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

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

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Abstract

UK viticulture is benefitting from climate change with increase in vineyard area and a move towards French grapevine varieties, primarily Chardonnay and Pinot Noir, to produce sparkling wine. Doubt remains, however, as to how good UK still wine can be from these varieties. The simple Chablis vintage model uses only three climatic indices: mean temperature from April to September; mean minimum temperature in September (cool night index); and total rainfall from June to September. It was applied to the UK for the periods 1981-2000, 2010-19 and, with climate change projections, to 2040-59, to locate sites in the UK with the climate potential to produce high-quality Chardonnay still wine. Weather data for 1981-2000 and 2010-19 were taken from the Met Office's HadUK-Grid at a resolution of 5 x 5 km and climate projections for 2040-59 were derived from UKCP18, using intermediate emission scenario RCP 4.5 at the 5th, 50th and 95th percentile probabilities. Recent and current climatic conditions throughout most of the UK were unsuitable for sustainable production of high-quality still Chardonnay wine (only 0.2 to 1.8 % of UK land area suitable), but model scores corresponded with high-quality Chardonnay still wine production observed in some regions of England in 2018. Under the 5th percentile RCP 4.5 projection for 2040-59, climatic conditions are similar to 2010-19 and generally unsuitable for sustainable high-quality still Chardonnay wine production. Under the median and 95th percentile projections for 2040-59, however, South East England and East of England have the potential for high-quality still Chardonnay wine production in an average year; and Central England also with the 95th percentile projection. Overall, climate change is expected to benefit the production of high-quality still

Chardonnay wine in the medium-term, with up to 42.4 % of UK land possibly climatically (but not necessarily agronomically) suitable by mid-century. The model does not account for extreme events, however, and there is uncertainty over future inter-annual weather variability, and so the sustainability of high-quality still wine production. Planting Chardonnay clones suitable for both sparkling and still wines in the most-suitable areas of England would provide flexibility and so resilience.

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

Introduction

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

Climate change has already benefitted viticulture in England and Wales (Nesbitt *et al.*, 2018), with a fivefold increase in vineyard hectarage from 2004 (761 ha; Food Standards Agency, n.d.) to 2021 (approximately 3800 ha; WineGB, 2021). This has been accompanied by a move away from hardy German grape varieties that are suited to the coldest possible climates under which grapes can grow, such as Muller-Thurgau, towards French varieties such as Chardonnay, Pinot Noir and Pinot Meunier that require warmer growing season temperatures (Ashenfelter and Storchmann, 2016; Nesbitt *et al.*, 2019). Chardonnay is one of the most popular white wine grape varieties, accounting for around 6.7% (332,000 hectares) of all vineyards worldwide (Easton, 2015). It can produce popular 'everyday' wines as well as some of the greatest wines that fetch some of the highest prices at auction.

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

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

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

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

The Chablis vintage model is an empirical model of inter-annual variation in Chablis vintage quality (Biss and Ellis, 2021). It estimates vintage quality of still Chardonnay wine as a function of mean temperature from April to September (curvilinear relation, maximum score at 16–17 °C), mean minimum temperature in September (cool night index (*CNI*) during ripening; negative relation), and total rainfall from June to September (from around flowering and fruitset to harvest; negative relation). That model is applied here to identify climatically suitable sites for the production of still Chardonnay wine in the UK for the periods 1981-2000, 2010-19 and out to 2040-59 in order to understand the potential for producing high-quality still Chardonnay wine in the UK. No consideration of soils, topography, or viticultural and winemaking skill is made as part of this paper.

Method

1. The Chablis vintage model

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

$$\text{(Equation 1) Vintage Score} = 22.38\ Tmean_{Apr\text{-}Sep} - 0.6790\ Tmean_{Apr\text{-}Sep}^{2} - 0.4089\ CNI - 0.006918\ P_{Jun\text{-}Sep} - 170.9$$

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

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

2. Applying the Chablis vintage model to the UK

2.1 UK weather data

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

The HadUK-Grid data was obtained at a resolution of 5 km x 5 km (Met Office *et al.*, 2020) for i) the 20-year period from 1981 to 2000, which is the reference period for climate change projections in the UK, and ii) annually from 2010 to 2019, and loaded into a QGIS Geographical Information

System (QGIS; QGIS Association, http://www.qgis.org). It comprised monthly measurements for mean temperature (°C), mean minimum temperature (°C), mean maximum temperature (°C), and total precipitation (mm). These values were used to calculate, in QGIS, the three climate indices needed for the Model (summarised by administrative region in Table 1) and then to map UK climate suitability for 1981 to 2000 (the base period), 2010 to 2019 (recent decade), 2012 and 2018 (the worst and best vintages of the recent decade, respectively) (Robinson, 2022).

