Impact of recent climate change and weather variability on the viability of UK viticulture – combining weather and climate records with producers' perspectives

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Abstract

Background and Aims: From 2004 to 2013, the vineyard area in the United Kingdom (UK) increased 148%. Observed climate change and underlying weather variability were assessed for their influence on the development and viability of UK viticulture.

Methods and Results: The perspectives of grapegrowers in the UK on climate change and weather variability were complemented by a quantitative analysis of climate and weather data (1954–2013) for the main UK viticultural regions. The variability of growing season average temperature (GST) was calculated and also mapped using a modelling approach. Since 1993, GST has consistently been above the 13°C cool climate viticulture threshold. Alone, GST does not reliably assure yield predictability but does correlate more closely following the recent increasing UK focus on sparkling wine cultivars. June precipitation demonstrates the strongest relationship with yield.

Conclusions: Increasing GST superficially suggests enhanced UK cool climate viticultural opportunities, but critically masks the additional impact of shorter term temperature and precipitation events and a high degree of inter-annual variability that continues to threaten productivity. A recent change in dominant UK vine cultivars appears to have increased viticultural sensitivity to inter-annual weather variability.

Significance of the Study: This first quantitative and qualitative analysis of climate vulnerability in UK viticulture identifies threats and opportunities and helps steer studies of the impact of future climate change.

Keywords: bioclimatic index, climate change adaptation, climate variability, cool climate viticulture, UK viticulture, weather research and forecasting model

Introduction

In 2013, the Intergovernmental Panel on Climate Change concluded that warming of the world's climate system was unequivocal (Intergovernmental Panel on Climate Change 2013). Since 1960, the UK has seen warming occur faster than the global average (0.23 and 0.28°C per decade, in winter and summer, respectively, [Met Office 2014a]) and records show that post-1910 the seven warmest years in the UK have all occurred since 2002 (Met Office 2014b). These temperature changes are likely to affect agro-economic activity temporally and spatially, an effect that is potentially being witnessed through the recent (2004–2013) 148% increase in UK land area devoted to viticulture, to 1884 ha (Food Standards Agency 2014). This climate viticulture link has not been explicitly analysed in the UK until now.

Evidence points to the existence of vineyards in southern England during the Medieval Warm Period (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, the number of vineyards in the UK declined. The subsequent revival of UK viticulture began in the early 1950s, and up until 1993, the volume and spatial distribution of UK vineyards increased. From 1993 to 2004, however, both vineyard area (total area) and number declined 29%, which have been attributed to a combination of factors, 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 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 the number of vineyards to 448 in 2013 (Figure 1).

Average vineyard size has also risen from 2.24 in 2004 to 4 ha in 2013 (Food Standards Agency 2014). Area in production, shown in Figure 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 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 (Figure 2), but the

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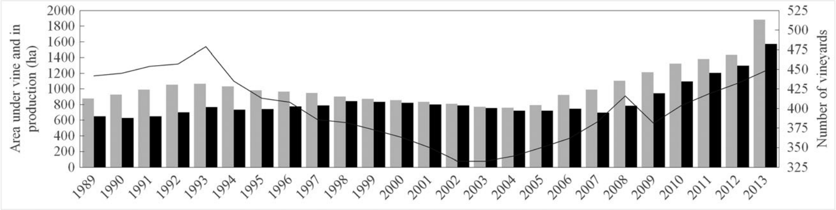

Figure 1. Area under vine in the United Kingdom (▨), area in production (■), and vineyard numbers (1989–2013) (—), based on data from the Wine Standards Branch of the Food Standards Agency (2014).

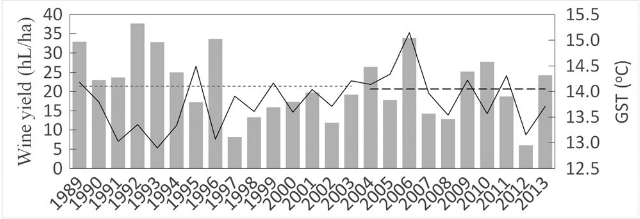

Figure 2. Wine yield in the United Kingdom (▨) including the average in 1989–2003 (-----) and 2004–2013 (– – –), with GST for south-east and south-central United Kingdom (——).

reason for the decline is unclear. 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 1, relate solely to commercial vineyards and may partly explain the reason for the drop.

Recent vineyard plantings have predominantly occurred in southern England (50–52^{o}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 (Skelton 2014a). Figure 3 (based on vineyard location details and scale data from the UK Vineyard List [Skelton 2014a]) shows that the majority of larger commercial vineyards are positioned within these areas; however, the overall spatial distribution of vineyards is much larger. The potential future distribution of vineyards is not explored in this work, but an extension to higher latitudes under future climate change scenarios has been suggested (Selley 2004).

