and south-central England have now been shown to have become warmer and wetter, bringing the potential for increased disease pressure at this time. Kenny and Harrison's (1992) focus on the frequency of 'good' and 'bad' years, rather than average conditions, can be seen through this work to be particularly relevant to conditions in England and Wales. In Chapter 4 it has been shown that yield still faces regular threats from unfavourable weather at key points in the calendar. Viticultural opportunities can be realised in years where these threats do not materialise or when they can be managed.

Critically, it has been demonstrated that vulnerability to climate variability has increased, as a result of changes in dominant vine cultivars. Viticulture in the UK is vulnerable to weather variability resulting from England and Wales's geographical positions, a vulnerability recognised by producers and evidenced in this work. Subsequent seasons (2014 and 2015) have also been warmer than the 1961–1990 mean (see Figure 7.1). Whilst 2014 was potentially a high yielding year (figures still to be released), 2015 was affected by rainfall at flowering and a cool spring affecting bud burst, further indicating intra-seasonal risks. For those investing in English and Welsh viticulture, climatic risks may be ameliorated through management strategies and their ability to cope, financially, with lower yielding years, but the adaptive capacity and resilience of growers or the sector remains unquantified.

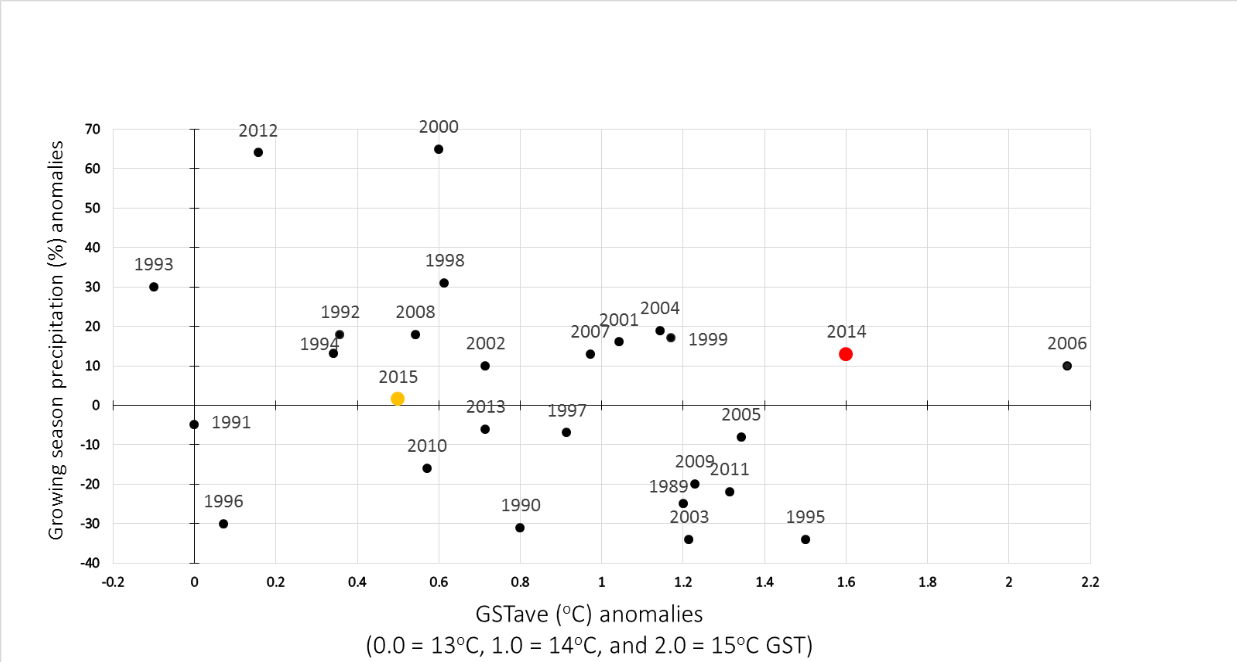


Fig 7.1: South-east and south-central England growing season precipitation (%) and growing season temperature (°C) anomalies for 1989–2015 against 1961–1990 means. Source: Met Office 2014b

