OENO One VINE AND WINE OPEN ACCESS JOURNAL | By IVES International Viticulture & Enology Society

DOI: https://doi.org/10.20870/oeno-one.2022.56.3.5398

OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Climate change projections for UK viticulture to 2040: a focus on improving suitability for Pinot noir

Alistair Nesbitt[1,2*], Stephen Dorling[2,4], Richard Jones[2], Dan K.E. Smith[2,4], Marcus Krumins[4], Kate E. Gannon[3] Lewis Dorling[4] , Zoë Johnson[4] and Declan Conway[3]

[1] Vinescapes Ltd, Dorking, Surrey, RH5 6SX, England
[2] School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, Norfolk, NR4 7TJ, England
[3] Grantham Research Institute on Climate Change and the Environment, London School of Economics, London, WC2A 2AE, England
[4] Weatherquest Ltd, Enterprise Centre, University of East Anglia, Norwich Research Park, Norwich, Norfolk, NR4 7TJ, England

*correspondence: alistair@vinescapes.com

Associate editor: João Santos

Received: 7 February 2022
Accepted: 6 June 2022
Published: 8 July 2022

ABSTRACT

Between 1981–2000 and 1999–2018, growing season average temperatures (GST) in the main UK viticulture regions have warmed ~1.0 °C and are now more reliably > 14.0 °C GST. This warming has underpinned the rapid expansion of the UK viticulture sector and its current focus on growing grape varieties for sparkling wine. Near-term (2021–2040) climate change may condition opportunities for further variety and/or wine style changes. Using the latest high-resolution (5 km) ensemble (× 12) of downscaled climate change models for the UK (UK Climate Projections; UKCP18) under Representative Concentration Pathway (RCP) 8.5, we calculate near-term trends and variability in bioclimatic indices (BCIs). We simulate the projected repetition of the UK's highest yielding season—2018—and use an analogue approach to model the 1999–2018 mean growing season temperatures from Pinot noir producing areas of Champagne (France), Burgundy (France) and Baden (Germany) over the UK during 2021–2040. We also project, across the UK for the 2021–2040 period, BCI values of recent high-quality vintage years from Champagne and Burgundy. GST are projected to increase from a 1999–2018 spatial range of 13.0 (minimum threshold)–15.7 °C to a future (2021–2040) range of 13.0–17.0 °C, and Growing Degree Days (GDD) from 850 (minimum threshold)–1267 to 850–1515. Growing season precipitation (GSP) is projected to decline in some UK viticulture areas but is not modelled as a limiting viticulture factor. High inter-annual weather variability is simulated to remain a feature of the UK viticulture climate and early season frost risk is likely to occur earlier. Large areas of the UK are projected to have > 50 % of years within the bioclimatic ranges experienced during the 2018 growing season, indicating potential higher yields in the future. The 1999–2018 mean Champagne, Burgundy and Baden GST and GDD are projected for much of England and some areas in the far south and south-east of Wales during 2021–2040, with significant areas projected to have > 25 % of years within the BCI ranges of top Champagne vintages. These results indicate greater potential for Pinot noir for sparkling wines and shifting suitability to still red wine production. Accounting for changes in variety suitability and wine styles will be essential to maximise opportunities and build resilience within this rapidly expanding wine region.

KEYWORDS: bioclimatic indices, climate resilience, climate adaptation, climate change, Pinot noir, viticulture suitability.

INTRODUCTION

Viticulture in the UK expanded nearly 400 % from 761 to 3800 hectares (ha) between 2004 and 2021 (Figure 1), the period when sparkling wine started to dominate the country's production (Nesbitt *et al.,* 2016; WineGB, 2021a). While the sector's full market capacity remains unclear, significant potential exists to develop prime vineyard land in the UK (Nesbitt *et al.,* 2018). Enhanced investor confidence and widening variety and geographical suitability have been underpinned by recent climate change, particularly by warming growing seasons (approximately April–October). The UK's ten warmest years on record have all occurred since 2002, and heatwaves like those seen in the summer of 2018 (the warmest summer in south-east and south-central England since records began in 1884; Met Office, 2020a) that contributed to record UK average winegrape yields of 48 hectolitres per hectare (hL/ha) (Figure 1; WineGB, 2020a) are estimated to now be 30 times more likely to happen than would have been the case without human-induced climate change (Met Office, 2018). Conversely, whilst a lack of rainfall during the growing season has not historically been a limiting factor for UK viticulture, high rainfall during the growing season and around grapevine flowering have correlated with lower yields (Nesbitt *et al.,* 2016). Intra- and inter-annual weather variability and extreme events such as early season air frosts (when the air temperature is below the freezing point of water at a 1.5 m height above the ground) have contributed to high UK yield fluctuations (Figure 1). Until now, however, the broader consequences of further climate change for UK viticulture, beyond a likely positive correlation between increasing growing season temperatures and yields, have not been explored using the latest high-resolution UK climate change projections (UK Climate Projections 2018, UKCP18; Met Office, 2020b). This work uses UKCP18 scenarios to assess future variety and wine style suitability and potential for viticulture investments, sector adaptation and resilience over the near term 20-year period (2021–2040).

Pre-2004 the dominant grape varieties grown in the UK were cooler-climate tolerant Reichensteiner, Seyval Blanc and Müller-Thurgau (Nesbitt *et al.,* 2016). In contrast, the dominant varieties grown in 2020 were Pinot noir, Chardonnay and Pinot Meunier, respectively representing 33, 32 and 13 % of the total planted area, and made up predominantly of clones best suited to sparkling wine production using the Traditional Method. Bacchus (~5 % of UK vineyard area), meanwhile, currently dominates UK still wine production (WineGB, 2020b). These varieties are grown with specific wine styles and markets in mind, potentially with Protected Designations of Origin (PDO) or Protected Geographical Indication (PGI) or Varietal Wine certification targets, but also as an adaptation and opportunity response to warming growing season temperatures (Nesbitt *et al.,* 2016). Wines produced in the UK, particularly sparkling wines, now regularly attract international recognition and acclaim for quality (International Wine and Spirits Competition, 2017).

Grapevines, especially the species *Vitis vinifera* L. that is commonly grown for grapes for wine production, are generally grown in narrow climatic bands, in local conditions characterised by a lack of extreme heat and cold (Schultz and Jones, 2010). Grapevines are cultivated on six of the seven continents, across a large diversity of climates; however, the general temperature bounds of suitability for viticulture are found between 12.0–22.0 °C averaged over the seven-month growing season in each hemisphere, which depicts a largely midlatitude (30–50 °N and °S) suitability for winegrape production (Gladstones, 2004; Jones, 2006; Jones and Schultz, 2016).

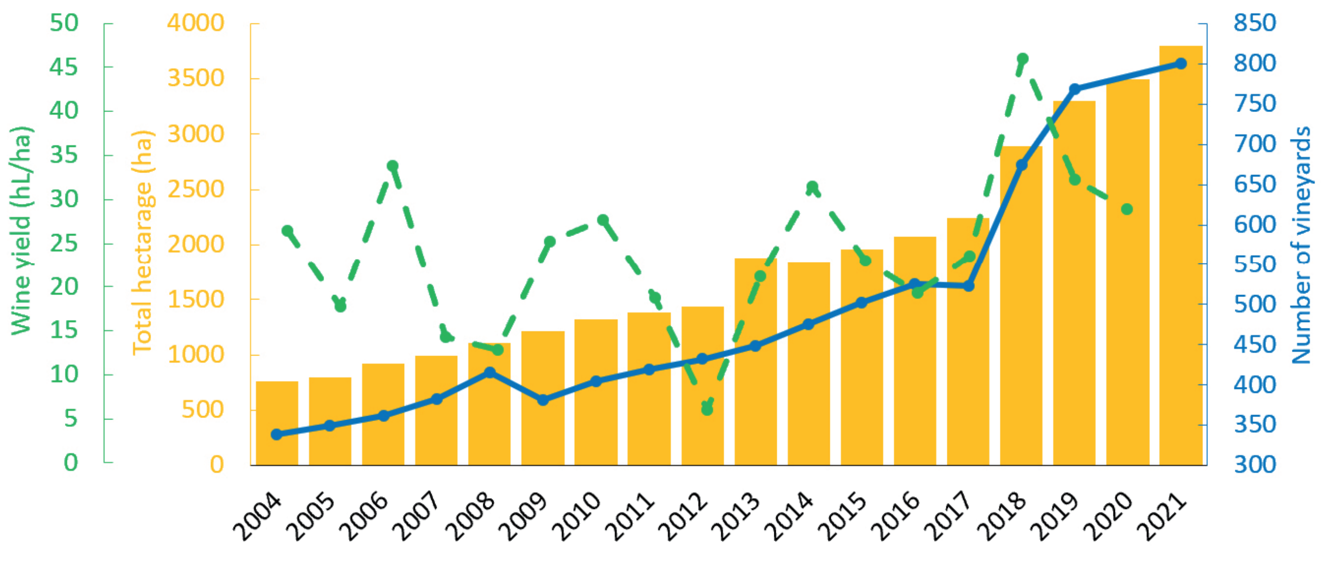

FIGURE 1. 2004–2021 UK vineyard numbers, total hectarage (no vineyard number is available for 2020) and national wine yield (no data is presently available for 2021). Data sources: Skelton (2020), WineGB (2020a), WineGB (2021a) and WineGB (2021b).

On a regional scale, suitability for viticulture is ultimately determined by the effects of mesoscale and local atmospheric processes (Schultz and Jones, 2010; Fraga *et al.,* 2013). Early or late season frost events, wind exposure, a lack of sunlight or water availability, or too much rainfall can all be detrimental to viticulture suitability (Nesbitt *et al.,* 2018). Conversely, where more favourable climate conditions are found and where irrigation, frost and wind protection are not required, the potential for viticulture and the commercial production of favourable grape varieties is likely higher. Within suitable climates, grapevine phenological development, berry composition and yields are influenced by a range of factors, including site-specific geophysical conditions (including soil), variety, clone and rootstock differences, disease and pest pressure, seasonal weather and viticulture management practices. Ultimately though, local and regional climates play significant roles in determining viticulture and variety suitability (Jones *et al.,* 2010; Santos *et al.,* 2012). The sensitivity of *Vitis vinifera* L. to even relatively small changes in the growing-season climate indicates that climate change could alter the current global distribution of winegrape varieties and viticulture (Webb *et al.,* 2013; Tóth and Végvári, 2016).

Varieties and clones selected for UK vineyards require suitability both now and over their lifespan. However, neither the near-term suitability of today's most common UK vine varieties nor opportunities for change in variety mix under climate change scenarios have been assessed. For the first time, we show how projected climate trends and variability in the growing season out to 2040 may support the expansion of still and sparkling wine production opportunities for the UK's most dominant variety—Pinot noir (WineGB, 2020b).

Pinot noir is one of the world's most common red grape varieties, often recognised for its use in Burgundy for high-value still red wine and by Champagne houses to produce sparkling wines. It has been described as the 'ultimate terroir grape' with infinite nuances of expression and a complex array of aromas and flavours (Lewin, 2011). Usually, different clones of Pinot noir are grown to produce still or sparkling wines, although, in some regions, including the UK, clones are sometimes used interchangeably across wine styles. Pinot noir is predominantly grown in the UK for sparkling wine production because achieving adequate ripeness levels for high-quality still red wine has, historically, only been possible in a few locations, in exceptionally warm years such as 2018. As climate change continues, however, Pinot noir clones planted for still red wine may increasingly become consistent performers across a wide UK growing area. Conversely, other more established regions of the world may move out of the bioclimatic range and/or adaptive capacity for reliable production of Pinot noir for still or sparkling wine (Jones and Goodrich, 2008; Tóth and Végvári, 2016). In such circumstances, variety and clonal migration could be further fuelled by market demand.

In this work, we present highly tailored near-term (2021–2040) projections of the UK viticulture climate, accounting for projected changes to bioclimatic indices (BCIs), which constitute essential metrics for supporting current strategic decision-making: Growing Season average Temperatures (GST), Growing Degree Days (GDD), Growing Season Precipitation (GSP), inter-annual variability and early season frost days. Viticulture-climate change studies to date have mainly focused on impacts in long-established and relatively warm and dry viticulture regions of the world, where increasing heat and, in some areas, lower rainfall to drought-like conditions are significant challenges to maintaining wine styles and quality (Jones and Goodrich, 2008; Webb *et al.,* 2008; Tomasi *et al.,* 2011; Neethling *et al.,* 2012; Fraga *et al.,* 2013; Fraga *et al.,* 2014; Hannah *et al.,* 2013; and, Santos *et al.,* 2020). Jones and Schultz (2016) is one example of just a few studies that have paid specific attention to emerging 'cool-climate' viticulture regions, where the nature of future challenges and opportunities may be different.