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

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

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

2.2 UK climate projections

UK climate projections for the period 2040 to 2059, using RCP 4.5 emissions scenario, were obtained from the Met Office UKCP18 dataset (Met Office, n.d.[a]) for each administrative region; see Fung *et. al.* (2018) for a discussion of the data caveats and limitations. UKCP18 is the most recent set of climate projections offered by the UK Met Office, providing probabilistic projections using a perturbed parameter ensemble (PPE) of many different variants of the HadCM3 climate model. The data comprised projected absolute changes, by month, in mean air temperature (for calculation of $Tmean_{Apr\text{-}Sep}$), minimum air temperature (for calculation of *CNI*), and percentage change in precipitation (for calculation of $P_{Jun\text{-}Sep}$), from the base reference period of 1981 to 2000. For each of these variables, three thousand samples were extracted and the 5^{th}, 50^{th} (median) and 95^{th} percentile probability changes calculated (Table 2).

Table 2. RCP 4.5 projections (UKCP18) at the 5^{th}, 50^{th} and 95^{th} percentile probability for changes in climate indices ($Tmean_{Apr\text{-}Sep}$, *CNI* and $P_{Jun\text{-}Sep}$) from 1981-2000 to 2040-59, by administrative region. Projections for Scotland are calculated as the mean of East Scotland and West Scotland only, excluding North Scotland.

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

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

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

The RCP 4.5 pathway was selected because it is an intermediate greenhouse gas emissions scenario and also because the range in projected values for increase in mean summer temperature to 2040-59 for England and Wales (+0.3 °C and +3.2 °C at the 5th and 95th percentiles, respectively) exceed those of RCP 2.6 (+0.5 °C and + 3.1 °C) and the other intermediate UK scenario RCP 6.0 (+0.3 °C and + 3.0 °C) (Table S1) (Met Office, n.d.[b]). Thus RCP 4.5 covers a greater range of possible climate scenarios. The period 2040 to 2059 was chosen to reflect the investment horizon of a new vineyard planted over the current decade, given it takes approximately 4 years for a new vineyard to achieve full cropping production and the expected productive life of a vine is around 30 years (Skelton, 2020a).

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

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

2.3 Two estimates of CNI

We questioned the extent to which *CNI* will rise as projected (see Results). As such, for each of the three percentile probability projections (5%, 50%, 95%), two estimates of *CNI* were applied to calculate vintage score. The first assumed *CNI* would change according to UKCP18 projections (Table 2). An alternative value (*CNI2*) was calculated in proportion to that for the change in *CNI* and the change in $Tmean_{Apr\text{-}Sep}$ that occurred between 1981-2000 and 2010-19 (see Results 1.1). Hence *CNI2* assumed the recent historic relationship between the two indices would continue, and we used the UKCP18 projection for $Tmean_{Apr\text{-}Sep}$ for its calculation (Equation 2):

(Equation 2)

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

3. UK vineyards and county data

In the Results and the Discussion, reference is made to several current UK vineyards. Details of these vineyards were extracted from Skelton (2020b), which includes details of 895 vineyards (total 3,494.9 hectares). The postcode locations of 819 of these UK vineyards (totalling 3,380 hectares) were successfully geocoded into QGIS using the MMQGIS plugin (Figure 1). A number of these postcodes relate to company premises rather than exact vineyard locations (Nesbitt *et al.*, 2018), but this was not considered a material issue given the 5 x 5 km resolution of this study (compared to Nesbitt *et al.* (2018) who investigated site suitability at a considerably higher spatial resolution (50 x 50 m)).

The UK vineyards dataset was used to assess the suitability of existing vineyard land and, as a first approximation, to generate data at the county scale. To do this, the vineyards were grouped into counties and then the various climate indices and potential vintage scores sampled on the QGIS maps and weighted as a proportion of each vineyard's size to the total vineyard area in that county. In this way, mean county data was generated based on existing vineyard locations, but not overly affected by small vineyards in unusual (for example, urban) settings.