7.1.2. Viticulture suitability in England and Wales is limited to existing dominant regions of production

False. The regional temperate maritime climate in England and Wales remains defined by a relatively low mean GST, the potential for wet weather both seasonally and at critical phenological stages, spring frosts, and significant inter-annual variability; conditions that have unsurprisingly been found to have a negative effect on English and Welsh wine yield (Section 4.6). Spring and early summer (April to June) are critical to bud formation and flowering in *Vitis vinifera* L., the dominant wine grape species. Both of these phenological stages influence yield, but as noted by Kington (2010) this period contains the most changeable weather of all seasons in the British Isles due to their positioning between the mid-latitude westerly wind belt on the edge of the Atlantic Ocean and the continental influences of mainland Europe. English and Welsh geographical sensitivity to small changes in the positioning of major atmospheric pressure systems results in marked intra and inter-annual weather variability, which in-turn can affect the quantity and stability of wine-grape yields from year-to-year. Although wine yields are not the only consideration defining business viability, relationships between yield, weather and climate suggest that where atmospheric conditions are more stable, and where growing-season temperatures are higher, within cool-climate regions such as England and Wales, sustainable opportunities for viticulture could be greatest. To reduce existing exposure to weather and climate risks, and help identify future opportunities for viticulture investment, an analysis of spatial biophysical and climatic suitability was undertaken (see Chapter 5).

Results demonstrate significant opportunities (>200,000 ha) for viticulture in areas with equivalent or higher GSTs (2004–2013) to those observed in existing large vineyards in England. Biophysical suitability across England and Wales is significant, with suitable land area containing chalk or limestone soils of almost the same scale (37,000 ha) as can be found in the Champagne region of France (35,000 ha). Interestingly opportunities for expansion were presented outside of the currently dominating south-east of England with high degrees of fuzzified suitability observed in Essex and Suffolk. Only 50% of existing vineyards fell within the suitability model, illustrating significant potential for adaptation to more suitable sites. An analogue approach of examining bioclimatic values in other cool-climate viticulture areas in north-western Europe uncovered a 2004–2013 1^{o}C GST difference between large vineyards in England (cooler) and the Champagne region of France (warmer), and greater similarity between temperatures in these vineyards and eastern Denmark and the Mosel region of Germany. Observations of temperatures in the small but emerging region of eastern Denmark possibly indicate increasing potential for Scandinavian viticulture (Gustafsson & Mårtensson 2005; Olsen et al. 2011; Stainforth et al. 2013). Yet, as recognised through this work it is both biophysical land suitability, precipitation, and shorter term acute events that largely drive yield and viability where thermal conditions could be deemed 'suitable'. The analogue modelling approach also suggested a potential for cultivar adaptation and indicated suitability for Müller-Thurgau, a previously dominant grape cultivar in England and Wales (Table 3.3).

The first fuzzified suitability model applied to viticulture, presented in Chapter 5, integrated GST, growing-season rainfall, June rainfall, growing season sunshine hours, April and May air frosts, and degrees of inter-annual variability of both GST and growing season rainfall (Figure 5.7 and 5.8). Areas with lower frost risk and inter-annual variability, namely south Norfolk, Suffolk and Essex, currently have few vineyards established in them (Table 5.1) but represent opportunities for expansion and diversification. When, as a case study, suitability in east-Anglia was examined relative to sugar beet production, over 500 sugar beet growers were found to be established on biophysically suitable land for viticulture. Furthermore, a rudimentary economic analysis of investment returns indicated, at present, higher profitability in viticulture.