Winegrapes are generally grown in narrow latitudinal bands (30–50^{o}N and 30–40^{o}S) and under favourable climatic conditions, characterised by a lack of extreme heat and cold (White et al. 2006, Schultz and Jones 2010) and a growing season average temperature (GST) (April–October: Northern Hemisphere, October–April: Southern Hemisphere) in the range of 12–22°C (13–21°C for high-quality wine production) (Jones 2010). Within such environments, suitability is further determined by local conditions. Grapevine phenological development, yield and berry composition are influenced by a range of factors including management practices, site specific geophysical conditions, disease pressure, pests, cultivar type, local climate and weather. Ultimately, local and regional climate play a significant role in determining spatial viticultural and cultivar suitability (Jones and Davis 2000, Jones 2010, Jones et al. 2010, Santos et al. 2012). Understanding how viticultural suitability in the UK is affected by weather and climate is central to evaluating the risks to, and opportunities for, UK viticulture.

Recent research suggests that under future climate change higher latitude regions may have increasing viticultural suitability (Stock et al. 2005, Jones 2007, Etien et al. 2008, Hall and Jones 2008, Schultz and Jones 2010) including the UK (Kenny and Harrison 1992, Fraga et al. 2013). Simulations employed in such research, typically using one or more climate models for one or more emission scenarios, commonly base viticultural suitability on 20–30-year thermal averages. These are often assessed through the use of bioclimatic indices that represent an integration of conditions over periods of single or multiple growing seasons. While the application of bioclimatic indices in analysing viticulture and/or cultivar suitability, and in zoning viticultural regions is common (Kenny and Harrison 1992, Tonietto and Carbonneau 2004, Duchêne and Schneider 2005, Blanco-Ward et al. 2007, Hall and Jones 2010, Jones et al. 2010, Anderson et al. 2012, Santos et al. 2012, Fraga et al. 2013, 2014, Irimia et al. 2013), the ability of a bioclimatic index to reliably indicate UK viticultural suitability has not been previously ascertained. Bioclimatic index values commonly include categorisations of viticulture and cultivar suitability based on empirical observations rather than on physiological modelling. Therefore, the climatic envelopes of *Vitis vinifera* cultivars, as depicted through bioclimatic indices, could perhaps be expanded. As such, these indices make a rudimentary but valuable initial indicator of suitability. Bioclimatic indices, however, are also limited by their inability to quantify the adaptive capacity of viticulture to climate change and warming conditions. As illustrated by van Leeuwen et al. (2013), it is difficult to establish precise upper

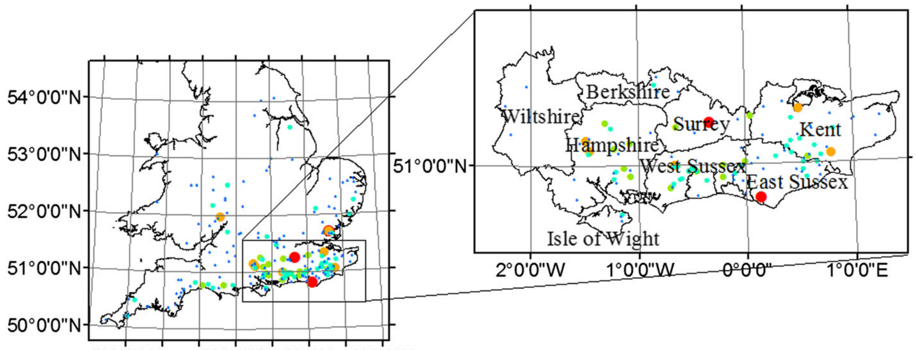

Figure 3. Spatial distribution of vineyards >2 ha in the United Kingdom [2–5 (●),5–10 (●),10–25 (●),25–50 (●),50–110 (●) ha].

limits by cultivar for wine production, and bioclimatic suitability values may alter depending on adaptive capacity. Climate change adaptation is not taken into account in our approach 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 with which our work is concerned.

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 (Hanna et al. 2014) 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, we hypothesise that, particularly in the UK's marginal climate (Kenny and 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 the UK, under warming conditions, according to bioclimatic index values, mask or understate threats from shorter term weather conditions, extreme events and climate variability.

This study: (i) assesses the perspectives of UK grapegrowers on the risks and opportunities related to weather and climate change impacts; (ii) quantifies averages, extremes, trends and variability in growing season temperature and precipitation since the revival of UK viticulture (1954–2013), in the main grapegrowing regions, south-east and south-central UK; (iii) analyses their relationship with available wine yield data (1989–2013); (iv) evaluates the reliability of GST as a bioclimatic indicator of UK viticultural suitability; and (v) establishes a relationship between GST, wine yield and dominant UK vine cultivars.

Materials and methods

Producers' perspectives

This research was guided by the responses of UK grapegrowers/producers to a questionnaire about UK climate viticulture relations (see Supporting Information). All grapegrowers/producers in the UK were invited to respond to the questionnaire which was advertised through a combination of emails to producers, regional vineyard associations, 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 could be completed in hard copy or online. Of specific relevance to this work, grapegrowers/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 and 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 the responses that have been adopted and investigated here.