Future grape-growing BCI values have previously been projected for different areas of the world, but the projections in these studies were commonly derived from just one or two climate models and limited scenario simulations (See examples in Supplementary Information, Table 1).

Multi-model climate ensembles have been applied in a few studies of future viticulture climates. Santos *et al.* (2012) for Douro, Portugal, and Fraga *et al.* (2013) for Europe employed 16 regional climate models. Meanwhile, Cardell *et al.* (2019) used 14 regional climate models for Europe and Webb *et al.* (2013) analysed 23 global climate models of the world's wine-producing regions. Crucially, employing climate model ensembles in such studies allows inherent model biases or uncertainty in climate change projections to be captured and represented (Webb *et al.,* 2013). For Europe, these studies have used both the earlier Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) and the Representative Concentration Pathways (RCPs; van Vuuren *et al.,* 2011), the latter forming the basis of the IPCC Fifth Assessment Report (AR5). Future viticulture climates for areas in Scotland have also recently been modelled at high resolution (Dunn *et al.,* 2019), but future grape growing seasons have not been modelled for the UK as a whole using the Met Office Hadley Centre's UK Climate Projections 2018 (UKCP18), which constitute the most up-to-date and highest resolution multi-model assessment of how the climate of the UK may change over the 21st century (Met Office, 2020b). Using UKCP18 projections, this work presents high resolution (5 × 5 km) future growing season climates and BCIs across the UK. Our focus is on RCP8.5 (defined in Materials and Methods) because progress on emission reductions remains elusive and climate projections are relatively insensitive to the choice of emission scenario in the short-medium term.

The paper is structured as follows. Firstly, we review UK climate viticulture impacts through the lens of the 2012 (wet) and 2018 (warm) seasons, and then we assess HadUK (Met Office *et al.,* 2019) and UKCP18 data suitability to determine any required bias-adjustments to future projections. Projected BCI changes in the UK under RCP8.5 from 1999–2018 to 2021–2040 are then analysed before the focus turns to UKCP18 multi-model GST projections and inter-annual variability out to 2040 for a small cluster of UK vineyards. Finally, we employ an innovative analogue approach, transposing bioclimatic values from the high-quality Pinot noir growing locations and vintages of recent years in Europe to new areas (under projected climate change) as a means of modelling the potential impact of climate change on UK wine styles, wine quality and near-term spatial suitability. The spatial and temporal (means and as 'Years in 20') BCI occurrence are projected across the UK during 2021–2040, consistent with a) the UK's most high-yielding season of 2018, b) 1999–2018 mean BCI values for Champagne (for sparkling wine), Burgundy and Baden (for still wine), and c) recent high-quality Champagne and Burgundy vintages. In so doing, this work identifies areas of the UK with future potential for still and sparkling Pinot noir production.

MATERIALS AND METHODS

1. Bioclimatic indices (BCIs)

BCIs provide simplistic illustrations of viticulture and/or variety suitability (Kenny and Harrison, 1992; Tonietto and Carbonneau, 2004; Hall and Jones, 2010; Anderson *et al.,* 2012). They commonly place numerical or descriptive envelopes around summed or averaged daily or monthly growing-season climate variables to express suitability ranges. They do not necessarily resolve the full range of climatic processes, intra-annual variability, seasonality of weather, or critical daily or hourly timescale events, which can also influence climate-viticulture relationships (Jones *et al.,* 2009). Furthermore, BCI suitability classification envelopes have been derived from observations of varieties in established regions, which may not adequately reflect full variety suitability 'potential' or the adaptive capacity of viticulture through vineyard management techniques (Jones and Storchmann, 2001; Webb *et al.,* 2008; Tomasi *et al.,* 2011). BCIs are, in essence, crude measures of suitability that may mask or overstate true viticulture potential in a specific location. However, notwithstanding their limitations, they have been extensively applied in different regions, over different timescales, at different spatial resolutions and driven by both observed and modelled climate data as a means of depicting variance and broad suitability for viticulture and winegrape varieties. In this work, BCIs are employed to provide comparative spatial and temporal models to illustrate variability, trends and analogues that could affect viticulture suitability in the UK. BCI selection is restricted to those that are more commonly used to represent indicative suitability (Supplementary Information, Table 2): GST (Jones, 2006) and GDD (from which the Winkler Index is derived; Amerine and Winkler, 1944). These are complemented by GSP (Blanco-Ward *et al.,* 2007; Santos *et al.,* 2012; here extended to include October) and mid-March–May air frost frequency, as high values of these two meteorological variables have been previously shown to have a negative impact on UK wine yields (Nesbitt *et al.,* 2016).

The GST 'Cool' climate and the GDD Region Ia (Supplementary Information, Table 2) classifications are representative of BCI values associated with most UK vineyards over the last 30–40-years. In the development of the Winkler Index, used to classify GDD, Amerine and Winkler (1944) did not specify a lower-class limit for Region I or an upper-class limit for Region V. Subsequent research (Jones *et al.,* 2010; Hall and Jones, 2010), using high-resolution spatial climate data, identified these limits for California, Oregon, Washington, Idaho, and Australia. The results provided a lower bound to Region I of 850 GDD and an upper bound to Region V of 2700 GDD. Additional research in other wine regions resulted in Region I being sub-divided into a Region Ia (very early ripening varieties, mostly hybrid grapes) and Region Ib (early ripening varieties, mostly *Vitis vinifera* L.) (Anderson *et al.,* 2012; Jones *et al.,* 2012). The GST 'Cool' climate classification, meanwhile, is broadly representative of viticulture regions with the GST climate-maturity requirements for varieties such as Müller-Thurgau, Pinot Gris and Gewürztraminer and some regions where Riesling, Chardonnay, Pinot noir and Sauvignon Blanc are grown (Jones, 2006).

2. Historical climate data

Few vineyards in the UK have long-term historic site-specific weather data available for analysis. Therefore, Met Office regional monthly average temperature and precipitation data (1981–2020) were used to calculate GST and GSP values for the south-east and south-central England region—where most vineyards are currently located (Figure 2). Anomalies were calculated relative to a 1981–2010 climate normal period (baseline) to quantify and illustrate climate trends and to highlight growing season characteristics in low (2012) and high (2018) yielding years (Figure 3). The 1981–2010 climate normal period has been widely used in climate change research and in previous climate and wine work (Bois *et al.,* 2018; Nesbitt *et al.,* 2018; Dunn *et al.,* 2019; Hewer and Brunette, 2020). Met Office regional monthly average temperature data are derived from station daily means and rainfall data from summed daily station totals, interpolated onto a 5 × 5 km grid before being averaged for a region, enabling a macroclimatic regional analysis of historic growing season conditions (Met Office, 2020a).

We also use HadUK 1 × 1 km gridded data (interpolated from meteorological station data onto a uniform grid; Met Office *et al.,* 2019) to calculate UK BCIs for other specific reference periods (Figures 4, 5, 7 and 8). In addition, we employ the ERA5-Land re-analysis (ECMWF, 2020; Hersbach *et al.,* 2020) as our source of high-resolution gridded European air temperature, with a spatial resolution of ~9 km, to support the calculation of historic GST and GDD values for European viticultural regions (Supplementary Information, Tables 3 and 4, and Figure 1). For equivalent GSP values in Europe, we use historic nearest station measurement data (Infoclimat, 2021).

3. Climate change projections

UKCP18 (Met Office, 2020b; Met Office *et al.,* 2021) provides a set of spatially coherent future climate projections for the globe based on 15 Met Office Hadley Centre model variants: HadGEM-GC3.05 (Perturbed Parameter Ensemble 15 (PPE-15)) and 13 other global climate models/simulations from the CMIP5 multi-model ensemble that was used to inform the IPCC 5th Assessment (CMIP5-13). Regional (Europe) and local (UK only) projections (12 km and 2.2 km spatial resolution, respectively) were downscaled from the global projections (PPE-15) using the Met Office Hadley Centre model: HadREM3-GA705 (to regional level) and then HadREM-GARA11M (to local level), leading to 12 high-resolution simulations in total (Gohar *et al.,* 2018). Only 12 of the PPE-15 were made available through UKCP18 due to computational restrictions and following assessment of model performance against observations in the historical period (Murphy *et al.,* 2018). For the local projections, the original climate model gridded data at 2.2 km spatial resolution had been regridded to 5 km resolution for the British National Grid (Ordnance Survey National Grid) prior to use in this work (Met Office, 2019).

RCP8.5 most closely reflects society's limited response thus far to climate change mitigation, and, as a result, this scenario has been the context for the most detailed climate modelling for the UK undertaken within UKCP18 (at 2.2 km resolution). Hence, to present changes over the near term 2021–2040 period—when climate projections are not very sensitive to emission pathways and emissions are not the largest source of uncertainty—we focus on analysing these 2.2 km projections (using daily values of maximum and minimum temperature and precipitation, regridded to 5 km) for 2021–2040 driven by RCP8.5, and the difference between that period and 1999–2018 (HadUK). UKCP18 does provide a longer-term (2061–2080) time slice, but this is not assessed here because large uncertainties exist around the world's RCP track and response to climate change over this longer timeframe, i.e., there is an opportunity now to change course from this 'high-emissions' or 'business as usual' scenario. The 2021–2040 time horizon is highly relevant to current viticultural decision-making as investment and grower focus is currently on the next 20–30-years. Hence, we assess uncertainties in climate projections by focusing on climate model uncertainty (using a multi-model ensemble) and upon inter-annual climate variability rather than through alternative emission scenarios.

4. Yield data and Pinot noir vintage data

Regional grape yield data for the south-east and south-central England, where most vineyards are located (Figure 2), are not available. Nationally aggregated yield data—the only 'official' wine yield data that is available in the UK—were therefore used to examine the relationship between south-east and south-central England GST and GSP and wine yields in 2012 and 2018. 1989 marks the start of 'official' records of UK wine yields. UK yield data (hL/ha) was obtained from the Wine Standards Branch of the Food Standards Agency via Wines of Great Britain (WineGB, 2020a). The use of national, non-regionally specific yield data could lead to some distortion of climate–yield relationships; however, national yield values were deemed indicative of those in our focus region due to its significant contribution to the total UK vineyard area (74 %; WineGB, 2020b). An analysis of national weather/climate data, meanwhile, would disproportionally include areas where few or no vineyards exist.

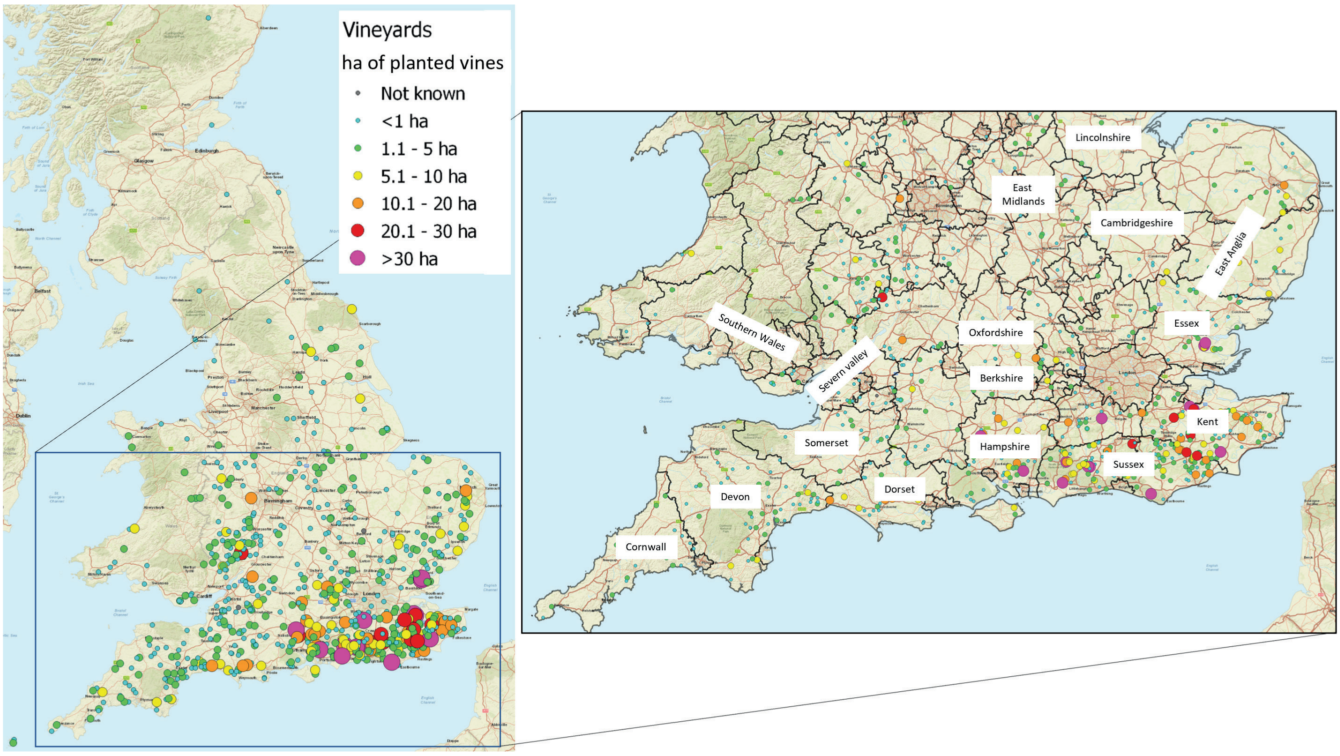

FIGURE 2. UK vineyards and hectarage (ha) 2019. Vineyard data source: Skelton (2020).