7.1.3. Future climate change presents increasing opportunities for viticulture in England and Wales

True. Results presented in Chapter 6 for short term (2021–2040) and medium term (2041-2060) temperature change in south-east England, indicate warming conditions during the growing season, that could present opportunities for greater spatial and cultivar distributions. Higher GSTs would also likely result in higher yields, in both warmer and relatively cooler years. Comparisons, in Section 6.5, between high quality Champagne vintage temperature conditions and those projected for south-east England show a shift by 2041–2060 towards temperatures found in Champagne during 1990, 1996, and 2002, all years noted for excellent quality. Chardonnay, Pinot noir and Pinot meunier are now the dominant cultivars being grown in south-east England, the same cultivars grown in Champagne during these high quality years. Furthermore temperature projections for this period in south-east England, at a monthly scale, are more similar to those during 2006, the highest yielding year on record in the UK. These findings suggest both increasing opportunities for viticulture and specifically, increasing potential for the production of Champagne cultivars and increased yields in south-east England under either RCP 2.6 or 8.5 during 2041–2060. A shortage of precipitation was not identified by grape-growers as being a climatic threat to viticulture in England and Wales, but excessive precipitation was highlighted as being problematic through the growing season, and particularly during flowering in June (Section 4.6). High levels of precipitation, usually accompanied by reduced sunlight, can negatively affect vine growth, berry quantity and quality through associated issues such as increased disease pressure, reduced flowering, millerandage, coulure and a sugar/acidity imbalance. Results presented in sections 6.4 and 6.5 indicate a projected overall reduction in growing-season precipitation in south-east England to 2041–2060, from a 1991–2010 baseline and throughout most the growing season. However, the 20-year mean model results indicate a potential increase in precipitation during May and September

(Figure 6.6) which could negatively affect flowering and harvest, under a scenario of advanced phenology. Although the overall projected reduction may be regarded as positive from a quality perspective, significant reductions in precipitation may result in a requirement for irrigation, which could increase production costs and increase demand for water.

Projections of temperature and precipitation changes as 20-year means, under two RCPs, do not illustrate the degree of, or changes to, inter-annual variability. Whilst mean conditions may present increasing opportunities over-time, yield, grape quality and potential viticulture viability will remain affected by variations in seasonal conditions from year to year, as demonstrated in Section 6.5 using monthly projections from all models for all years, under both RCPs.

To further assess projections of climate change impacts on the growing season different methodological approaches, such as statistical or dynamic downscaling from RCMs would be beneficial to provide a comparative assessment. This would be particularly useful at higher resolution and with a greater number of climate models and RCPs. Furthermore, results presented in section 6.4 and 6.5 only relate to monthly mean temperature and precipitation totals. An examination of projected changes to extreme weather that could play a crucial role in viticulture stability is absent.

7.1.4. Future climate change presents likely repetition of high quality Champagne vintages

False. Projected warming (2041–2060) in the Champagne region would take one of the currently dominant cultivars, Pinot noir, above its observed climate/maturity grouping (Figure 4.1 and Table 6.4) and bring the Champagne region into temperature thresholds for 'new' cultivars such as Sauvignon blanc, Semillon and Cabernet Franc. Yet perhaps even more concerning for the Champagne region are model mean projections of a 11–22% reduction in growing season precipitation by 2041–2060 under RCP 2.6 and 8.5 respectively. Projected warming and a decrease in precipitation during the growing season against a 1991–2010 baseline, and particularly during maturation in August and September may result in significant vine stress unless water availability can be increased. Here it should be recognised that inter-annual variability may still result in high quality vintage years, although the trends suggest these may become fewer in number.

As with Section 7.1.3 and as recommended in Section 7.3 further climate modelling work, using different methodologies, would be advantageous to further test this research question.

7.2. Recommendations

There are a number of relevant audiences for whom the results presented in this thesis are of value, not least, those considering investing in viticulture in England or Wales. Understanding that growing season temperatures are currently relatively low and variable and that inter-annual variability affects yields, in some years to critical levels, provides important insight. This is not just from a perspective of which cultivars to grow as such decisions are largely market orientated, but also from a spatial suitability perspective. The ability to map climatic and biophysical risk and optimise spatial potential is a significant step towards building greater weather resilience into the English and Welsh viticulture sector. It also allows for a desk-top analysis of multiple locations at high resolution and provides a level of objectivity to the process not currently available. Where suitability exists in areas with lower levels of inter-annual variability, opportunities for more stable yields could be realised.