Regional focus

This work focuses its viticulture-climate analysis in the south-east and south-central region of the UK, covering the counties of Berkshire, Hampshire, the Isle of Wight, Kent, Surrey, East and West Sussex and Wiltshire (Figure 3). Since 1989, these regions have represented ~50–60% of national vineyard area (Skelton 2001, 2008, Food Standards Agency 2013). Vineyards and potential viticultural opportunities are, however, more spatially diverse, and therefore, the focus extends to a larger geographical area, covering England and Wales, to examine growing season temperatures and inter-annual variability (2004–2013).

Weather and climate analysis

Few vineyards in the UK have site specific weather data available for analysis. Met Office data for monthly average temperature and precipitation data (1954–2013) for regional growing seasons (April–October) were used to calculate averages and identify extremes, trends and variability for the south-east and south-central UK region. Anomalies and comparison with a 1961–1990 baseline period were calculated to illustrate climate trends, this baseline having been widely used in climate change research and in previous climate and wine work (Hulme et al. 1999, Webb et al. 2007, Giorgi and 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. Met Office regional monthly average temperature and rainfall data are derived from station daily means ($[Tmax + Tmin]/2$) and summed daily totals, respectively, interpolated onto a 5 × 5 km grid before being averaged for a region. The data are accessible online (Met Office 2014b) and enabled a macroclimatic analysis of historic growing season conditions.

To illustrate the spatial and inter-annual variability in growing season air temperature (2 m), GST's for England and Wales (2004–2013) are presented using dynamically downscaled outputs based on a weather research and forecasting (WRF) model climatology, created by Steele et al. (2014), at 9-km resolution. 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

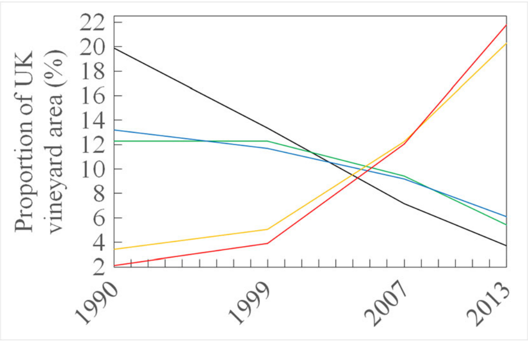

Figure 4. Changing distribution of dominant (by volume) vine cultivars (1990–2013), Müller Thurgau (——), Reichensteiner (——), Seyval Blanc (——), Pinot Noir (——) and Chardonnay (——) in the United Kingdom, as a proportion of total vineyard area.

YSU planetary boundary layer scheme (See their Figure 4). A similar bias was also reported by Hu et al. (2010). For the purposes of this research, version 3.3.1 of WRF was used, based on the advanced research WRF dynamical core. A detailed description of the model formulation is available in Skamarock and Klemp (2008).

Bioclimatic index

Growing season average temperature has been found to be functionally identical to another commonly applied bioclimatic index; growing degree days, and was selected for this work because of the availability of monthly averaged daily data as opposed to individual daily data required to accurately calculate growing degree days (Jones et al. 2010). Growing season average temperature represents the average of growing season monthly mean temperature, which is calculated from daily data (Table 1).

While limitations to the power of bioclimatic indices have been previously identified (Moriondo et al. 2013), GST has been applied to other wine producing regions, such as those in the western USA (Jones et al. 2010), Portugal (Jones et al. 2009, Jones and Alves 2012), New Zealand (Anderson et al. 2012), Australia (Hall and Jones 2010), Italy (Jones et al. 2009, Tomasi et al. 2011) north-east Spain (Ramos et al. 2008) and in Germany and France (Jones et al. 2009). Additionally, GST values have previously been classified into five climate/maturity groups for grapevines, as shown in Table 1 (Jones 2006, 2007). This index classification correlates broadly to the maturity potential for winegrape cultivars grown across many wine regions and provides the basis for placing latitudinal boundaries on viticulture zones in both hemispheres (Schultz and Jones 2010). Specific cultivar 'maturity' parameters were not measured in this work, 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. Importantly, when used in conjunction with higher spatial and temporal resolution weather data, its value as an indicator of suitability can be further assessed.

Climate and yield relations

Yield data from individual vineyards were sought and supplied by seven UK vineyards; however, the data provided were limited in terms of historical length, robustness and overall volume so could not be used with confidence. Yield data for the south-east and south-central UK 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. United Kingdom yield data (1989–2013; hectolitres per hectare [hL/ha]) were obtained from the Wine Standards Branch of the Food Standards Agency. Yield data collection officially began only in 1989; data were previously voluntarily provided by producers and were not deemed sufficiently complete for use in this analysis. The use of national, non-regionally specific yield data could lead to some distortion of climate–yield relationships, but national yield values were deemed indicative of those in our regions of interest because of their significant contribution to total UK vineyard area. An analysis of national weather/climate data would disproportionally include areas where few or no vineyards exist.

Table 1. Growing season average temperature index and classifications.