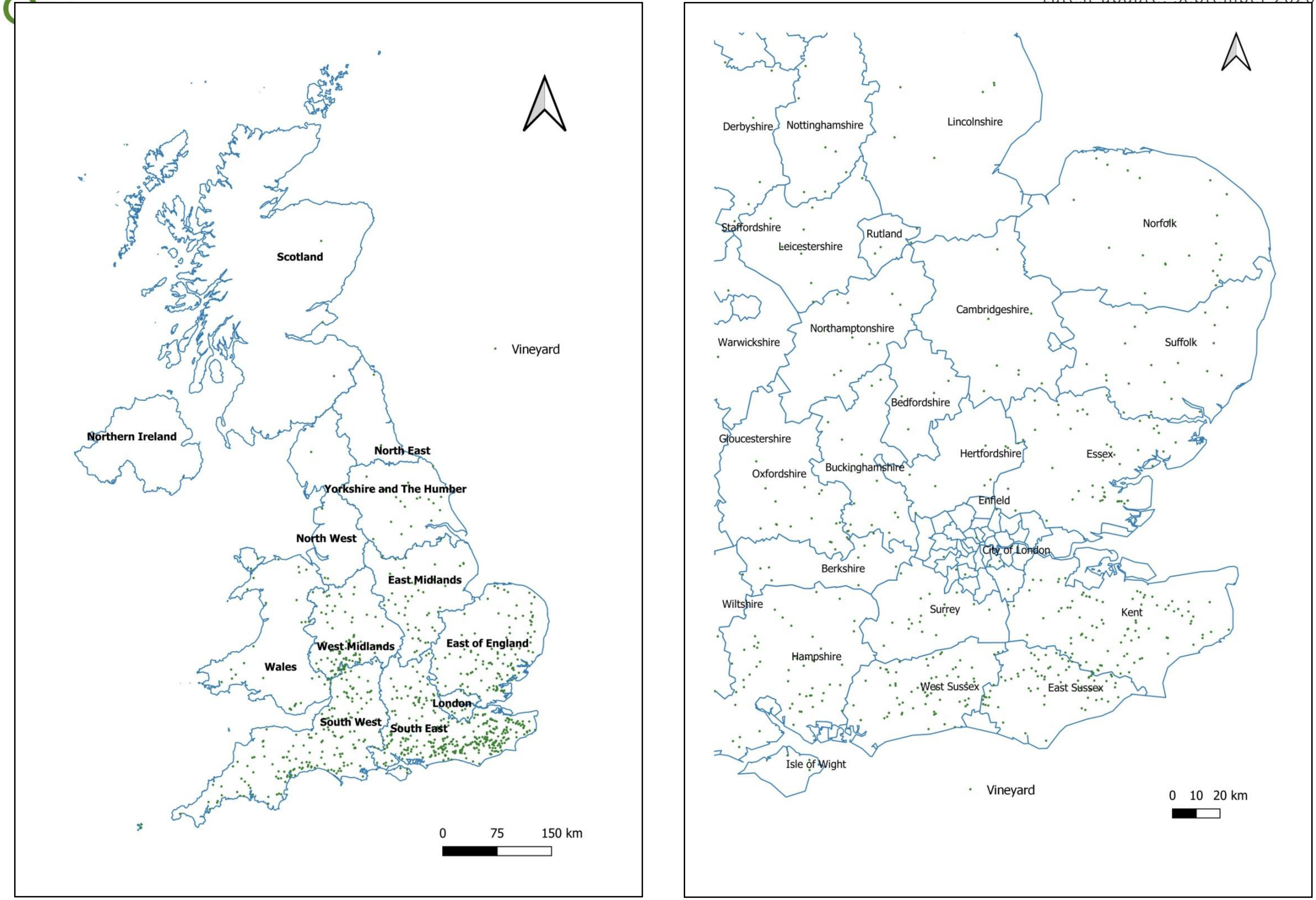

Figure 1. Location of vineyards in relation to administrative regions of the UK (left panel) and the counties of East of England, East Midlands and South East England (right panel, with Greater London's Enfield and City of London also marked). Location of vineyards as of 11 November 2020 from Skelton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

4. Assessing inter-annual variability for 2040-59

UKCP18 projections for 2040-59 were provided as mean figures for the period. The following methodology was used to derive an approximate 80% confidence interval for the estimated inter-annual variability in vintage scores for 2040-59. For each 5 x 5 km grid, the standard deviation (SD) for each of the three climate indices from 2010 to 2019 was calculated. These standard deviations were applied as follows to the 2040-59 projections to estimate a 10-year lower and upper limit for vintage score:

4.1 Lower Limit:

4.1.1 $Tmean_{Apr\text{-}Sep\_2040\text{-}59}$ decreased by 1.282 x SD $Tmean_{Apr\text{-}Sep\_2010\text{-}19}$

4.1.2 $CNI_{2040\text{-}59}$ or $CNI2_{2040\text{-}59}$ increased by 1.282 x SD $CNI_{2010\text{-}19}$

4.1.3 $P_{Jun\text{-}Sep\_2040\text{-}59}$ increased by 1.282 x SD $P_{Jun\text{-}Sep\_2010\text{-}19}$

4.2 Upper Limit:

4.2.1 $Tmean_{Apr\text{-}Sep\_2040\text{-}59}$ increased by 1.282 x SD $Tmean_{Apr\text{-}Sep\_2010\text{-}19}$

4.2.2 $CNI_{2040\text{-}59}$ or $CNI2_{2040\text{-}59}$ decreased by 1.282 x SD $CNI_{2010\text{-}19}$

4.2.3 $P_{Jun\text{-}Sep\_2040\text{-}59}$ decreased by 1.282 x SD $P_{Jun\text{-}Sep\_2010\text{-}19}$

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

5. Tools

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

Results

1. Change in Model climate indices from 1981-2000 to 2010-19

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

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

For example, while $Tmean_{Apr\text{-}Sep}$ rose in North-West England and East of England by 0.5 and 0.7 °C respectively, *CNI* increased by 0.5 °C in North-West England but only by 0.1 °C in the East of England (Table S2). This distribution was consistent with changes in the Diurnal Temperature Range (*DTR*) for September (Figure 2b), where mean maximum temperatures increased more than mean minimum temperatures in the East of England, South East England, and the Midlands, but *vice versa* for Cornwall, North West England, Northern Ireland, Western and Northern Scotland, and South Wales.

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

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

Rainfall ($P_{Jun\text{-}Sep}$) increased from 1981-2000 to 2010-19 by between 2.0 and 21.9 %. The increase was small (<10%) in southern regions and large (>20%) in the North East and North West of England (Table S2).