Pinot noir is currently the most planted variety in the UK, accounting for approximately 33 % of the vineyard area (WineGB, 2020b). Vineyards in south-east England planted with Pinot noir, and Pinot noir growing vineyard areas in Champagne (Montagne de Reims and Côte des Bar), Burgundy (Côte de Nuits) and Baden were overlain with HadUK (UK) or ERA5-Land (Europe) gridded climate data, or paired with a local weather station (Europe), to extract BCI values for a high UK yielding year (2018) and high-quality European vintage years. In the case of the Montagne de Reims, Côte des Bar, Côte de Nuits and Baden, 1999–2018 mean BCI values were also extracted to provide a 20-year average of the growing season climate. These European areas were selected as analogue regions because they are globally recognised for their high-quality Pinot noir production (Lewin, 2011) while also in close geographical proximity to the UK, relative to Oregon (U.S.A.) or Otago (New Zealand), for example.

To define and select historic high-quality vintages from the Champagne and Burgundy regions of France (the former to evaluate reliability/resilience of sparkling wine production, the latter to evaluate the potential transition to still red Pinot noir in the UK), vintage ratings or scores were obtained from independent sources. Less vintage rating information has so far been released for post-2015 vintages and no single source of information has overall authority on the designation of a 'high-quality' vintage. As such, high-quality vintage years from the 1996–2015 20-year period were derived from ratings by commercial and individual 'experts': from Decanter Magazine's Vintage Guides (Decanter, 2020); Jancis Robinson (Robinson, 2020); Berry Bros & Rudd (Berry Bros and Rudd, 2021); Wine Spectator (Wine Spectator, 2020), and Robert Parker: The Wine Advocate (Parker, 2020). It is accepted as a limitation of this work that subjectivity around vintage ratings exists, that regional ratings may be skewed by classification ratings, and that vintage ratings may change with time. For this study, only two of the best vintages from each region—those with the highest scores, best score classification or highest descriptive rating from at least three out of the five selected sources (Supplementary Information, Table 3)—were selected and used as analogue years from which BCI occurrence was simulated in the UK under projected climate change.

5. Modelling suitable years in 20

Intra- and inter-annual weather variability can drive grape production and quality parameters beyond 'acceptable' vintage variation bounds. 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. As an additional dimension to our analysis, we hypothesise that, particularly in the UK's relatively marginal climate (Kenny and Harrison, 1992; Nesbitt *et al.,* 2016), vulnerability to weather variability is a limiting factor to viticulture viability, at annual or longer timescales. Through this work, investment and variety adaptation decisions are also, therefore, meaningfully guided by the frequency of bioclimatic values akin to those of 2018, over a 20-year period (2021–2040), as well as by projected averages.

6. Vineyard location data

ArcGIS (ESRI, 2020) was used for climate data and vineyard location integration and as a rapid means of spatial analysis at high resolution. No 'official' database of UK vineyard locations nor size (ha) was publicly available. The UK Vineyards List (Skelton, 2020), although not independently verified, was deemed the most reliable and up-to-date (November 2020) source. Postcodes from this list, however, were often found to relate to premises and not precise vineyard locations, so, to maximise model accuracy, individual vineyards in south-east England (≥1 ha) were visually located utilising Google Earth (Google, 2020). Once located, the presence of Pinot noir grape production in the vineyards was confirmed with producers (through online material or personal correspondence). Coordinates (British National Grid) of approximate vineyard centres were imported as point features into ArcGIS to enable an analysis of their growing season climates when overlain with HadUK and UKCP18 gridded BCI data layers. The BCI data were imported into ArcGIS as Network Common Data Form (NetCDF) files.

European vineyard areas were mapped using the CORINE landcover data (Copernicus, 2020; which omits UK vineyards) and integrated into ArcGIS. Specific vineyard areas in the Montagne de Reims, Côte des Bar, Côte de Nuits and Baden, where Pinot noir grapes of international renown are grown, were identified using guides and maps from Lewin (2011) and Johnson and Robinson (2001). An illustration of the mapped European vineyard areas, gridded ERA5-Land climate data overlay, and the employed data extraction process is shown in Supplementary Information, Figure 1. Data were not extracted from grid cells in which only very small areas of viticulture existed.

RESULTS

1. Vulnerability of the UK viticulture sector to current climate variability

Annual GST and GSP for the south-east and south-central England region (the dominant viticulture areas; Figure 2) for 1989–2020 are presented in Figure 3, expressed as anomalies relative to a 1981–2010 average baseline of 13.6 °C and 421 mm, respectively. There was an even split (16 of 32-years) of positive and negative GSP anomalies, although twice as many growing seasons (8) were > 20 % drier than wetter (4). Of the 32 growing seasons, 21 were warmer than the GST baseline, and 16 of these occurred since 2000. Of these 21, 16 were > 14.0 °C GST, which is 1.0 °C above the 13.0 °C climate-maturity baseline for 'cool climate' wine production, as provided in the groupings set out in Supplementary Information, Table 2 (Jones, 2006). Indeed, the peak in 2006 of 15.1 °C just reached the 'intermediate' climate maturity classification (15.0–17.0 °C GST; Jones, 2006), which constitutes the climate-maturity

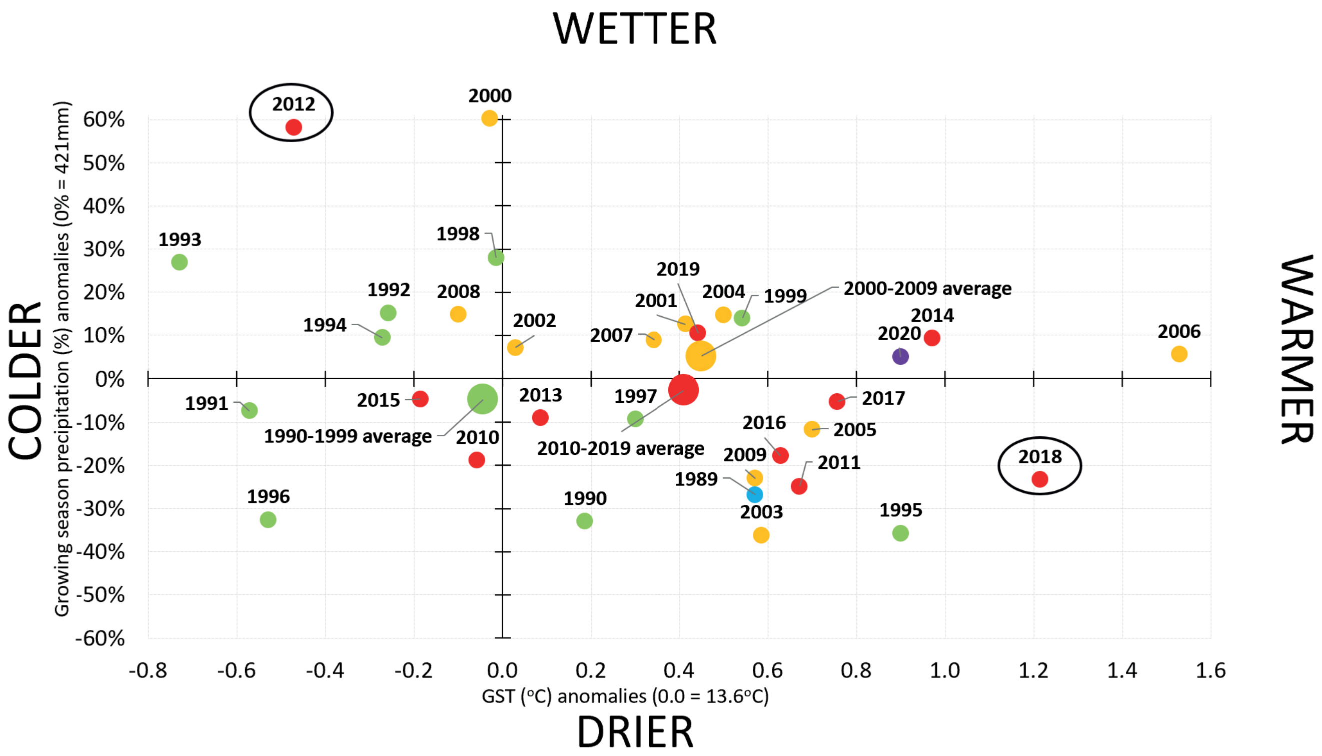

FIGURE 3. South-east and south-central England Growing Season Precipitation (GSP, y-axis) and Growing Season Temperature (GST, x-axis) anomalies for 1989–2020 relative to 1981–2010 means of 421 mm and 13.6 °C, respectively. Blue dot: 1989, Green: 1990–1999, Orange: 2000–2009, Red: 2010–2019, and Purple: 2020. Data source: Met Office (2020a).

threshold for a wider selection of commercially popular grape varieties: Pinot Gris, Gewürztraminer, Riesling, Pinot noir, Chardonnay, Sauvignon Blanc, Semillon and Cabernet Franc.

Correlations in this same geographical region between growing season weather variables, acute/extreme events and UK wine yields have previously been explored, and their relationships with high inter-annual yield variability documented (Nesbitt *et al.,* 2016). The lowest UK wine yield on record (6 hL/ha) was recorded in 2012 (Figure 1) and was attributed to wet and cold weather during flowering and fruit set. Conversely, 2018 was an outlier which saw the UK's highest wine yield of 48 hL/ha (Figure 1; WineGB, 2020a) following an exceptionally dry and warm season (Figure 3).

The larger green dot in Figure 3 shows the 1990–1999 10-year average anomaly, which is closely aligned to the 1981–2010 mean. However, the larger orange and red dots (2000–2009 and 2010–2019 means, respectively) show a shift in GST to 0.4–0.5 °C warmer decades than the baseline period. In the last two decades, the growth in UK vineyard numbers (Figure 1) has happened alongside this increase in growing season temperatures.

2. HadUK and UKCP18 data suitability

The suitability of UKCP18 projections for application in this study was evaluated through a bias assessment between modelled (UKCP18) and observed (HadUK) gridded historic (20-yr mean) data for the UK (Figure 4—right-hand panels). The bias assessment was undertaken using ESRI ArcGIS (resampling HadUK to a 5 × 5 km grid and employing the Spatial Analyst Map Algebra function to calculate biases; ESRI, 2020). UKCP18 1981–2000 GST minus HadUK GST for the same period yielded a spatial mean UKCP18 bias of -0.3 °C (i.e., a cold bias; range: -3.2 to 3.5 °C). The UKCP18 GDD mean bias was -22 GDD (range: -332 to 898 GDD). In the dominant viticulture areas (Figure 2) of south-east and south-central England, the GST bias range was circa -0.5 to 0.3 °C and the GDD bias range circa -100 to 50 GDD (Figures 4a and 4b). The UK-wide comparison between UKCP18 and HadUK 1981–2000 GSP revealed a -9.7 mm GSP mean bias (i.e., a dry bias; range: -774 to 474 mm). The GSP mapped bias generally ranges from 50 mm to -100 mm (10 to -15 %) in the dominant viticulture areas (Figure 4d). Mid-March to May Air Frost days were higher in the UKCP18 model for the 1981–2000 period, with a mean UK bias of 0.9 days (i.e., a cold bias). The bias range in south-east and south-central England was circa ± 3 days. Subsequently, UKCP18 values used in this study have been subjected to spatially dependent bias-adjustments using ESRI ArcGIS Data Management and Spatial Analyst tools.