Bioclimatic index	Equation	Months	Class limits (°C)
Growing season average temperature (GST)	$\frac{\sum_{d=1}^{n}[Tmax+Tmin]/2}{n}$	1 April–31 October	Too cool <13 Cool = 13–15 Intermediate = 15–17 Warm = 17–19 Hot = 19–21 Very hot = 21–24 Too hot >24

Numerous factors can affect yield, but our analysis is limited to weather and climate. We subjected yield and average temperature (growing season and monthly), and yield and frost days (April and May), 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 cultivars play an important role in yield, because of their relative climatic suitability, and from one time period to the next, there was a change in concentration of cultivars grown in the UK. The dominant cultivars during 1990–2003 (Müller-Thurgau, Seyval Blanc and Reichensteiner) were superseded during 2004–2013 by Chardonnay and Pinot Noir as the industry focus increasingly shifted to sparkling wine production (Figure 4). Figure 4 uses data compiled from the available Wine Standards Branch Vineyard Registers (1990, 1999, 2007 and 2013) as published in Skelton (2008, 2010, 2014b). Data for intervening years were not available. Cultivar information preceding 1990 was collected by the Ministry of Agriculture, Fisheries and Food through voluntary surveys but is not deemed sufficiently comprehensive to present in this work. We do refer to yield data from 1989 as there is no evidence of a significant change in dominant cultivars in production between 1989 and 1990.

Weather variability and extremes

We quantified inter-annual weather variability as the standard deviation and coefficient of variation for GST and precipitation. The coefficient of variation was used to enable a comparison between the relative variability of temperature and precipitation. To assess changes to the degree of variability, we compared the results for 1989–2013 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 9, 10) to show the degree of dispersion allows for an illustration of changes to monthly average temperature and total precipitation extremes. They also enable conditions during critical phenological periods to be more closely examined. Of particular interest were conditions during periods deemed problematic by producers, namely, flowering and fruitset. Although dependent on factors, such as cultivar, rootstock and site, it has been observed that since the 1990s flowering in UK vineyards occurs typically in mid to late June (Skelton 2014b). This represents a phenological advance from the 1970–1990s where flowering in most years occurred in early July, a shift that Skelton (2014b) attributes to increasing temperature, and that signifies a lengthening growing season.

The number of air frost days in April and May (1961–2013) is presented and analysed because air frost days are considered an extreme event indicator (Frich et al. 2002), and because questionnaire responses stated that spring air frost is an acute threat to UK winegrape yields.

Results

Survey responses

The survey resulted in 42 responses from producers responsible for 313 ha of vineyards (17% of the UK total). Most of the respondents were from the south-east and south-central UK and owned or managed vineyards ranging in size from just over 1 to more than 20 ha. Survey responses can be summarised as follows:

Causes of high and low yielding years, as attributed by producers. High yielding years (Figure 2; 1996, 2006 and 2010) were primarily attributed to good or 'optimum' temperature and weather conditions at flowering and fruitset, 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 2; 1997, 2007, 2008 and 2012) were primarily attributed to wet and cold weather during flowering and fruitset, wet and cold growing seasons, low levels of sunlight, poor summers in preceding years and spring frosts.

These high and low yielding years fell outside the interquartile yield ranges for the two-time periods and thus help delineate between the impacts on yield from weather and other effects. Questionnaire responses confirmed that weather was likely to have impacted yield during these years.

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 growth of the industry; 23% stated that it had not or were doubtful that it had contributed, and 11% did not know.

Producers were subsequently asked: 'What other factors have contributed to its growth?' Responses provided some insight into the structural adaptation associated with expansion of the sector. The majority concerned increasing awareness of quality; awards and further marketing; increasing cultivar suitability; education and better management; increasing investment; the fashion for the style of wines produced in the UK; and support for 'buy local'.

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. 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 previous 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 addressed in the discussion section and is a key driver for this research. Table 2 presents a summary of the reasons given for climate change being a threat or opportunity.

Wine yield in the UK

Wine yield (1989–2013) in the UK reveals 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 2). Average yield for the period was 21.5 hL/ha. When examined for 1989–2003 and 2004–2013 [periods distinguished by cultivar differences (Figure 4)], mean yield was 21.43 and 20.70 hL/ha, respectively.

Climate analysis

Temperature is a key climate parameter by which viticultural suitability is commonly determined (Jones 2007, Fraga et al. 2012). Questionnaire results, however, also indicated that high precipitation was an important determinant of yield in the UK. Figure 5 shows the average temperature and precipitation for south-east and south-central UK for the 1954–2013 growing seasons.

The south-east and south-central UK decadal mean GST for 1954–1963, 1964–1973 and 1974–1983 was consistently 13°C. 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, 2007). Equivalent period average growing season precipitation total was 431, 424, 411, 416 and 427 mm, respectively. Over the 60-year period (1954–2013), an imposed linear trend line reveals increasing GST, with 31.5% of variation in GST 'explained' by its relationship with

Table 2. 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 yield and quality	3
Extreme weather	5		
Increased disease pressure due to warm and wet weather	5	More viable cultivars	2
Weather during critical periods of flowering and maturation	4	Later harvest dates and increased ripening potential	1
Unpredictable weather	4		
Increased disease pressure due to mild, wet winters and lack of winter frost	3	Average temperatures will go up in 10–20 years	1
Wind affecting physiological development	2	Weather may settle over time	1
Increasing gulf between good and bad years	1		
One year effecting the next	1		
Gulf stream may end	1		