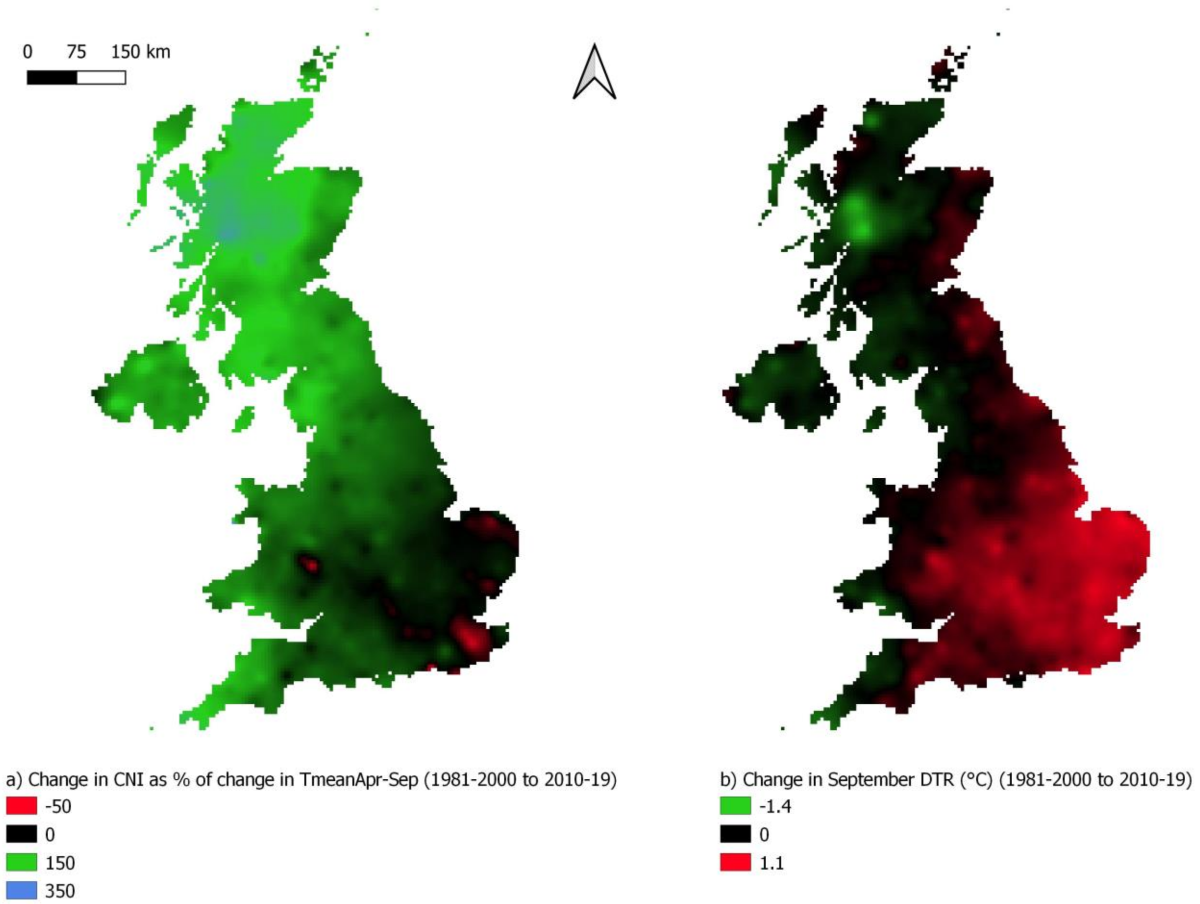

Figure 2. Change in climate indices from 1981-2000 to 2010-19 in the UK: (a) change in mean *CNI* as a percentage of change in mean *$Tmean_{Apr-Sep}$*; (b) change in mean Diurnal Temperature Range (DTR) for the month of September. Colours are graduated in the maps, from red to black to green (and to blue in (a)), to reflect the non-discrete variation in change.

2. Applying the Model retrospectively

2.1 The UK, 1981-2000

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

2.2 The UK in 2010-19

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

Places that would have been suitable for producing *Good* Chardonnay wine between 2010 and 2019 would be land in and around London (including parts of south Hertfordshire, north Surrey, and south Essex), areas that fringe the Thames Estuary (south Essex and north Kent), and some isolated areas in the East of England and Midlands, such as in Cambridgeshire, Suffolk, and Oxfordshire (Figure 3b). Existing vineyards would have experienced similar *CNI* and $P_{Jun\text{-}Sep}$ in 2010-19, and marginally better $Tmean_{Apr\text{-}Sep}$, compared to 1981-2000, but still c. 0.5 to 1.0 °C lower than the ideal climate projected by the Model (solid circles, Figure 4).

The mean score for 2010-19 (Table 3) hides significant vintage score variation: 2012 would likely have been *Poor* everywhere (maximum score achieved for any one 5 x 5 km grid square 5.9), 2018 *Excellent* at the best sites (maximum score 9.0), with the other eight years scoring in-between (maximum score 6.8 to 7.3). The highest-scoring existing vineyard of size (> 1 hectare) for 2010-19 was Forty Hall Vineyard in Enfield, London (its grid square scoring a mean 6.6 for the 2010-19 period; 4.7 for 2012, 8.4 for 2018, and 5.9 to 6.8 for the the other eight vintages).