Such a suitability model also has value for those working in policy fields, particularly land use policy or agro-economic spheres. Initial findings in Chapter 5 also demonstrate favourable economic returns for viticulture under low, medium and high yield scenarios, compared for example to sugar beet, potentially driving conversion decisions. Recognising opportunities for high 'value' viticulture land is likely to be of interest to those in estate agency enterprises. Additionally, the model was used to 'test' higher resolution (1 x 1 km) WRF model output. Further testing is expected to result in a fine-scale suitability model that will generate interest from the same communities, but will also attract attention from those involved in vineyard insurance, especially where frost risks can be accurately determined.

Climate change projections presented in Chapter 6, for south-east England, represent new findings which have consequences for those considering investing in viticulture, or those already established. They illustrate changes in the temporal distribution of both mean monthly temperatures and precipitation for 2021–2041 and 2041–2060 from a 1991–2010 baseline period. Projected increases in growing season temperatures under RCPs 2.6 and 8.5, in both south-east England and the Champagne regions, and projected decreases in precipitation will alter the status quo and present medium term opportunities for Champagne cultivar establishment and quality wine production in south-east England, but will threaten the Champagne region's ability to maintain its current production without means of climate change adaptation.

For wine investment communities the unlikely repetition of conditions that resulted in high quality Champagne vintages (Figure 6.7) may spur investment in high quality wines from these years. Wine as an investment, like any stock market, can offer financial returns often based on confidence in a sector. Intelligence regarding future stock value, driven upwards by limited supply, could be beneficial to those investment communities, and the market itself. For those producing Champagne, findings presented in this thesis may indicate future risks that spur or inform adaptation planning, including root-stock, clone and cultivar combinations, and irrigation to 'deal' with future conditions, or migration.

Lastly, one critically important recommendation is that site and cultivar-specific production data and meteorological data should be collected at English and Welsh vineyards to better inform future studies of weather, climate and viticulture relationships, and to provide more detailed and robust analysis of the wine production sector. Furthermore such data could be used to better understand grapevine phenology and inform management decisions.

7.3. Future research

The results presented in this thesis underpin the provision of weather and climate services to the English and Welsh wine production sector. Several issues raised also warrant further investigation. Firstly, a relationship between regionally averaged climatic conditions in an area that has ~50–60% of the English and Welsh vineyard area, and UK-wide wine yield has been presented in Chapter 4. Analysis in this work was constrained by the lack of available regional or vineyard specific grape vine yield data, with which more precise correlations between meso or microclimatic conditions and yield could be made. This would be enhanced further with higher resolution climatic data and data regarding wine-grape quality parameters. The lack of these data could be considered an investment risk. Whilst there is value in thermal indices their simple aggregated nature masks acute weather events, including those at key phenological stages that have a significant relationship with yield and viability. Higher resolution temporal meteorological data (hourly or daily) would provide an ability to analyse local conditions at a finer-scale and additionally, as recognised in section 4.7, to overcome the limitations of comparing two different time-periods (1961–1990 (30 years) and 1989–2013 (25 years), future research (post-2018), be undertaken to provide a comparison of 20 or 30–year periods regarding temperature, precipitation and inter-annual weather variability.

Secondly, with regard to relationships between weather, climate and viticulture it should be noted that relationships between seasons (the formation of reproductive organs in grapevines extends over two successive years separated by winter dormancy in cool and cold climate regions (Lebon et al. 2008), and risks related to increased disease pressure have not been examined in this study but require further research because both were expressed as concerns, related to climate change, by producers.