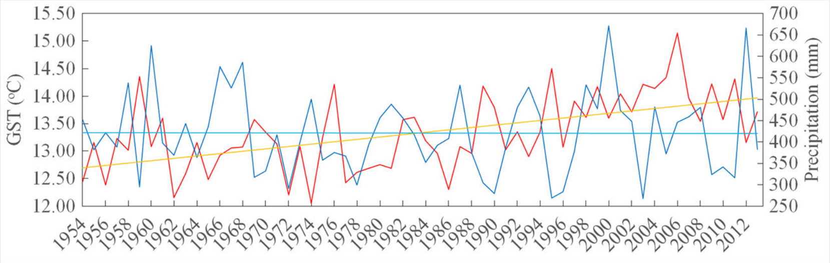

Figure 5. Growing season average temperature (GST) (——) and growing season precipitation (——) for south-east and south-central United Kingdom (1954–2013) with imposed linear trends for GST (——) and precipitation (——). GST, $y = 0.0216x + 12.674$, $R^2 = 0.3153$; precipitation, $y = 0.0271x + 421.52$, $R^2 = 2E\text{-}05$.

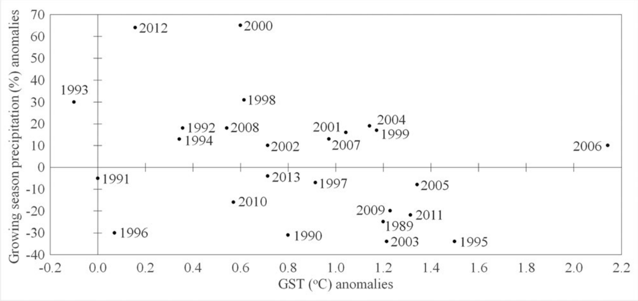

Figure 6. South-east and south-central United Kingdom growing season precipitation (%; *y*-axis) and growing season average temperature (GST) (°C; *x*-axis) anomalies for 1989–2013 against 1961–1990 means of 407 mm and 13°C, respectively. 0.0 = 13°C, 1.0 = 14°C and 2.0 = 15°C GST.

time. The standard deviation, however, of inter-annual GST (1954–2013) is 0.7°C, demonstrating considerable variability between years. Strong inter-annual variability (standard deviation = 96 mm) in growing season precipitation is also visible, but no positive or negative linear trend for the 1954–2013 period was found.

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 6, all years, except 1991 and 1993, were warmer than the baseline average with a relatively even spread of positive and negative precipitation anomalies, typically ±30% (excluding the wet outliers in the years 2000 and 2012). 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). These changes to growing season temperature indicate an increase in viticultural suitability if GST is considered a reliable bioclimatic index.

Maps generated with the WRF model (Figure 7) show GST for 2004–2013 and illustrate inter-annual GST variability over a wider geographic area (England and Wales). This series, with a 9-km resolution, depicts temperature in some years above 13°C in areas well beyond the south-east and south-central UK. The years 2006 and 2012, identified by questionnaire responses as 'extreme' high and low yielding years, respectively, can be seen to remain 'extreme' at a national scale. The tendency for higher GST can be seen for south-east, south-central and eastern England, areas with a higher proportion of UK vineyards (Figure 3). Southern areas with greater coastal proximity can also be seen to have higher GST in general.

Average growing season conditions obscure shorter periods of fluctuation in temperature and precipitation, which are significant for grapevine phenology and potentially to yield. Our analysis was limited to monthly averaged daily temperature and summed monthly precipitation data, but hourly or daily data would allow for increased analytical assessment of acute events, such as air frost, heavy precipitation or hail. It can be seen from Figure 8 that the number of days with air frost is both higher and more variable in April than in May, phenologically significant months, in south-east and south-central UK (1961–2013). An imposed 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 our recent period of interest (1989–2013), 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, but these are not discussed here.

While calendar months do not equate directly to phenological stages in grapevines, they are used here as temporal indicators. South-east and south-central UK 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 9 and 10 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 maximum 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, and 1996 was identified as a high yielding year, evidenced in Figure 2. 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 and the poor 2007 yield to wet conditions during flowering. There appears to be little correlation between outlying or extreme temperature and yield at this monthly scale.

Between 1961–1990 and 1989–2013, October precipitation volumes rose in all quartiles. Median precipitation volumes 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 volumes (44.2 and 32.9 mm, respectively). April also experienced an interquartile precipitation range expansion of 53%. Significantly, little change to the interquartile or overall distribution (including the 2012 outlier) of precipitation in June occurred between the two periods. This suggests that the risk of damagingly high precipitation during flowering (when it occurs in June) remains unchanged. The years 1997, 2007 and 2012 were low yielding (Figure 2) and had June precipitation volumes in the top six of the last 100 years.

Relationships between weather, climate and UK wine yield

The inter-annual variability in UK wine yield and south-east and south-central UK GST can be seen in Figure 2, 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 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 yield, and subsequently the value of GST as an indicator of viticultural suitability expressed through yield, we subjected GST values and yield to a standard linear regression analysis for the periods, 1989–2003 and 2004–2013.