2.2.1 The 2012 vintage

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

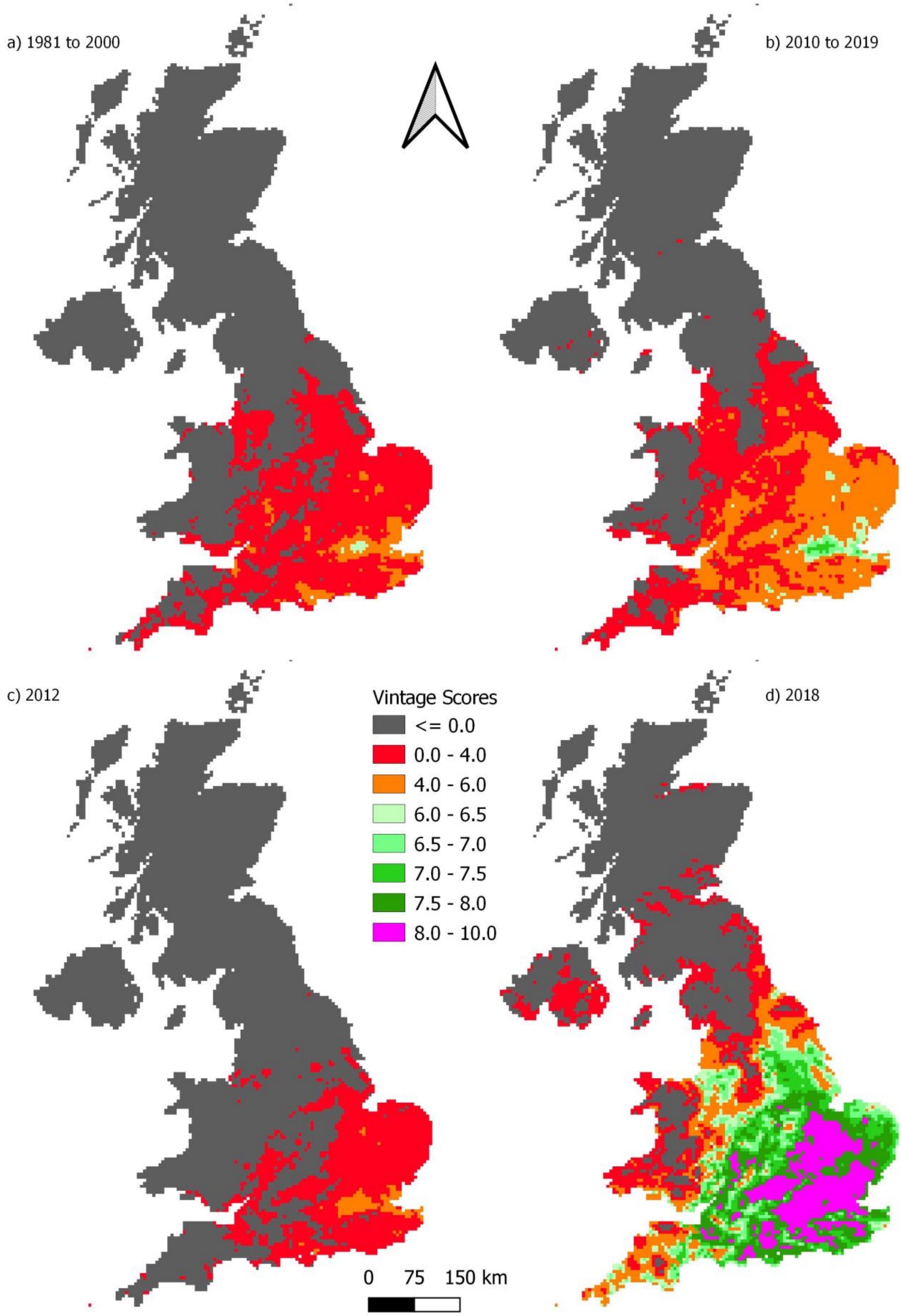

Figure 3. Chardonnay still wine quality score estimates across the UK provided by the Chablis vintage model: (a) 1981 to 2000 (percentage of UK land where wine quality rated

Good **0.2%,** ***Excellent*** **0.0%); (b) 2010-19 (*****Good*** **1.8%,** ***Excellent*** **0.0%); (c) 2012 (*****Good*** **0.0%,** ***Excellent*** **0.0%); (d) 2018 (*****Good*** **25.2%,** ***Excellent*** **8.8%). Green is** ***Good*****, purple is** ***Excellent*****.**

Table 3. Estimates of UK vintage scores for Chardonnay still wine quality, and percentage of UK land scoring ≥ 6 (i.e. *Good* or *Excellent*), from the Chablis vintage model for 1981 to 2000, 2010 to 2019, and RCP 4.5 projections (UKCP18) for 2040-59 at the 5^{th}, 50^{th} and 95^{th} percentiles; CNI2 indicates estimates with a modified *CNI* (see text). The two right-hand columns show the highest scoring existing UK vineyard (> 1ha) and its score in each period or scenario.