Figure 4a highlights a recent warming in the observational record of ~1 °C GST in much of south-east and eastern England (Cambridgeshire and East Anglia) between the 1981–2000 and 1999–2018 periods, a shift which has been one of the key enablers for growth and variety change in the UK viticulture sector over this time interval, significantly

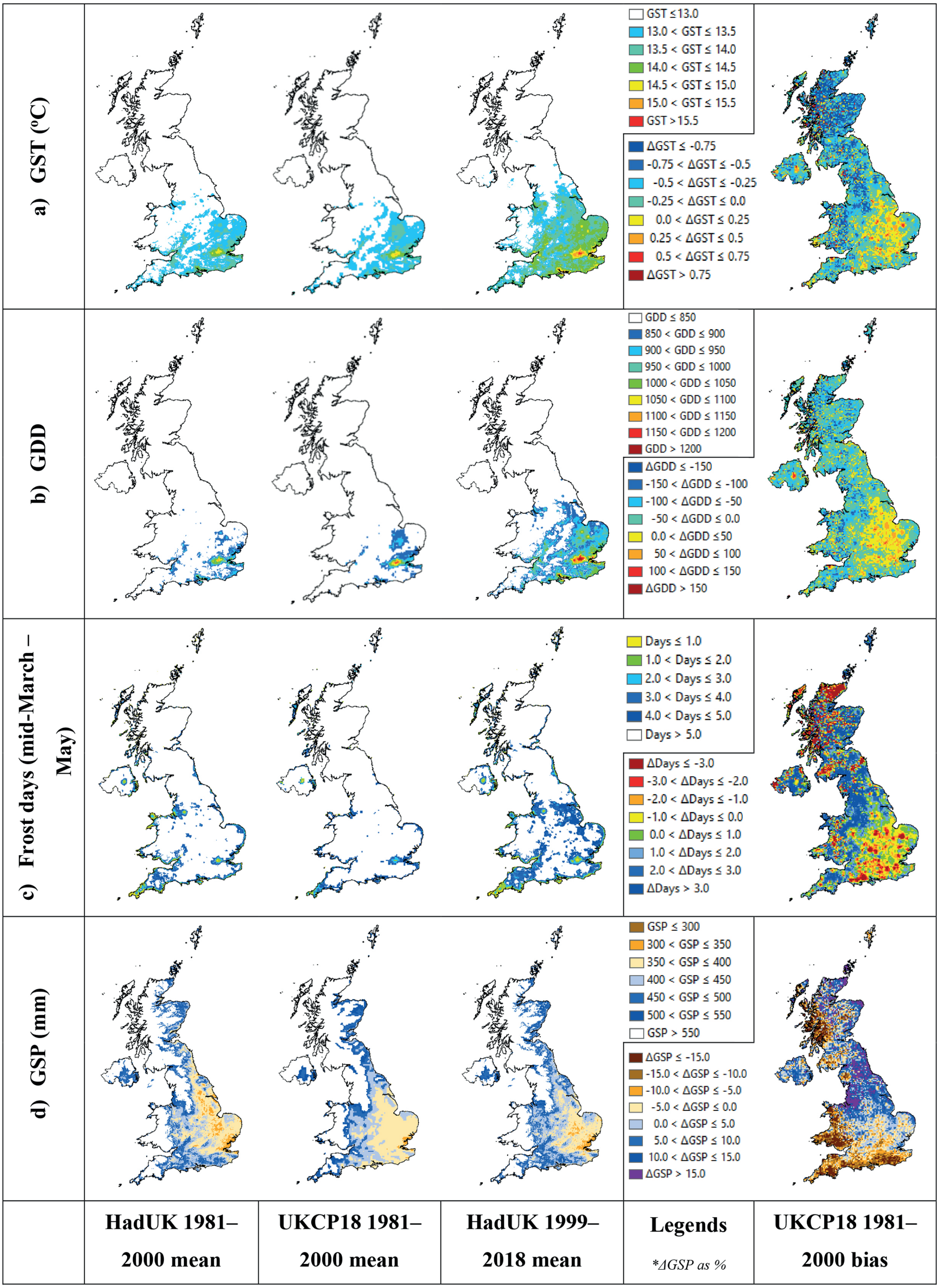

FIGURE 4. HadUK 1981–2000 (left; 1 × 1 km), UKCP18 multi-model mean 1981–2000 (centre left; 5 × 5 km), HadUK 1999–2018 (centre right; 1 × 1 km), UKCP18 multi-model mean bias 1981–2000 (right; 5 × 5 km). (a) GST (°C), (b) GDD, (c) Air Frost days and (d) GSP (mm/%).

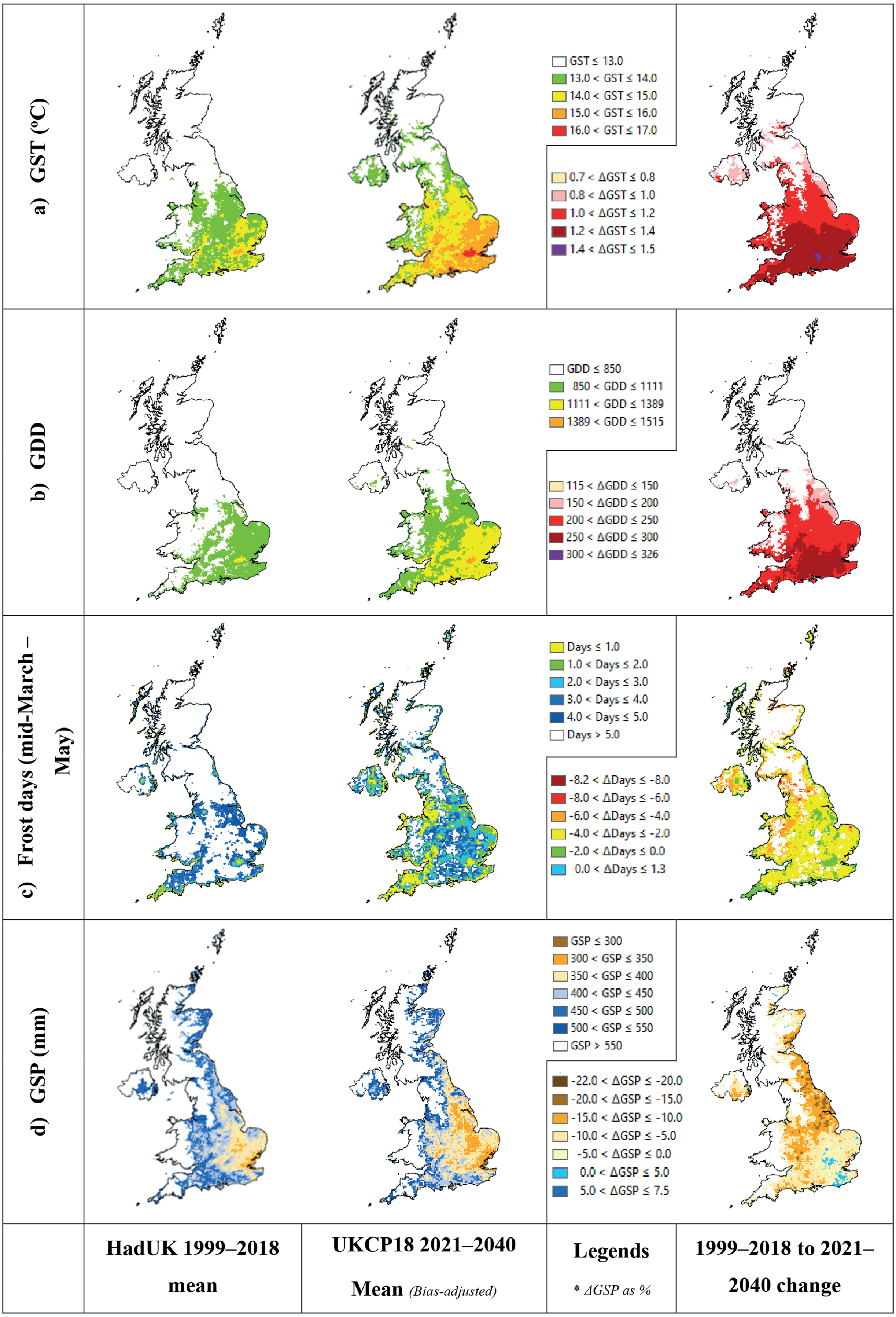

FIGURE 5. Recent (left: HadUK 1999–2018, 1 × 1 km), projected (centre: UKCP18 2021–2040, ensemble mean, RCP8.5, 5 × 5 km) and change from 1999–2018 to 2021–2040 (right—resampled to 5 × 5 km) for (a) GST (°C), (b) GDD, (c) Air Frost days and (d) GSP (mm/%) in the UK.

expanding the area within the 'cool climate' GST and Region Ia GDD (Figure 4b) classifications (Supplementary Information, Table 2). Over the same time, Air Frost days during the sensitive mid-March to end of May season have become less common but have remained a hazard everywhere (Figure 4c). Meanwhile, trends in GSP are less homogeneous and impactful in the main UK viticulture regions: south-east England has, in general, become marginally drier by 1–50 mm during the growing season and areas of south-central England and East Anglia marginally wetter by a similar amount (Figure 4d).

Comparing the 1981–2000 and 1999–2018 periods shown in Figure 4, based on the gridded 1 km HadUK dataset, the following points are apparent:

While the area where mean GST > 14.0 °C is confined to the Greater London region during 1981–2000, this area expanded significantly and rapidly in the 1999–2018 period to embrace substantial parts of East Anglia, south-east and south-central England and the River Severn Valley (Figure 4a). These same areas see mean GDD increasing from 850–900 in the most suitable local areas during 1981–2000 to 1000–1050 (or even higher) in the most favoured locations by 1999–2018 (Figure 4b). The (white) area in Figure 4c recording, on average, > 5 days of air frost during the mid-March to end of May period clearly shrinks over much of England from the earlier to the later period, although the more inland areas remain more vulnerable to air frosts. Of course, bud heights are typically lower (0.5–1.0 m) than air frost measurements (1.5 m), and so bud vulnerability to cold air damage is higher than indicated here. Growing Season Precipitation is never insufficient for viticulture in either the 1981–2000 or 1999–2018 periods, however, the 2012 vintage showed, for example, that very wet seasons can be disastrous for yields.

3. Projected bioclimatic changes in the UK under RCP8.5 from 1999–2018 to 2021–2040

The evidence of recent warming during the growing season in south-east and south-central England and recent rapid growth of the sector illustrates the impact of climate change on viticulture viability. Future UK climate change may further impact viability, variety suitability, and wine style potential. Figure 5 shows the projected 20-year multi-model mean BCI changes in the UK under RCP8.5 from 1999–2018 (HadUK) to 2021–2040 (UKCP18; bias-adjusted).

Literature suggests that high-quality Pinot noir wines come from grapes grown in regions spanning 'cool' to 'intermediate' climates with GST that range between 14.0 and 16.0 °C, e.g., Champagne, Northern Oregon and Burgundy (Jones *et al.,* 2005). These regions have been documented as having average GDD of 923, 1081 and 1118, respectively, during the 1950–2000 period (Jones *et al.,* 2009; Anderson *et al.,* 2012). In Figure 5, we can see that significant areas within England and Wales are projected to become warmer during the growing season over the next 20-years and fall within the GST suitability range for Pinot noir, as well as for other widely known varieties such as Sauvignon Blanc, Riesling and Semillon, which are scarcely grown in the UK at present. In the dominant grape-growing regions of south-east and south-central England, GST are projected under RCP8.5 to increase by up to 1.4 °C and GDD by 300 (Figure 5a and b, respectively) to a 15.0–16.0 °C GST 'Intermediate' range and 1111–1389 GDD 'Region Ib' range. We can also see significant GST and GDD increases in areas thus far relatively 'untapped' for their viticulture potential, for example, within Cambridgeshire, Oxfordshire, Berkshire, the East Midlands, the Severn Valley, Southwest England, and Southern Wales (Figure 2).