Table 3 shows that a significant relationship was established only for the period 2004–2013 in which 44% of 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, were found.

These results indicate that independent of GST, the average temperature in August and July accounts best for the variation in 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 the discussion section.

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 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) were also subjected to the same statistical analysis. Where significant relationships were found, output values are presented in Table 5. For all other variables, no discernible linear relationship between yield and any of the predictors was found.

For the full 1989–2013 period and the 2004–2013 period June precipitation had a 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 commented on in the discussion. Results 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.

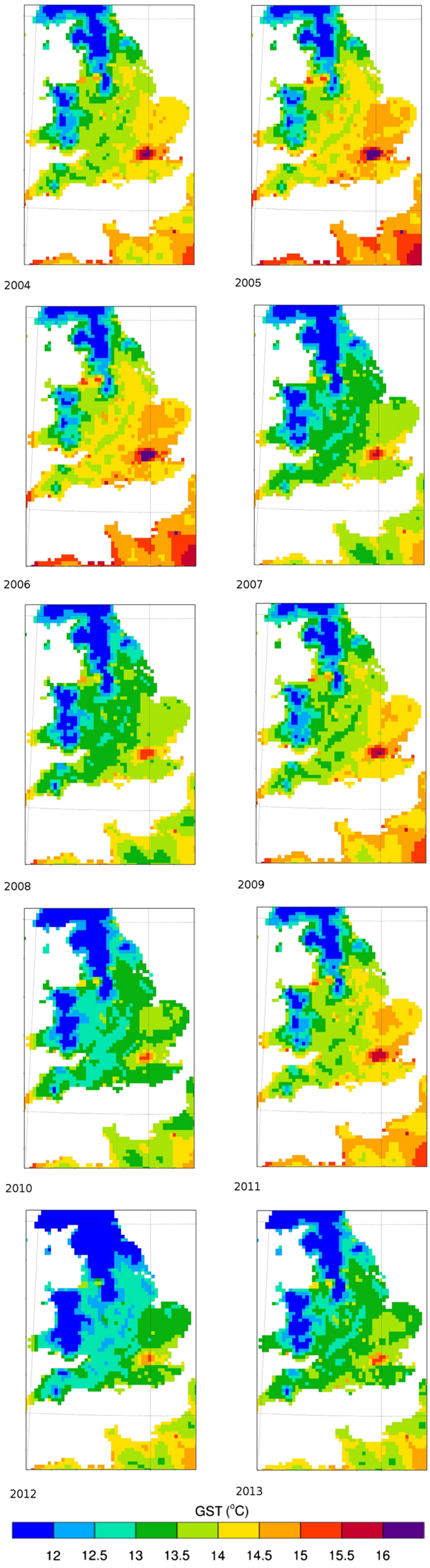

Figure 7. Growing season average temperature (GST) for 2004–2013 over England and Wales.

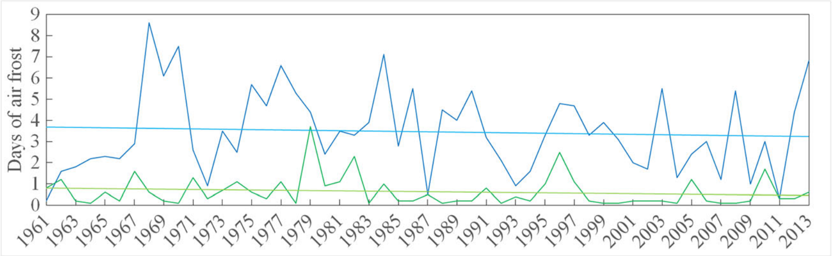

Figure 8. April (——) and May (——) air frost frequency (1961–2013) across south-east and south-central United Kingdom with imposed linear trends for April (——) and May (——). April, $y = 0.0087x + 3.6946$, $R^2 = 0.0046$; May, $y = 0.0069x + 0.8171$, $R^2 = 0.0221$.

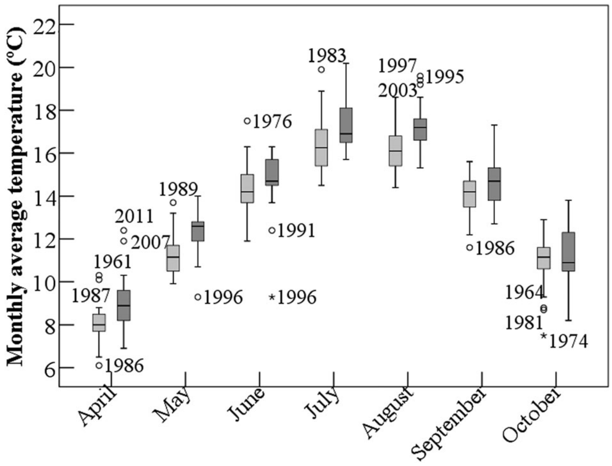

Figure 9. South-east and south-central United Kingdom growing season monthly mean temperature dispersion for 1961–1990 (□) and 1989–2013 (■). Outlier (1.5–3 × box length) (○), extreme (>3 × box length) (*).