Thirdly, the suitability model presented in this work would be significantly enhanced with more accurate soil information, including soil water holding capacity, from which suitability could be derived and critical choices made regarding root-stocks and cultivars. Furthermore the model would benefit from the ability to show inter-annual variability as CV rather than just SD, particularly for precipitation. The use of SD does not indicate the relative magnitude of the standard deviation and the CV would potentially illustrate the relative variability. It was noted in section 5, in relation to Figure 5.11, that the HI resulted in some south-eastern coastal areas having lower bioclimatic values, a configuration not observed through the other bioclimatic index results. Potential reasons for this phenomena were not explored further but could relate to issues of WRF model alignment into ArcGIS or as a function of the HI algorithm. Further investigation is required into this phenomena.

Fourthly, climate change projections in this thesis were derived from a pattern scaled approach, the limitations of which are discussed in Sections 1.2.7 and 2.5.6. Now higher resolution (0.11 degree, ~12.5km) downscaled regional climate model output is available from EURO-CORDEX (World Climate Research Programme 2015), but it didn't become available early enough in this study to be used. The EURO-CORDEX simulations also consider the global climate simulations from the CMIP5 long-term experiments up to the year 2100.

Additionally, only two future time periods were considered in this work (2021–2040 and 2041–2060) which didn't allow for an analysis of finer scale time periods, potential changes to inter-annual variability, or longer-term projections. The pattern scale climate projection method was employed in this work due to the accessibility of ClimGen output for the time periods and desired locations. However, in recognition of the limitations of the pattern scaling method (Sections 1.2.7 and 2.5.6) dynamical or/and statistical downscaling GCMs to the regions of interest is recommended, to enable a comparison with the pattern scale derived results presented in this thesis. Regional impacts may be stronger or weaker than the global mean signal, which highlights the need for regional climate change assessment studies to regionally downscale models (Christensen et al. 2007). Furthermore when looking either regionally or globally, because different GCMs produce regionally varying responses, resulting in a range of plausible future climates (Fraga et al. 2013a; Watterson 2008), it is important to represent this range of outcomes. The use of multi-model ensemble projections enables quantification of model uncertainties which is important because model uncertainty may lead to different actions/responses (Deser et al. 2012). Quantification of the uncertainty associated with climate change projections may be as important to the winemaking sector as the climate change signal itself (Fraga et al. 2013a). In this work 12 models were employed and the spread of results was found to suggest greater uncertainty regarding future precipitation during the growing season in south-east England than Champagne, and greater uncertainty in GST towards 2100 across both regions. A higher number of climate models would likely illustrate greater representation of uncertainty but perhaps more substantially valuable would be a comparative modelling process using dynamic or statistical downscaling. Additionally, only mean monthly values were employed in this study but analysis of projected changes in extremes would be beneficial, particularly those identified as risks, i.e. frost, heatwaves and drought.

Fifthly, the model mean projected increase between 2021–2040 and 2041–2060 for precipitation in south-east England warrants further research to better understand this finding, using a greater number of GCMs, and/or comparative regional climate change studies using different downscaling approaches, i.e. dynamic or statistical.

Sixthly, work within this thesis has been constrained to future analysis of temperature and precipitation. Analysis of wind, solar radiation, and soil water holding capacity would aid in more complete analysis of climate change risks for viticulture. In addition, changes to temperature and precipitation have been examined using monthly mean and total data respectively. Further research, regarding precipitation in particular, would be useful to understand projected changes to extremes of these variables, i.e. number of rain days vs monthly rainfall.

Finally, further work in quantifying the adaptive capacity in both the Champagne region and England to changing growing season conditions would likely increase sector resilience to climate change and help maximise opportunities for investment.

The work delivered through this thesis is envisaged to support a range of weather and climate services to the viticulture sector. Anecdotally, within the wine production sector there is greater interest in predicted weather conditions in the next week, month, season or year. Whilst tools could facilitate such hunger for knowledge this thesis strongly indicates investment risks in the medium-term that require information and processes to encourage and support decisions now, particularly in one of the fastest growing agriculture sectors in England – viticulture.