Period	Mean Score[a]	Max Score[b]	UK Land (%) scoring ≥ 6[c]	Highest-Scoring Vineyard (> 1 ha)[d]	Top Vineyard Score[e]
1981 to 2000	-7.4	6.5	0.2	Forty Hall Vineyard, Enfield, London[f]	5.3
2010 to 2019	-4.8	7.2	1.8	Forty Hall Vineyard, Enfield, London[f]	6.6
2040-59 (RCP 4.5)					
5%	-5.6	7.1	1.0	Forty Hall Vineyard, Enfield, London[f]	6.2
5% *(CNI2)*	-5.8	7.0	0.8	Forty Hall Vineyard, Enfield, London[f]	6.1
50%	-1.0	7.5	20.7	Bothy Vineyard, Oxfordshire	7.4
50% *(CNI2)*	-0.9	8.3	24.8	Bardsley Farms Vineyard, Kent	8.2
95%	2.3	7.7	39.1	Wolf Oak Vineyard, Berkshire	7.6
95% *(CNI2)*	2.7	9.1	42.4	Mereworth Wines, Kent	9.1

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

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

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

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

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

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

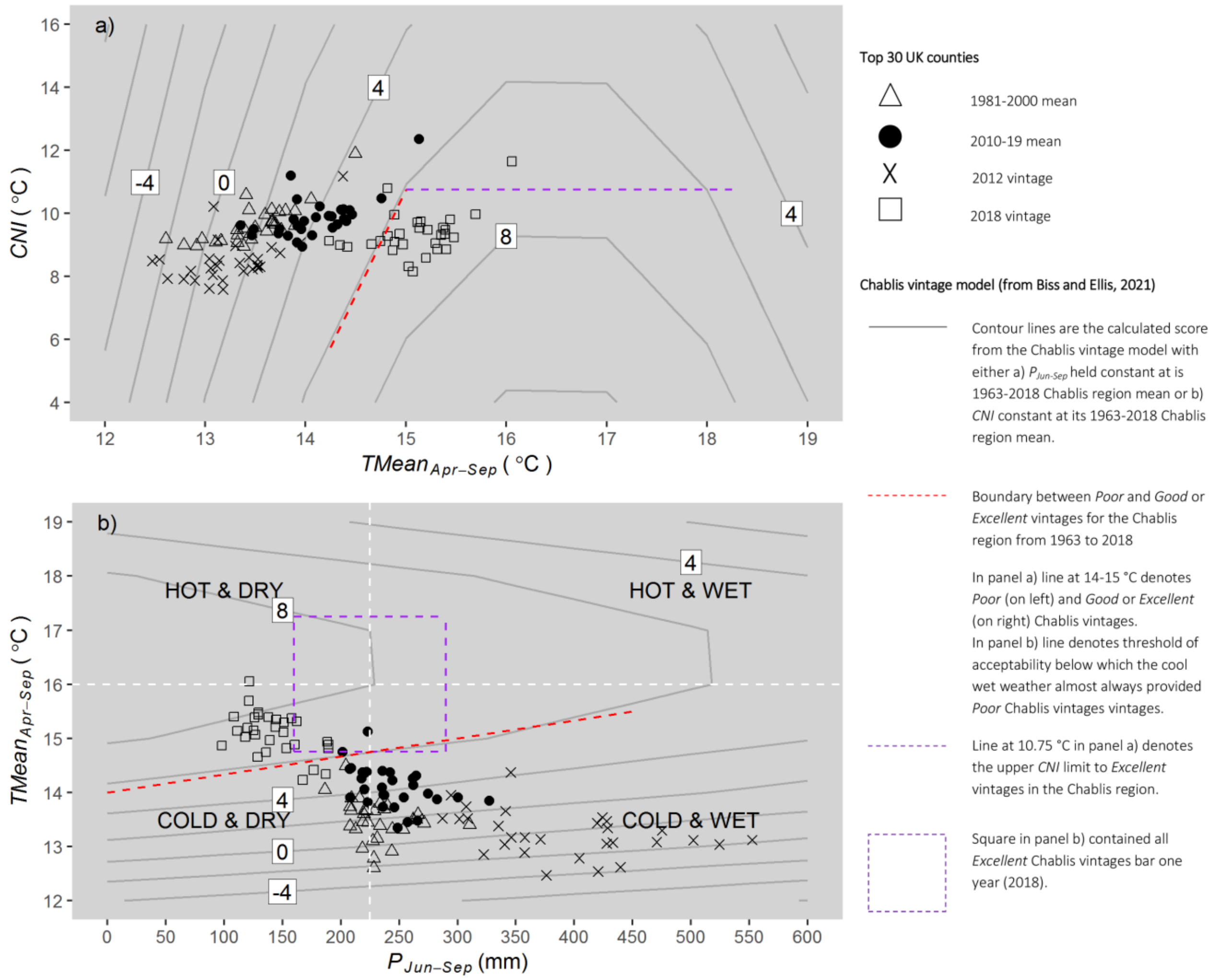

Figure 4. Comparison of climates for the top 30 UK counties (Table 4) in 1981-2000, 2010-19, 2012 and 2018, and the Chablis region, France, from 1963 to 2018. Contours (vintage score) and dashed lines from Biss and Ellis (2021).