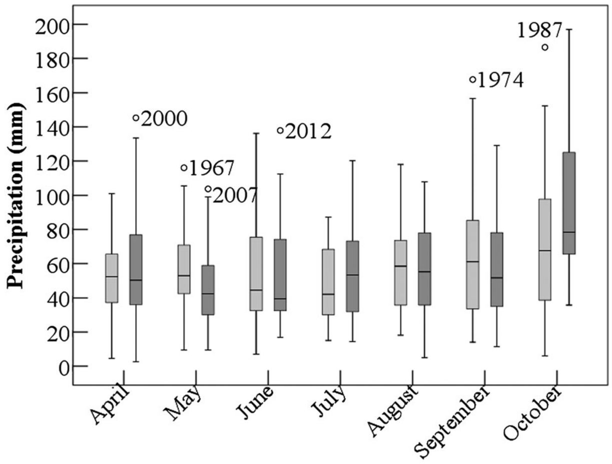

Figure 10. South-east and south-central United Kingdom growing season monthly precipitation dispersion for 1961–1990 (□) and 1989–2013 (■). Outlier (1.5–3 × box length) (○).

Table 3. Linear regression results between growing season average temperature and wine yield (1989–2003, and 2004–2013).

Period	*P*-value	R^2 (%)
1989–2003	0.070	23
2004–2013	0.038	44

Table 4. Significant linear regression results between monthly temperature and wine yield (1989–2003 and 2004–2013).

Period	Variables	*P*-value	R^2 (%)
1989–2003	August	0.034	30
2004–2013	July	0.018	52

Table 5. Stepwise regression relationships between monthly temperature, precipitation and wine yield for 1989–2013, 1989–2003 and 2004–2013.

Period	Variables included	Indicators	*P*-value	R^2 (%)
1989–2013	GST, monthly temperature, seasonal and monthly precipitation	1. June precipitation	0.002	34.7
1989–2003		1. August temperature	0.034	30.1
		2. August temperature and season total precipitation	0.002	64.6
2004–2013		1. June precipitation	0.005	64.1

GST, growing season average temperature.

Table 6. Variability in growing season average temperature and precipitation (1961–1990 and 1989–2013).

Variable	Period	Standard deviation	Coefficient of variation (%)
Growing season average temperature	1961–1990	0.6°C	4.3
	1989–2013	0.5°C	3.8
Total precipitation volume	1961–1990	81 mm	20
	1989–2013	112 mm	27

GST, growing season average temperature.

Weather variability

One of the perceived threats to wine production in the UK (Table 2) was weather variability. We compared GST and total precipitation variability for 1989–2013 against a baseline period of 1961–1990 to identify degrees of variability and any recent changes. Inter-annual variability in GSTs has decreased by 0.5% between the periods, whilst precipitation variability has increased by 7% (Table 6).

Discussion

This study was established primarily in response to producers' comments about threats to and opportunities for UK viticulture, in relation to climate change. We examined regional climate and weather data to assess averages, extremes, trends and variability in growing season temperature and precipitation, and their relationship with UK yield (1989–2013), employing a commonly used bioclimatic index (GST) and monthly temperature and precipitation data.

Sixty-six per cent of grapegrowers and wine producers who responded to the questionnaire stated they thought climate change had contributed to the growth of the viticultural sector in the UK. Evidence presented in Figures 5 and 6 shows a warming of climate in south-east and south-central UK, during the grapevine growing season (1954–2013 as an imposed linear trend, and 1989–2013 as anomalies against a 1961–1990 climatic normal), supporting the majority of questionnaire responses. Here, it should be pointed out that these observed changes are derived from weather station data averaged over the south-east and south-central England region. Research focused on New Zealand by Sturman and Quénol (2013), however, showed that the sign of recent trends in minimum temperature and frost frequency varied as a function of station and region, even if the trends of maximum temperature were homogeneously positive across the country. This was attributed to large scale circulation and topographic effects on cloud cover. This interesting complexity is not seen in the UK; observations from a UK network of meteorological stations over the period 1961–2006, interpolated and mapped, show that minimum, mean and maximum temperature have all increased in all seasons across the whole country, and annual air frost frequencies have all decreased, when linear trends are applied (Jenkins et al. 2008).

The climate in the south-east and south-central UK, and more widely in other parts of England and Wales (Figure 7), 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 UK 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 2 and Table 5 illustrate the relationship can be weak because GST does not closely correspond to yield in all years.

In the context of Champagne, UK 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 UK 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 22.3 hL/ha. In addition, during the latter period, there was an increase in young vines coming into production; initial production yields are likely to be lower than in more established vines/vineyards, potentially influencing the overall mean yield. The change in dominant cultivars since 2004 (Figure 4), however, 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 3). Most significantly, this change in dominant cultivars appears to have increased sensitivity to climate variability.

Where there is no real evidence for change in the variability of inter-annual growing season temperature (Table 6), 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 grapegrowing 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). 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 (flowers fail to set and are shed at or after flowering) or millerandage. It is, however, likely that the significance of this relationship depends on other growing season weather events and viticultural impacts. 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.