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Appendix A: Producers questionnaire

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11th March 2014

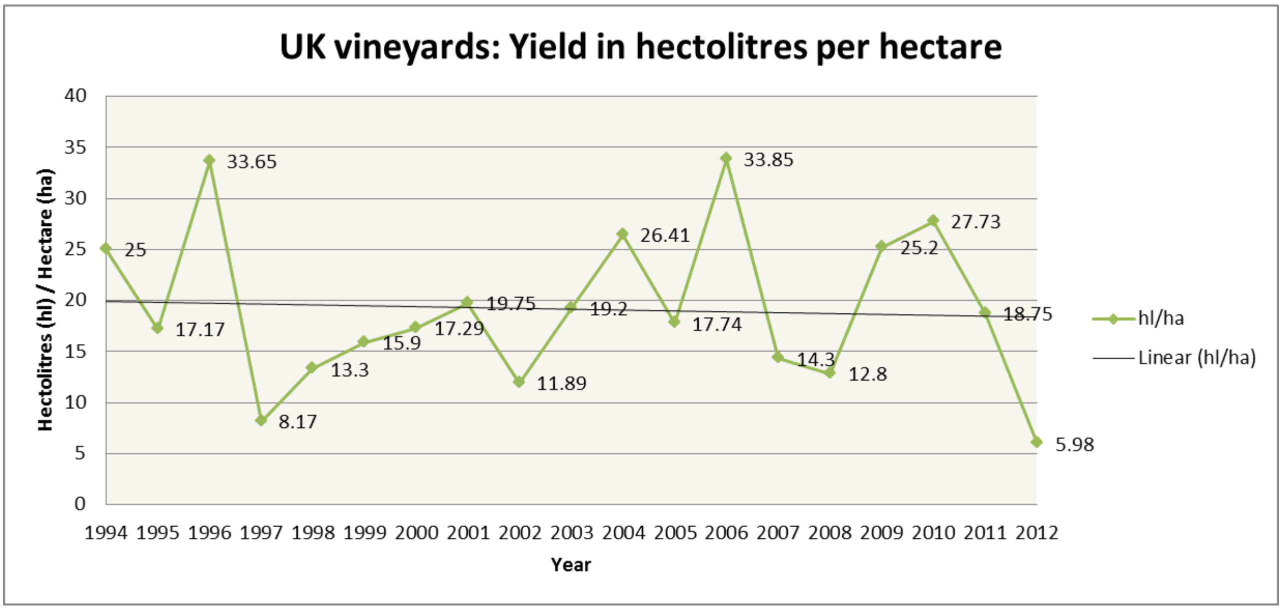
Viticulture-Climate Producer Perspective Questionnaire

1. Which vineyard are you involved with in the UK?

2. On average what is your best yielding cultivar, clone and rootstock combination?

3. What is your worst?

Have a look at the graph below:



Data supplied by the Food Standards Agency (2013)

4. Looking back as far as you can, what were the main causes of **lower** yields in the following years:

    a. 2012

    b. 2008

    c. 2007

    d. 2002

    e. 1999

    f. 1998

    g. 1997

5. What were the main causes of **higher** yields in the following years:

    a. 2010

    b. 2006

    c. 2004

    d. 1996

    e. 1989

6. Over a 10 year period roughly what average yield do you need to achieve to be economically viable? *(Please state in t/ha)*

7. Has Climate Change contributed to the growth of the UK wine production industry? *(Please circle or cross out as appropriate)*
    a. Yes
    b. Maybe
    c. Don't know
    d. Doubtful
    e. No

8. What other factors have contributed to its growth?

9. Do you think climate change is a threat to, or opportunity for wine production in the UK, and why?

Thank you for your contribution. Please return to: a.nesbitt@uea.ac.uk by the 21st March 2014.