Precipitation during the growing season is projected to decline over the next 20-years by 10 % across much of southern and eastern England and decline up to 15 % in southern Dorset, Devon and parts of Cornwall, areas where too much GSP has previously been a key climatic challenge for viticulture (Figure 5d). Meanwhile, parts of south-eastern and central England are projected to see a small precipitation increase of up to 5 % during the growing season. In some areas where projected temperature increases indicate the bottom end of cool-climate viticulture potential, such as Northern Ireland and southern Scotland, projected growing season rainfall remains high at 400 mm or more, and possibly prohibitively so (Dunn *et al.,* 2019). However, within these regions, there are areas where projected precipitation ranges are similar to those currently found in existing grape-growing areas of southern England. In parts of Cambridgeshire, Oxfordshire, Berkshire, Hampshire, eastern England (Essex and Suffolk in particular) and much of south-central England (Figure 2), GSP is projected to decline to below 350 mm (~17 % lower than the 421 mm 1981–2010 average for south-east and south-central England (Figure 3)). The full impacts of reduced rainfall remain unqualified as they depend on soil water holding capacity, evapotranspiration rates and, critically, the seasonal distribution of rainfall. However, 10 of the 32-years plotted in Figure 3 had GSP values less than 350 mm without any recorded water deficit issues. Indeed, the highest UK wine-yield year on record (2018) recorded a GSP of 323 mm in south-east and south-central England, demonstrating that lower rainfall during 2021–2040 need not be limiting in terms of grape yields or quality.

Early season air frosts have historically been a significant challenge for UK grape-growers during the sensitive budburst period (Nesbitt *et al.,* 2016), when sub-zero temperatures can damage emerging buds and young shoots, leading to crop and potential quality loss. Notwithstanding the potential for frost protection adaptation measures, and although somewhat subjective, many areas of England and Wales have been deemed too 'frosty' during mid-March–May (> 5-days; Figure 5c) for reliable viticulture. Figure 5c shows projected reductions in the occurrence of early-season air frosts under RCP8.5 by 2–6-days in many areas of England, Wales and Northern Ireland, bringing them into the occurrence range in which many existing UK vineyards are presently established. However, it should be noted that where frost protection is not present and/or where a vineyard location is prone to cold air accumulation or advective frost occurrences, a single freeze event could still cause significant damage.

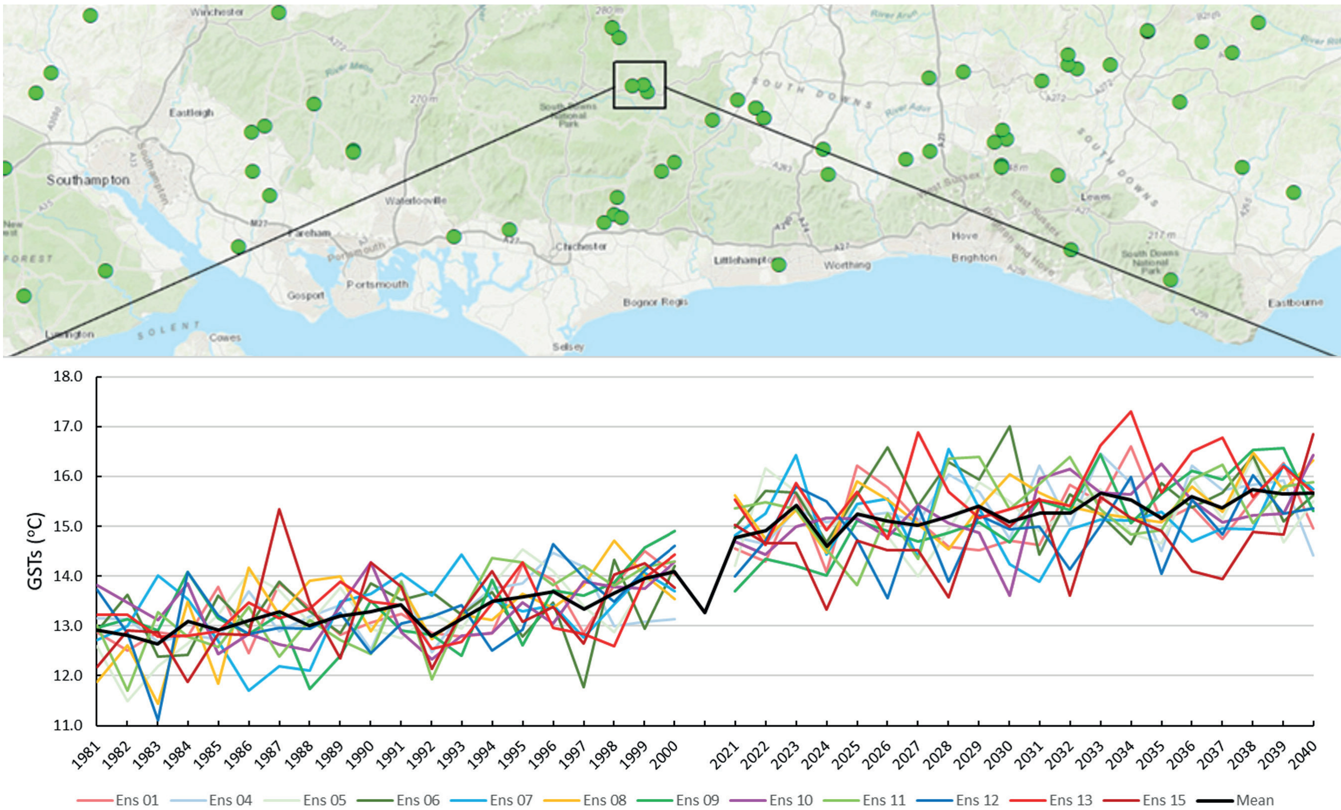

FIGURE 6. UKCP18 downscaled and bias-adjusted climate model simulations (×12) and ensemble mean GST for 1981–2000 (left) and 2021–2040 (right) for a single 5 × 5 km grid cell encompassing several vineyards (green dots) in south-east England, showing both ensemble spread and inter-annual variability.

Therefore, any location with > 0 Air Frost Days remains at some degree of risk. Where budburst occurs earlier in response to warming spring temperatures, the frost risk period will likely advance, and while major phenological changes may not occur in this study's time frame (to 2040), this may not be the case later in the century.

4. UKCP18 climate model simulations' range of annual GST projections and inter-annual variability out to 2040 for a cluster of UK vineyards

The UKCP18 multi-model 12-member ensemble means for 2021–2040, presented in Figure 5, do not reveal the ensemble range and, therefore, the associated model uncertainty, nor the inter-annual variability, which is so critical to viticulture (Nesbitt *et al.,* 2016). To illustrate these important outputs, Figure 6 presents bias-adjusted GST from the 12 simulations (see Methods—Climate Change Projections section), as well as the ensemble means for each year during 1981–2000 and 2021–2040 for a single 5 × 5 km grid cell in southern England, in which a cluster of established vineyards are located.

A positive GST trend is clear both between and within periods for all simulations. Nevertheless, considerable inter-annual variability looks to remain a consistent feature of the UK viticulture climate.

When the UKCP18 bias-adjusted GST of all years and all 12 ensemble members for this single grid cell are viewed in the form of box and whisker plots (Supplementary Information, Figure 2), the ensemble range, inter-annual variability and projected GST increase are further highlighted. Mean GST rises by over 2 °C (13.3–15.3 °C GST) from 1981–2000 to 2021–2040, and the interquartile range increases from 12.8–13.8 to 14.8–15.7 °C GST, within the previously defined 14.0–16.0 °C GST maturity thresholds for Pinot noir (Jones, 2006).

5. Projected spatial and temporal repetition (No. of years in 20) during the 2021–2040 period of the UK's most high-yielding season of 2018

2018 was a year that produced exceptional yields and grape quality across most of the UK's grape-growing regions (WineGB 2020a). BCI values derived from HadUK grid cells (1 × 1 km) overlain onto 97 vineyards (> 1 ha) producing Pinot noir (predominantly for sparkling wine) in south-east England show that GST during 2018 ranged from 14.1–15.5 °C, GDD from 974–1223 and GSP between 273–449 mm. Based on the bias-adjusted UKCP18 12-member ensemble for individual years during 2021–2040 (n = 12 × 20 = 240), the number of years when these BCI ranges are projected to occur was calculated (Figure 7).

Figures 7a–c show that during 2021–2040 large areas of central, southern and eastern England are projected to have GST, GDD and GSP within the ranges that occurred in vineyard localities in south-east England in 2018, in more

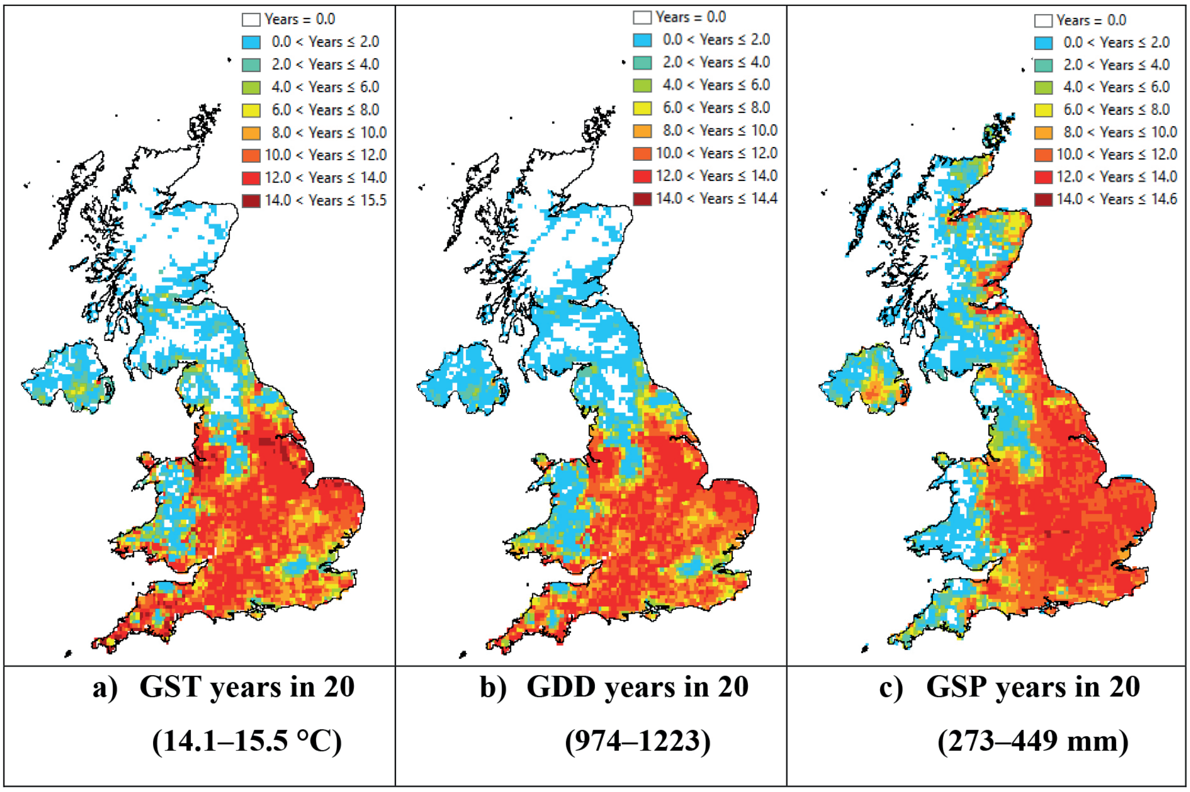

FIGURE 7. The projected years in 20 repetitions in the UK during 2021–2040 of 2018 BCI ranges (a—GST; b—GDD; c—GSP) derived from HadUK 1 × 1 km grid cells overlain with Pinot noir producing vineyards in south-east England.

[Note that London and Greater London are often outside the upper end of this temperature range].

than 10-years out of 20. Furthermore, areas in East Anglia, Cambridgeshire, Lincolnshire, south-central England, north-east Wales and coastal areas in south-west England and southern Wales are projected (under RCP8.5) to have 2018 GST and GDD ranges during 2021–2040 in 60–75 % of years during 2021–2040 (Figures 7a and b). Much of England and areas of eastern Scotland are projected to have 50 % or more years during 2021–2040 within the 2018 rainfall range (273–449 mm; Figure 7c).