The volume of total precipitation during the growing season has increased from 407 (1961–1990) to 420 mm (1989–2013). The 16% rise in median precipitation during October (Figure 10) 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 5). This result confirms producers' comments regarding reasons for low yielding years, which is the impact of conditions at flowering. The recent outlying precipitation event in June 2012 (138 mm; 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 volume since 1910, followed by the sixth highest precipitation volume in

June, since 1910. Combined these conditions were attributed by producers to the low yield. June precipitation volume in 1997 was the fourth highest since 1910. 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 UK 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 5), also suggests that precipitation during the season as a whole, is a critical yield determining factor. This possibly supports growers/producers comments 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 6).

Producers expressed concerns about increasing variability. It can clearly be seen from Figures 2 and 5 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 meaningful change in temperature and precipitation variability in June suggests that the threats to flowering and fruitset 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 2). 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 winegrape 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 the south-east and south-central UK 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. 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 6 and 7 and as indicated in questionnaire responses, this was due to the wet and cold spring. Combined, these weather conditions remain a threat to productivity.

Bilateral 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. Whilst global warming has been associated with the migration of diseases poleward (Bebber et al. 2013), potentially increasing susceptibility to several pathogens and vectors affecting vineyards (Caffarra and Eccel 2011), the relationship between changing climatic conditions and viticultural disease pressures remains unquantified for the UK. In this context, we acknowledge that weather conditions during the growing season may also impact disease occurrence and thus yield.

A key aim of this work was to assess the ability of GST to adequately describe viticultural suitability in the UK. We have found that while it can act as a general indicator of thermal suitability, in the sense that *V. vinifera* 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.

Conclusions

Rapid recent growth (148% during 2004–2013) of the UK viticultural sector can in part be attributed to a warming temperature that has placed areas of England and Wales into a GST range (13–15°C), deemed suitable for cool climate viticulture. 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 UK is increasingly similar to 1961–1990 GST in the Champagne region. The upward trend in GST (1954–2013) 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 varied considerably (6–34 hL/ha). The degree of yield variability 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 has led to a significant change in dominant cultivars grown. Chardonnay and Pinot Noir are considered more 'marginal' cultivars than those they have replaced and are possibly more affected by poor weather conditions (Skelton 2014b). It is perhaps their greater sensitivity to the UK's cool climate conditions that is reflected in a closer relationship, post 2004, between yield and GST. The conclusion is that English sparkling wine production has risen, but as a result, the sector is now at greater risk from variability in average growing season conditions.

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. 2013), and grapegrowers/producers view increasing variability as a threat. A high degree of variability in temperature and precipitation in south-east and south-central UK, and in England and Wales, has been presented. 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 and has been attributed by growers/producers to low yielding years. The dispersion of precipitation volume 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, 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 explained through this work, the impact on yield represents a climatic risk.

Opportunities for UK viticulture, when examined at a monthly scale, can be seen through rising median, mean and maximum temperature in most growing season months. In particular, notable temperature increases in the spring months of April and May. 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 UK 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 the UK. Here, we have shown that UK 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.

We have presented a relationship between regionally averaged climatic conditions in an area that has ~50–60% of the UK vineyard area, and UK-wide wine yield represented through hL/ha. Analysis in this work is constrained by the lack of available regional or vineyard specific grape vine yield data, with which more precise correlations between mesoclimatic conditions and yield could be achieved. This would be enhanced further with higher resolution climatic data and data regarding winegrape quality parameters. The lack of these data could be considered an investment risk. Nonetheless, increasing regionally averaged temperature is likely to result in mesoclimatic and microclimatic changes that benefit production. Where vineyards exist in regions with lower GST, climatic suitability is not so advanced, and variability potentially poses a greater risk.

We have shown both the opportunities for and threats to UK viticulture, presented by two important climatic variables, for recent time periods. These have evidenced both changing climatic conditions and threats that remain more constant, that is June precipitation. We have also demonstrated the limitations of GST as an indicator of UK viticultural suitability and the need for higher resolution temporal and spatial analysis of UK viticultural conditions. Critically, we have demonstrated that vulnerability to climate variability has increased, as a result of changes in dominant vine cultivars. Under a scenario where greenhouse gas emissions continue to rise in the near term but stabilise by the end of the century (Representative Concentration Pathway 4.5), temperature in Northern Europe is projected to rise 1.1 (2016–2035), 2 (2046–2065) and 2.7°C (2018–2100) higher than the 1986–2005 average (Intergovernmental Panel on Climate Change 2013). Further work will investigate future climate scenarios for viticulturally suitable areas of the UK and the relationship at higher resolution, between multiple bioclimatic indices that include factors, such as latitude, day length, and sunlight.

Viticulture in the UK is vulnerable to weather variability resulting from the UK's geographical positioning, a vulnerability recognised by UK producers and evidenced in this work. For those investing in UK, viticulture climatic risks may be ameliorated through management strategies, market forces and their ability to cope with lower yielding years. Projections for future climate conditions in the UK will support future risk analysis.

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