2.2.2 The 2018 vintage

Estimates of the 2018 vintage were exceptional (Figure 3d) because the weather that year had the potential to produce high-quality Chardonnay wine throughout most of England (34.0 percent of UK land area). In fact, the weather in 2018 had the potential to produce *Excellent* Chardonnay wine across a greater area of the UK (8.8% of UK land area) than all but one (95th percentile projection with *CNI2*) of the mean projections for 2040-59 considered in this study (see below). The highest-scoring existing vineyard of size (> 1 hectare) was Laithwaites' Windsor Great Park Vineyard in Berkshire (8.8).

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

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

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

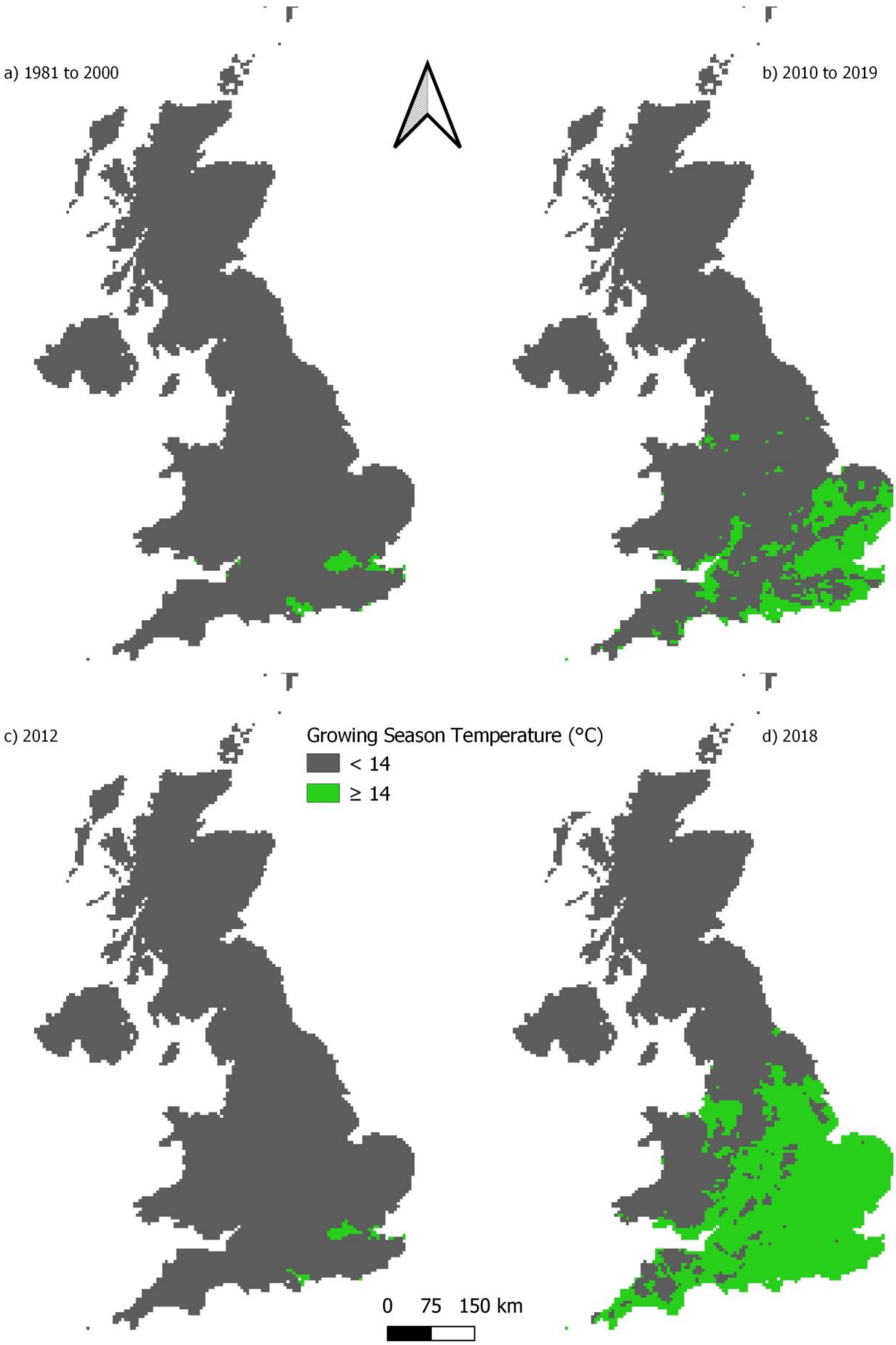

Figure 5. UK land suitability (in green) for Chardonnay viticulture, based on 14 °C GST

threshold (Jones, 2006): a) 1981 to 2000 (1.1% of UK area); b) 2010 to 2019 (11.0%); c) 2012 (0.7%); d) 2018 (34.1%).