6. Spatial occurrence in the UK, during 1999–2018 and 2021–2040, of the 1999–2018 mean BCI values for Champagne and for Burgundy and Baden

Mean BCI values for 1999–2018 in the Champagne, Burgundy and Baden regions are presented in Supplementary Information, Table 4. The GSP values for 1999–2018 are sourced from a set of weather stations for which a complete record was available for the period and which are within or near the regions of interest. They provide a useful indication of the 20-year mean GSP within the regions, but we acknowledge they are not fully representative of the GSP spatial variability across these areas. Lack of GSP is not a viticulture limiting climatic variable in the UK and nor is it projected to be so during the next 20-years, even allowing for likely enhanced evapotranspiration as a function of positive air temperature trends. The main viticulture areas in the UK and areas that are projected to fall within temperature-based BCI ranges of Baden and Burgundy during 2021–2040 (Figure 8) are projected (under RCP8.5) to have a GSP of 300–450 mm during 2021–2040 (Figure 5c), with a mean which is close to the 1999–2018 Champagne average but lower than that for Burgundy and Baden (where warm-season convective downpours are more common).

Therefore, in this work, only the GST and GDD temperature-based BCI 20-year mean values in Supplementary Information, Table 4, were used as analogue ranges (from across all grid cells) to define areas in the UK which satisfy their requirements under both current (1999–2018) and bias-adjusted UKCP18 multi-model ensemble 2021–2040 conditions (Figure 8).

For 2021–2040, large areas of eastern, south-eastern and south-central England are projected to fall within the 1999–2018 mean GST and GDD ranges of Baden (Germany) and Champagne (France). Parts of south-east Wales, Somerset and central England are also included in these bioclimatic ranges. Mean 1999–2018 BCI values found in the main Pinot noir producing areas of the Burgundy region have a narrower range of GST (15.4–15.9 °C) and GDD (1216–1307). When projected over the UK for the 2021–2040 period, these ranges cover both rural and urban areas in Cambridgeshire, Essex, Greater London, Kent and Sussex, coastal Hampshire and in the Severn Valley. These findings indicate that in terms of GST and GDD, at least, there could be increased potential for still Baden and Burgundy style Pinot noir production within the UK in the near term.

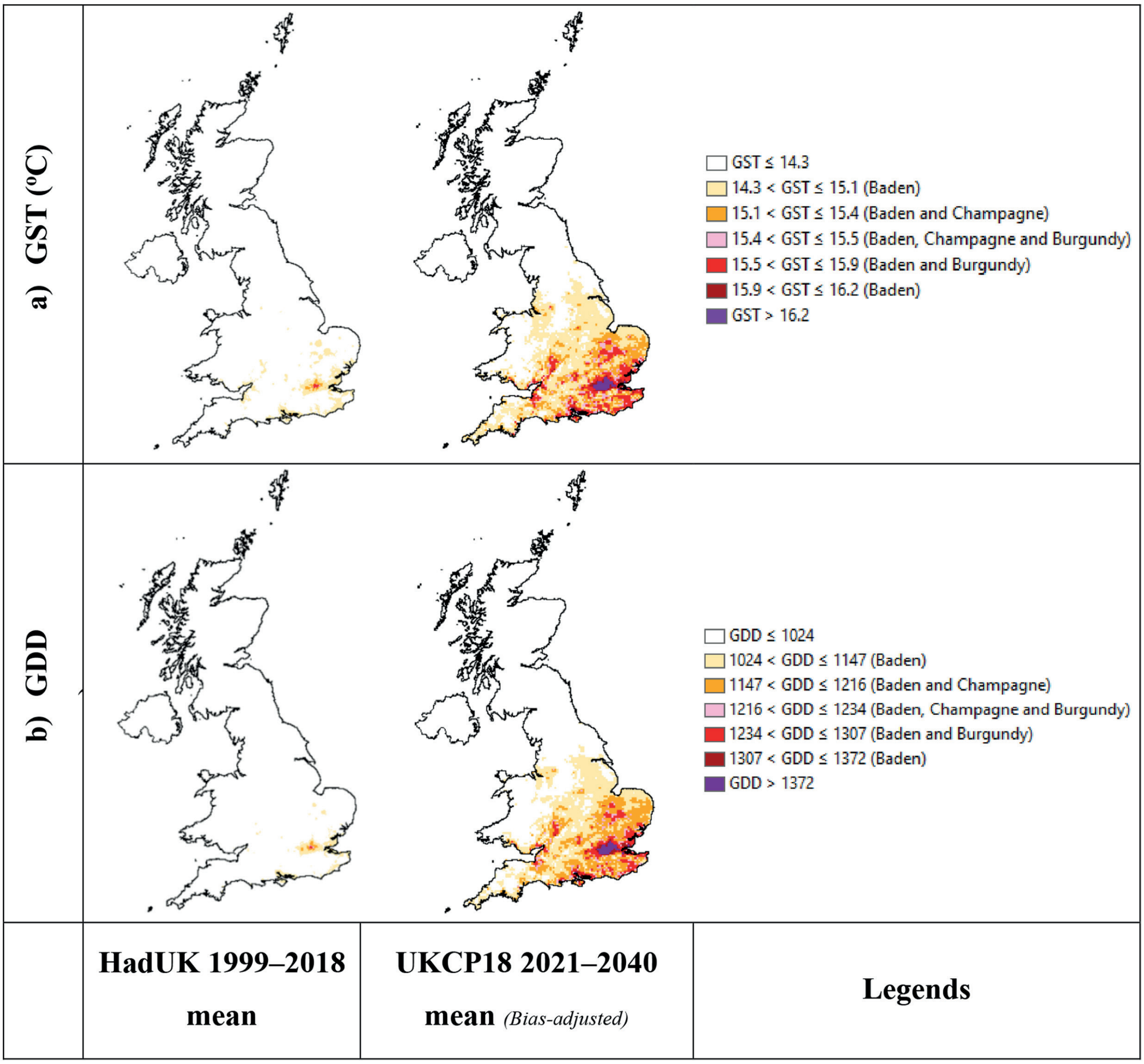

FIGURE 8. Burgundy, Baden (still Pinot noir) and Champagne (sparkling Pinot noir) 20-year (1999–2018) mean BCIs (a—GST; b—GDD) projected onto the UK, 1999–2018 (left, HadUK), 2021–2040 (right, bias-adjusted UKCP18 ensemble mean).

7. Projected spatial occurrence in the UK, during 2021–2040, of BCI values from high-quality Champagne (for sparkling wine) and Burgundy (for still wine) vintages

Table 1 summarises ‘expert’ scores for high-quality Champagne (2008 and 2012) and Burgundy (2005 and 2015) vintages over the period 1996–2015. Another year, 1996, was also rated as a high-quality Champagne vintage, but ‘ratings’ were not available from all ‘experts’. Pinot noir wines from Baden were not included in this vintage assessment or analogy as there were fewer published and reliable vintage results available for the region from the same ‘expert’ sources.

The BCI values in which such exceptional vintages were realised are presented in Supplementary Information, Table 3.

The two regional sets of vintage BCI ranges provide analogues to define spatial BCI patterns in the UK when applied as the projected years in 20 repetitions during 2021–2040 of top-quality vintage Champagne and Burgundy years as shown in Figure 9.

Figures 9a and 9b show increasing area in England and Wales, shifting northwards and westwards in the near future, where GST and GDD indicate suitability for high-quality sparkling Pinot noir wine grape growing in > 5 years out of 20 (25 % of years). However, the GST and GDD of exceptional red Burgundy vintages (2005 and 2015), which have very similar growing season average (GST) and accumulated (GDD) temperatures, are only projected to be occasionally achieved, in 5–10 % of years, over very restricted, favoured areas (Figures 9c and 9d).

What is also striking is that large parts of south-eastern England, where Pinot noir is currently grown for sparkling wine production, are projected to have 2021–2040 mean GST

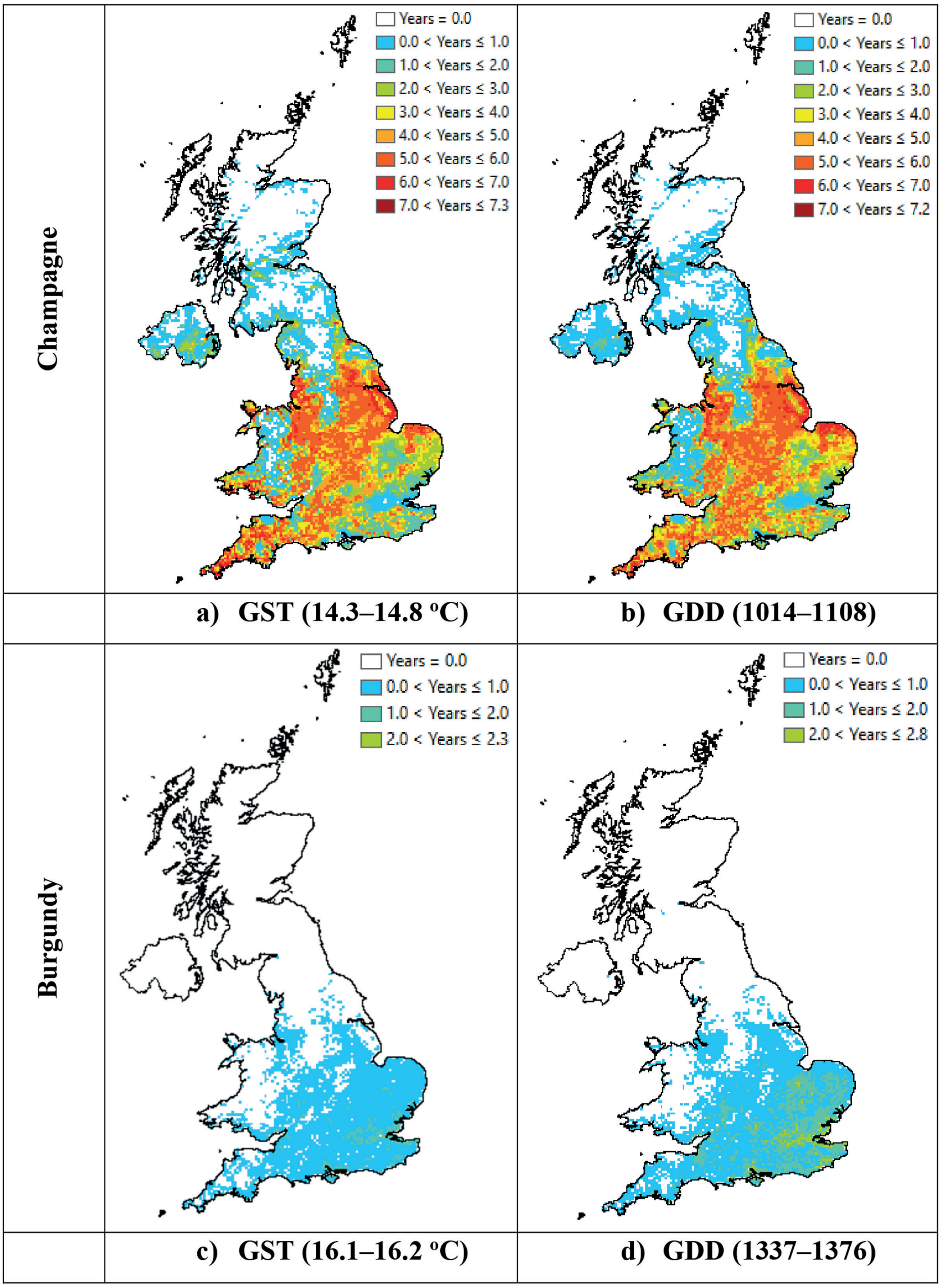

FIGURE 9. The projected years in 20 repetitions in 2021–2040 of high-quality Champagne (a & b) and Burgundy (c & d) vintage ranges (a & c—GST; b & d—GDD) (bias-adjusted UKCP18 12 × 20 multi-model ensemble).

and GDD (Figures 5 and 9) above those during the highest quality sparkling wine-producing years in Champagne and shift closer to the Burgundy 1999–2018 means (Figure 8), i.e., they could become reliable still red wine production areas within the next 20-years and only in cooler years would 'conditions' similar to high-quality Champagne vintages occur. As shown in Figure 5d, the projected mean GSP within these regions during 2021–2040 is 300–450 mm. This is within the high-quality Burgundy and Champagne GSP totals. However, seasonal GSP totals do not provide a full illustration of the relative rainfall climates.