Appendix B: Historic UK vineyard and wine yield data – From the Food Standards Agency (2014)

ADDITIONAL FIGURES

Year	Total ha	INCREASE (ha)	Table/varietalWines White	Table/varietalWines Red	Potential Quality Wines (PDO/PGI) White	Potential Quality Wines (PDO/PGI) Red	Total White	Total Red	Total Yield in Hl.	Ha in Production	Yield per Ha.	No. of Vineyards	Av. Size of vineyard	No. of Wineries	Production Bottles (m)
Surveys before 1989 were voluntary and data is therefore not reliable.															
1975	196														
1984	430									325		281		120	
1986	488								6,530	356	18.34				
1988	546								4,110	382	10.76				
Surveys from 1989 have been compulsory															
1989	876								21,447	652	32.89	442	1.98	147	2.9
1990	929						13,484	958	14,442	629	22.96	445	2.09	147	1.9
1991	992						14,465	964	15,429	650	23.74	454	2.19	150 (Est.)	2
1992	1,054						24,695	1,733	26,428	701	37.70	457	2.31	157	3.5
1993	1,065						15,845	1,659	17,504	767	22.82	479	2.22	148	2.3
1994	1,035						16,212	1,481	18,327	733	25.00	435	2.38	123	2.4
1995	984						11,734	917	12,795	745	17.17	413	2.38	115	1.7
1996	965						23,960	2,120	26,080	775	33.65	408	2.37	123	3.48
1997	949		3,523	444	2,392	101	5,915	545	6,460	791	8.17	386	2.46	114	1
1998	901		6,712	772	3,448	270	10,160	1,042	11,202	842	13.30	382	2.36	108	1.5
1999	872		10,003	1,025	2,048	195	12,051	1,221	13,272	835	15.90	373	2.34	106	1.8
2000	857		10,799	1,409	1,950	57	12,749	1,466	14,215	822	17.29	363	2.36	106	1.9
2001	836		12,180	1,414	2,063	160	14,243	1,574	15,817	801	19.75	350	2.39	105	2.1
2002	812	-24	7,035	1,219	999	131	8,035	1,350	9,385	789	11.89	333	2.44	114	1.25
2003	773	-39	6,315	1,437	5,350	1,401	11,665	2,838	14,503	756	19.20	333	2.32	109	1.79
2004	761	-12	5,559	958	10,581	1,973	16,140	2,931	19,071	722	26.41	339	2.24	106	2.5
2005	793	32	6,269	1,324	4,158	1,055	10,427	2,379	12,806	722	17.74	350	2.27		1.7
2006	923	130	12,437	2,928	7,747	2,155	20,184	5,083	25,267	747	33.85	362	2.55	102	3.37
2007	992	69	4,754	824	2,997	1,373	7,751	2,197	9,948	697	14.30	383	2.59	98	1.33
2008	1,106	114	4,499	1,145	3,334	1,109	7,833	2,254	10,087	785	12.80	416	2.66	116	1.34
2009	1,215	109	11,583	1,856	6,950	3,446	18,533	5,302	23,835	946	25.20	381	3.19	109	3.18
2010	1,324	109	15,684	2,554	8,856	3,252	24,540	5,806	30,346	1095	27.73	404	3.28		4.05
2011	1,384	60	7,830	1,597	10,245	2,987	18,075	4,584	22,659	1208	18.75	419	3.30	124	3.02
2012	1,438	54	1,211	457	4,358	1,724	5,569	2,181	7,751	1297	5.98	432	3.33	128	1.03
2013	1,884	446	17,099	6,173	7,172	2,941	24,270	9,114	33,384	1571	21.25	470	4.00	135	4.45
5 year Average			**10,681**	**2,527**	**7,516**	**2,870**	**18,198**	**5,397**	**23,595**	**1,223**	**19.78**				**3.146**
10 year Average			*8,692*	*1,982*	*6,640*	*2,202*	*15,332*	*4,183*	*19,515*	*979*	*20.40*				*2.507*

From 1994, figures exclude vineyards not in active production.
Data supplied by the Wine Standards Branch, Food Standards Agency
From 2012 vintage. 'potential Quality Wines includes PDO and PGI wines

Appendix C: Nesbitt, A., Kemp, B., Steele, C., Lovett, A. and Dorling, S. 2016. Impact of recent climate change and weather variability on the viability of UK viticulture – combining weather and climate records with producers' perspectives Impact of recent climate change and weather variability on the viability of UK viticulture. (Accepted for publication March 2016).