DISCUSSION

The results of this work demonstrate that the UK viticulture growing season has warmed dramatically over the last few decades (~1 °C in the main viticulture regions; Figures 3 and 4), and whilst UK wine yields have historically been low and very variable (Figure 1; Nesbitt *et al.,* 2016), production in warmer and drier years such as 2018 (Figures 1 and 3) has been very encouraging. The projected frequent repetition of 2018 GST (up to 15.5 °C in some vineyard areas) and GDD (up to 1223; Figure 7), in the near term,

TABLE 1. Vintage Champagne and Burgundy years.

	Vintage	Decanter (out of 5)	Jancis Robinson (non-numerical score)	Berry Bros & Rudd (1 = poor; 10 = outstanding)	Wine Spectator (95–100 = classic; 90–94 = outstanding)	Robert Parker (90–95 = outstanding; 96–100 = extraordinary)
Champagne	2008	5	'Initially, a difficult, damp year with widespread mildew; drier conditions in August and a fine, warm September proved many producers' saving grace. Classically styled wines with fresh acidity balanced by sound ripeness achieved late in the season.'	10	97	99
	2012	5	'An exceptional vintage in Champagne. Despite low yields thanks to frost, hail and disease early in the season, August saw conditions improve dramatically, resulting in exemplary maturity, acidity and grape health at harvest.'	9	95	96
Burgundy	2005	5	'As in Bordeaux, a quite exceptionally good vintage, although many wines may go through a prolonged stage of chewy adolescence.'	10	98	98
	2015	5	'Low yields and warm weather allowed for ample ripeness, small berries and an early harvest. Quality is looking extremely fine, with some people whispering comparisons with the outstanding 2005 vintage. Acid levels in individual wines may be crucial.'	9	98	98

will be welcome news to many UK wine producers because higher yields (2018 UK average yield: 48 hL/ha) and grape quality parameters indicate greater climatic suitability. Figure 5 presented the projected GST and GDD temperature increases (1.2–1.4 °C and 200–300 GDD) and a reduction in GSP in many temperature-suitable areas over the next 20-years, especially in south-central and eastern England. A small increase in GSP is modelled for parts of south-east and central England, but the projected 2021–2040 GSP values for much of southern and eastern England (300–450 mm) are not modelled as being limiting to viticulture as they are within the range of high yielding and quality years such as 2018 (323 mm) and high-quality Champagne and Burgundy vintages (364–423 mm). One of the limitations of this work is that by applying a 7-month seasonal precipitation total (GSP) and growing season temperature averages and accumulation, we do not uncover the intra-seasonal patterns of rainfall and temperature, which also play important roles in grape berry physiology, development and ultimate quality (Schultz and Jones, 2010). Nevertheless, within a 20-year period, there are projected to be 'better' and 'worse' grape growing seasons in the UK, as in other wine-producing regions of the world (Kenny and Harrison, 1992; Jones *et al.,* 2005; Jones *et al.,* 2012), and where seasonal ranges are analogous to other regions or vintages the potential for higher yields and high quality exists. Using an analogue approach, we demonstrate that Champagne region grape growing temperatures from 1999 to 2018 are projected to 'occur' in large areas of England and some areas in the far south and south-east of Wales during 2021–2040. Whilst it is difficult to place an upper suitability threshold on growing season average temperatures or temperature accumulation for Pinot noir grapes destined for sparkling or still wine production, the upper end of the mean 1999–2018 Champagne region GST was 15.5 °C (as was the 2018 bumper year in the UK; Figure 7)/1234 GDD and 14.8 °C/1108 GDD for top-quality vintages. The lower end of the mean 1999–2018 Burgundy (still Pinot noir) GST range was 15.4 °C/1216 GDD and 16.1 °C/1337 GDD for top-quality vintages. Mean 1999–2018 temperatures in Baden span the Champagne and Burgundy range. Figures 5a and 5b indicate a shift, under RCP8.5 in 2021–2040, particularly in south-eastern and eastern England, into a suitable range for Pinot Noir production. Whilst Pinot noir for sparkling wine has been successfully grown previously in the UK, the projected growing season temperature increases indicate the new and increasing opportunity for still Pinot noir production in some areas. Our results suggest in certain years, a few areas of the UK may see seasons similar to those that contributed to the best vintages of Champagne in the last 20-years (Figure 9).

Warmer and drier growing seasons in the UK may also reduce chronic risks, such as poor flowering due to high rainfall and/or mildew-based disease pressure and open up large new areas demonstrating good potential for viticulture. In particular, areas currently with little viticulture, such as Cambridgeshire, Oxfordshire, Berkshire, the East Midlands, the Severn Valley, south-western coastal regions and Southern Wales, are likely to see increasing opportunities (Figures 5, 7 and 8). Further warming of growing seasons over the next 20-years may also present greater opportunity for alternative grape varieties such as Sauvignon Blanc; increased opportunity for Chardonnay—the other widely planted variety in the UK—to be produced as a still white wine; greater potential for still rosé wine production; or, as presented in this work, clones of Pinot noir that are specifically suitable for still red wine production (Figures 8 and 9). Early season frost events (days with air frosts) are projected to decrease within most existing viticulture areas over the next 20-years; however, warming spring temperatures will likely advance budburst, potentially expanding the risk period for air frosts. Hence, in this work, the residual frost risk under near-term climate change remains unquantified and frost mitigation remains important.

Our results, derived from the latest UK climate model ensemble (UKCP18), driven by one high RCP (8.5), indicate that, despite inherent climate model uncertainty (shown in Figure 6), there is further opportunity for those involved with or considering investing in UK viticulture, from a climatic suitability perspective alone. However, our results also indicate the challenge of establishing wine identities and brands, in particular those tightly associated with varieties and wine styles, in a rapidly changing climate—one that both affords and increasingly requires variety and wine style flexibility.

The results in this paper are derived from a limited number of bioclimatic indices, which do not illustrate the intra-seasonal patterns or consider all extremes that play an important role in vintage variability in terms of yields, grape and wine quality (Jones and Goodrich, 2008). Nor are they likely, at the analysed resolution, to depict all the nuances of micro-climates from which a vineyard may be affected. Nevertheless, the chosen BCIs allow for local and regional comparisons of averaged or summed growing season temperatures and rainfall and critically offer a coarse but valuable analogue tool from which climate change trends and potential impacts can be modelled. Where the aim is to provide broad climatic suitability indicators within a limited time horizon, the small number of BCIs employed provides a useful means of doing this. Finer temporal and spatial analysis can be complemented with terrestrial suitability modelling (Nesbitt *et al.,* 2018).

CONCLUSION

Climate change impacts on wine style and quality have received little attention in the UK. Wine style, and specifically wine quality of a particular style, form the basis of the reputation of different producers, regions and vintages (Jones *et al.,* 2005; Tesic *et al.,* 2008; Briche *et al.,* 2014). Therefore, climate change impacts on variety suitability, wine style and potential wine quality are, in our experience, the very impact assessment that wine producers and investors value most.

Our approach attempts to address this gap for the UK by integrating: (1) an ensemble of the latest climate change models driven by one RCP (8.5; into which the climate system is locked in the near-term); (2) high-resolution projections for the next 20-years (2021–2040; within the expected lifespan of existing and new UK vine plantings); (3) an analogue approach for a viticulture area where climate change presents an opportunity. The 2021–2040 time horizon is of particular interest to the expanding UK viticulture sector because decisions about what and where to plant now benefit from climate change projections to help avoid future potential lock-in. Pinot noir's global reach and, in particular, its use by high-value wine producers in Burgundy, famous Champagne houses and in much English Sparkling Wine make it an attractive variety for which to model UK viticulture-climate suitability through climate analogues. Furthermore, although this is not a study that considers soils or other influences on grape quality or production parameters, it is interesting to note that Pinot noir for still and sparkling wines in the UK is grown on a range of rootstocks and different soil 'types' (Nesbitt *et al.,* 2018), including chalk-based soils similar to the Champagne region, and limestone and clay-based soils more similar to those found in Burgundy and Baden. Although we focus on Pinot noir, one of the other key findings of this work is that in the near-term, climate change may also afford the opportunity for the success of other varieties such as Sauvignon Blanc, Riesling and Semillon or more disease-resistant varieties that are not yet commonly grown in the UK.

In the context of climate change and viticulture, the potential UK transition is immense as well as rapid; from the greater suitability of cooler-climate varieties (Reichensteiner, Seyval Blanc and Müller-Thurgau) in the 1990s to varieties for sparkling wine (Chardonnay, Pinot noir and Pinot Meunier) in the first couple of decades of the 2000s and to still red wine production (and other still varieties) by 2040. Furthermore, a 50-year change from minor scale viticulture to a significant commercial viticulture area (~4000 ha)—producing high-quality sparkling, rosé, white and red wines—significantly alters the world wine map and clearly demonstrates the opportunity for viticulture migration. The very nexus that facilitated this 'transition'—climate change—may continue to provide opportunities for, and maybe even necessitate, further variety and/or wine style change. This may, of course, come at the expense of areas with hundreds or thousands of years of production history in more established viticultural regions of the world, for which climate change presents a more immediate threat. Where growing seasons within these regions become too warm, too dry, or where vintage variability goes beyond variety capacity, even with adaptation buffers, climate change may present a threat to variety suitability and wine styles on which regions have developed unique viticultural and wine identities.

Whilst variety and wine styles are relatively entrenched in some regions, the UK still has comparative flexibility to define the styles of wine that best suit current and future climates and to market wines accordingly.

Through successes with sparkling wines, the UK wine production sector has shown itself well-positioned to respond to recent climatic opportunities in viticulture. However, the strong focus on sparkling wine production (circa 72 % of overall wine production; WineGB, 2020b), which informs wine production strategy, branding, price points and market position, may lead to sector lock-in and entrenchment under future climate change scenarios and could place additional pressure on the supply and demand matrix. Maximising future opportunities will require a broader response, for example, overcoming barriers to achieving still wine market penetration. This runs counter to the focus of the UK's wine sector branding strategy, which is presently focused around sparkling wines, with many reputational gains and investments at the sector and business level focused here. As more established wine-producing regions are looking at ways to increase flexibility in terms of production processes and variety permissions, the UK will need to limit lock-in occurring in the first place, to maintain a climate-agile sector.

ACKNOWLEDGEMENTS

This paper is from the **C**limate **RE**silience in the **UK W**ine **S**ector (**CREWS-UK**) project (https://www.lse.ac.uk/granthaminstitute/resilient-wine/) funded by the UK Natural Environment Research Council (Grant number NE/S016848/1) as part of the UK Climate Resilience Programme (https://www.ukclimateresilience.org). D. Conway and K.E. Gannon are also supported by funding from the Grantham Foundation for the Protection of the Environment and the UK Economic and Social Research Council (ES/R009708/1) through the Centre for Climate Change Economics and Policy.

The authors also thank Wines of Great Britain (WineGB) for their support of this project through data provision and sector engagement opportunities.

REFERENCES

Amerine, M.A., & Winkler, A. (1944). Composition and quality of musts and wines of California grapes. *Hilgardia,* 15(6), 493-673. https://doi.org/10.3733/hilg.v15n06p493

Anderson, J. D., Jones, G. V., Tait, A., Hall, A., & Trought, M. C. T. (2012). Analysis of viticulture region climate structure and suitability in New Zealand. *OENO One,* 46(3), 149-165. https://doi.org/10.20870/oeno-one.2012.46.3.1515

Berry Bros and Rudd (2021) Chart giving an indication of the quality of recent vintages in the world's key wine regions. https://www.bbr.com/vintages

Blanco-Ward, D., García Queijeiro, J., & Jones, G. (2007). Spatial climate variability and viticulture in the Miño River Valley of Spain. *Vitis,* 46(2), 56-70. https://doi.org/10.5073/vitis.2007.46.63-70

Bois, B., Joly, D., Quénol, H., Pieri, P., Gaudillère, J.-P., Guyon, D., Saur, E., & van Leeuwen, C. (2018). Temperature-based zoning of the Bordeaux wine region. *OENO One*, 52(4). https://doi.org/10.20870/oeno-one.2018.52.4.1580

Briche, E., Beltrando, G., Somot, S., & Quenol, H. (2014). Critical analysis of simulated daily temperature data from the ARPEGE-climate model: application to climate change in the Champagne wine-producing region. *Climatic Change*, 123, 241-254. https://doi.org/10.1007/s10584-013-1044-5

Cardell, M.F., Amengual, A., & Romero, R. (2019). Future effects of climate change on the suitability of wine grape production across Europe. *Regional Environmental Change*, 19, 2299-2310. https://doi.org/10.1007/s10113-019-01502-x

Copernicus (2020). *Corine Land Cover (CLC) 2018, Version 2020_20u1* [Dataset]. https://land.copernicus.eu/pan-european/corine-land-cover/clc2018

Decanter (2020). *Vintage Guides*. https://www.decanter.com/learn/vintage-guides/

Dunn, M., Rounsevell, M.D.A., Boberg, F., Clarke, E., Christensen, J., & Madsen, M, S. (2019). The future potential for wine production in Scotland under high-end climate change. *Regional Environmental Change,* 19, 723-732. https://doi.org/10.1007/s10113-017-1240-3

ECMWF (2020). European Centre for Medium-Range Weather Forecasts. *ERA5* [Dataset]. https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

ESRI (2020). *ArcGIS Desktop: Release version 10.8.1*. [Computer software]. Environmental Systems Research Institute. https://www.esriuk.com/en-gb/arcgis/products/arcgis-desktop/overview

Fraga, H., Malheiro, A.C., Moutinho-Pereira, J., & Santos, J.A. (2013). An overview of climate change impacts on European viticulture. *Food and Energy Security*, 1(2), 94-110. https://doi.org/10.1002/fes3.14

Fraga, H., Malheiro, A.C., Moutinho-Pereira, J., Jones, G.V., Alves, F., Pinto, J.G., & Santos, J.A. (2014). Very high resolution bioclimatic zoning of Portuguese wine regions: Present and future scenarios. *Regional Environmental Change*, 14(1), 295-306. https://doi.org/10.1007/s10113-013-0490-y

Gladstones, J.S. (2004). Climate and Australian Viticulture. In: Dry, P.R., & B.G. Coombe, B.G. (Eds.), *Viticulture 1 – Resources* (pp. 255). Winetitles.

Gohar, L., Bernie, D., Good, P., & Lowe, J. (2018). *UKCP18 Derived Projections of Future Climate over the UK*. Met Office. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Derived-Projections-of-Future-Climate-over-the-UK.pdf

Google (2020). *Google Earth Pro: Version 7.3.4.8248 (64-bit)* [Computer software]. Google. https://earth.google.com/web/

Hall, A., & Jones, G.V. (2010). Spatial analysis of climate in winegrape-growing regions in Australia. *Australian Journal of Grape and Wine Research*, 16(3), 389-404. https://doi.org/10.1111/j.1755-0238.2010.00100.x

Hannah, L., Roehrdanz, P.R., Ikegami, M., Shepard, A.V., Shaw, M.R., Tabor, G., Zhi, L., Marquet, P.A, & Hijmans, R. (2013). Climate change, wine, and conservation. *Proceedings of the National Academy of Sciences*, 110(17), 6907-6912. https://doi.org/10.1073/pnas.1210127110

Hersbach, H., Bell, B., Berrisford, P., Hirahara, A., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M. ... Thépaut, J. (2020) The ERA5 Global Reanalysis. *Quarterly Journal of the Royal Meteorological Society,* 146*,* 1999-2049. https://doi.org/10.1002/qj.3803

Hewer, M.J., & Brunette, M. (2020). Climate change impact assessment on grape and wine for Ontario, Canada's appellations of origin. *Regional Environmental Change,* 20(86). https://doi.org/10.1007/s10113-020-01673-y

Infoclimat (2021). Climatologie globale [dataset]. https://www.infoclimat.fr/climatologie/globale/mois-de-mars/reims-champagne/07070.html

International Wine and Spirits Competition (2017). *English wines awarded record number of medals at IWSC.* https://www.iwsc.net/news/iwsc/english-wines-awarded-record-number-of-medals-at-iwsc

Johnson, H., & Robinson, J. (2001). *The World Atlas of Wine* (5th edition). Mitchell Beazley.

Jones, G.V. (2006). Climate and Terroir: Impacts of Climate Variability and Change on Wine. In: Macqueen, R.W., & Meinert, L.D. (Eds.), *Fine Wine and Terroir: The Geoscience Perspective* (pp. 203-216). Geological Association of Canada.

Jones, G.V., & Storchmann, K.H. (2001). Wine market prices and investment under uncertainty: An econometric model for Bordeaux Crus Classés. *Agricultural Economics,* 26(2), 115-133. https://doi.org/10.1016/S0169-5150(00)00102-X

Jones, G.V., & Goodrich, G.B. (2008). Influence of climate variability on wine regions in the Western USA and on wine quality in the Napa Valley. *Climate Research*, 35(3), 241-254. https://doi.org/10.3354/cr00708

Jones, G.V., White, M.A., Cooper, O.R., & Storchmann, K. (2005). Climate change and global wine quality. *Climatic Change,* 73(3), 319-343. https://doi.org/10.1007/s10584-005-4704-2

Jones, G.V., Moriondo, M., Bois, B., Hall, A., & Duff, A. (2009). Analysis of the spatial climate structure in viticulture regions worldwide. *Office International de la Vigne et du Vin. Bulletin: revue internationale,* 82, 507-518.

Jones, G.V., Hall, A., Duff, A., & Myers, J. (2010). Spatial analysis of climate in winegrape growing regions in the western United States. *American Journal of Enology and Viticulture,* 61(3), 313-326.

Jones, G. V., Reid, R., & Vilks, A. (2012). Climate, grapes, and wine: Structure and suitability in a variable and changing climate. *The Geography of Wine: Regions, Terroir and Techniques,* 9789400704, 109-133. https://doi.org/10.1007/978-94-007-0464-0_7

Jones, G.V. & Schultz, H.R. (2016). Climate change and emerging cool climate wine regions. *Wine & Viticulture Journal*, 31(6): 51–53.

Kenny, G.J., & Harrison, P.A. (1992). The effects of climate variability and change on grape suitability in Europe. *Journal of Wine Research,* 3(3), 163-183. https://doi.org/10.1080/09571269208717931

Lewin, B. (2011). *In search of Pinot noir*. Vendange Press.

Met Office (2018). *Chance of summer heatwaves now thirty times more likely.* https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2018/2018-uk-summer-heatwave

Met Office (2019). *UKCP18 Factsheet: UKCP Local (2.2km) Projections*. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-factsheet-local-2.2km.pdf

Met Office, Hollis, D., McCarthy, M., Kendon, M., Legg, T., & Simpson, I. (2019). *HadUK-Grid Gridded Climate Observations on a 1km grid over the UK, v1.0.1.0 (1862-2018). Centre for Environmental Data Analysis,* [dataset]. http://dx.doi.org/10.5285/d134335808894b2bb249e9f222e2eca8

Met Office (2020a). *Climate and climate change: UK and regional series*. https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-and-regional-series

Met Office (2020b). *About UKCP18*. https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/about

Met Office, Kendon, E., Short, C., Pope, J., Chan, S., Wilkinson, J., Tucket, S., Bett, P. & Harris, G. (2021). Update to UKCP Local (2.2km) projections. *Met Office*. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/ukcp18_local_update_report_2021.pdf

Murphy, J., Harris, G., Sexton, D., Kendon, E., Bett, P., Clark, R., …, & Yamazaki, K. (2018) UKCP18 Land Projections: Science Report. Met Office. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Land-report.pdf

Neethling, E., Barbeau, G., Bonnefor, C., & Quénol, H. (2012). Change in climate and berry composition for grapevine varieties cultivated in the Loire Valley. *Climate Research*, 53(2), 89-101. https://doi.org/10.3354/cr01094

Nesbitt, A., Kemp, B., Steele, C., Lovett, A., & 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. *Australian Journal of Grape and Wine Research*, 22, 324-335. https://doi.org/10.1111/ajgw.12215

Nesbitt, A., Dorling, S., & Lovett, A. (2018). A suitability model for viticulture in England and Wales: opportunities for investment, sector growth and increased climate resilience. *Journal of Land Use Science,* 13(4), 414-438. https://doi.org/10.1080/1747423X.2018.1537312

Parker, R. (2020) Chart giving an indication of the quality of recent vintages in the world's key wine regions. From *The Wine Advocate Vintage Guide.* https://www.robertparker.com/resources/vintage-chart

Robinson, J. (2020). *Vintages*. Jancis Robinson. https://www.jancisrobinson.com/learn/vintages

Santos, J., Malheiro, A., Pinto, J., & Jones, G.V. (2012). Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. *Climate Research*, 51, 89-103. https://doi.org/10.3354/cr01056

Santos, J. A., Fraga, H., Malheiro, A. C., Moutinho-Pereira, J., Dinis, L.-T., Correia, C., & Moriondo, M. (2020). A Review of the Potential Climate Change Impacts and Adaptation Options for European Viticulture. *Applied Sciences*, 10(9), 3092. http://dx.doi.org/10.3390/app10093092

Schultz, H.R., & Jones, G.V. (2010). Climate induced historic and future changes in viticulture. *Journal of Wine Research*, 21, 137-145. https://doi.org/10.1080/09571264.2010.530098

Skelton, S. (2020). *Vineyards in the UK, the Republic of Ireland and the Channel Islands; UK Vineyards List.* [dataset]. http://www.englishwine.com/vineyards.htm

Tesic, D., Woolley, D.J., Hewett, E.W., & Martin, D.J. (2008). Environmental effects on cv Cabernet Sauvignon (*Vitis vinifera* L.) grown in Hawke's Bay, New Zealand: 1. Phenology and characterisation of viticultural environments. *Australian Journal of Grape and Wine Research,* 8(1), 15-26. https://doi.org/10.1111/j.1755-0238.2002.tb00207.x

Tomasi, D., Jones, G.V., Giust, M., Lovat, L., & Gaiotti, F. (2011). Grapevine Phenology and Climate Change: Relationships and Trends in the Veneto Region of Italy for 1964-2009. *American Journal of Enology and Viticulture*, 62(3), 329-339. https://doi.org/10.5344/ajev.2011.10108

Tonietto, J., & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and Forest Meteorology*, 124(1-2), 81-97. https://doi.org/10.1016/j.agrformet.2003.06.001

Tóth, J.P., & Végvári, Z. (2016). Future of winegrape growing regions in Europe. *Australian Journal of Grape and Wine Research*, 22(1), 64-72. https://doi.org/10.1111/ajgw.12168

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., & Rose, S.K. (2011). The representative concentration pathways: An overview. *Climatic Change*, 109(1), 5-31. https://doi.org/10.1007/s10584-011-0148-z

Webb, L.B., Whetton, P.H., & Barlow, E.W.R. (2008). Modelled impact of future climate change on the phenology of winegrapes in Australia. *Australian Journal of Grape and Wine Research,* 13(3), 165-175. https://doi.org/10.1111/j.1755-0238.2007.tb00247.x

Webb, L.B., Watterson, I., Bhend, J., Whetton, P.H., & Barlow, E.W.R. (2013). Global climate analogues for winegrowing regions in future periods: Projections of temperature and precipitation. *Australian Journal of Grape and Wine Research*, 19(3), 331-341. https://doi.org/10.1111/ajgw.12045

WineGB (2020a). *Hectarage & production: 1975 onwards* [dataset]. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.winegb.co.uk%2Fwp-content%2Fuploads%2F2020%2F09%2FUK-vineyards-data-1975-.xlsx&wdOrigin=BROWSELINK

WineGB (2020b). *2020 Industry report: Great Britain's wine industry – a bright future.* https://www.winegb.co.uk/wp-content/uploads/2020/10/Survey-Report-2020-FULL-FINAL.pdf

WineGB (2021a). *Industry Press Briefing*. https://www.winegb.co.uk/wp-content/uploads/2021/09/WineGB-Industry-Press-Briefing-2021-final-002.pdf

WineGB (2021b). *Wine industry of Great Britain 2021: Latest figures.* https://www.winegb.co.uk/wp-content/uploads/2021/07/Preliminary-industry-stats-June-2021-with-infographics.pdf

Wine Spectator (2020). *Ratings: Vintage charts*. https://www.winespectator.com/vintage-charts