4. Medium-term projections for the UK in 2040-59

4.1 5th percentile projection

Under the RCP 4.5 5th percentile projections for 2040 to 2059, the vintage score estimates provided by the Model were similar to those presented in Figure 3b for the 2010-19 period, with only 1.0 % of UK land area capable of producing *Good* Chardonnay wine (Table 3). Hence this projection is not described in detail.

The 5th percentile mean scores for the top 30 counties (by existing vineyard area) for 2040-59 were all < 6; marginally lower than, or similar to, the 2010-19 period (Table 4).

4.2 50th percentile projection

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

The majority of existing vineyards from the top 30 counties provided *Good* Chardonnay wine in 2040-59, narrowly missing or just clipping the boundary for producing *Excellent* Chardonnay wine because *CNI* was too high (solid circles, Figure 7a). Rainfall ($P_{Jun\text{-}Sep}$) was not a limiting factor to high vintage scores (solid circles, Figure 7b).

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

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

Table 4. Estimated mean vintage scores (1981-2000; 2010-19; 2040-59) and ranges (2010-19 only; in parentheses) with estimated 10-year inter-annual variation (2040-59 only; in parentheses) for Chardonnay still wine for the 30 UK counties with the largest areas of planted vineyards. Scores (out of 10, where 6.0-8.0 is *Good* and >8.0 *Excellent*) provided by the Chablis vintage model (Biss and Ellis, 2021) with historic weather records (1981-2000; 2010-19), and projected climate change (2040-59). Vintage scores for each of the 819 constituent vineyards are provided in Table S4.

			Mean Vintage Score							
		Area of Planted Vines			2040-59 (RCP 4.5)[a]					
County	Region	(ha)	1981-2000	2010-19[b]	5% CNI	5% CNI2	50% CNI	50% CNI2	95% CNI[c]	95% CNI2[c]
Berkshire	South East England	34.4	2.0	4.1 (0.4 – 8.0)	3.8 (0.4 - 7.7)	3.6 (0.3 - 7.6)	6.5 (3.6 - 8.7)	6.9 (4.1 - 9.1)	7.3 (5.0 - 7.7)	8.5 (6.1 - 8.9)
Buckinghamshire	South East England	19.8	2.5	4.7 (1.3 - 8.3)	4.2 (1.0 – 8.0)	4.0 (0.8 - 7.8)	6.6 (3.9 - 8.7)	7.1 (4.4 - 9.2)	7.2 (5.0 - 7.4)	8.4 (6.2 - 8.7)
Cambridgeshire	East of England	10.0	2.7	5.0 (2.0 – 8.0)	4.2 (1.0 - 7.9)	4.1 (0.9 - 7.8)	6.6 (3.8 - 8.6)	7.1 (4.3 - 9.1)	7.2 (5.0 - 7.6)	8.4 (6.2 - 8.8)
Cornwall	South West England	30.4	0.6	2.0 (-1.8 - 5.9)	2.2 (-0.8 - 6.3)	1.8 (-1.4 - 5.9)	5.1 (2.1 - 7.3)	4.8 (1.8 - 7.1)	6.2 (3.4 - 6.7)	6.2 (3.4 - 6.7)
Devon	South West England	84.4	1.2	2.6 (-1.8 - 6.3)	2.7 (-0.6 – 7.0)	2.4 (-1.0 - 6.7)	5.5 (2.4 – 8.0)	5.7 (2.6 - 8.2)	6.5 (3.7 - 7.3)	7.2 (4.4 – 8.0)
Dorset	South West England	73.2	0.8	2.7 (-1.7 - 6.6)	2.5 (-1.1 - 6.8)	2.2 (-1.1 - 6.5)	5.5 (2.5 - 8.3)	5.7 (2.7 - 8.5)	6.8 (4.0 - 7.8)	7.6 (4.8 - 8.6)
East Sussex	South East England	379.9	2.9	4.7 (2.1 - 7.7)	4.5 (1.5 - 8.1)	4.4 (1.4 – 8.0)	6.6 (4.1 - 8.5)	7.2 (4.6 - 9.1)	6.9 (4.8 – 7.0)	8.2 (6.1 - 8.3)
East Yorkshire	Yorkshire and Humber	8.6	-2.1	1.1 (-3.6 - 5.1)	-0.2 (-4.1 - 4.3)	-0.4 (-4.3 - 4.1)	3.7 (0.1 - 6.7)	3.9 (0.3 - 6.9)	5.9 (2.8 - 7.5)	6.6 (3.4 - 8.2)
Essex	East of England	249.1	3.9	5.8 (3.4 - 8.2)	5.2 (2.4 - 8.3)	5.1 (2.4 - 8.2)	7.0 (4.8 - 8.5)	7.6 (5.3 - 9.1)	7.0 (5.4 – 7.0)	8.3 (6.6 - 8.2)
Gloucestershire	South West England	84.7	2.5	4.3 (0.4 - 7.5)	4.0 (0.7 - 7.9)	3.7 (0.5 - 7.6)	6.4 (3.6 - 8.6)	6.8 (4.0 – 9.0)	7.0 (4.6 - 7.6)	8.1 (5.7 - 8.7)
Hampshire	South East England	340.3	2.6	4.3 (0.8 - 7.8)	4.3 (1.1 - 8.1)	4.1 (1.0 – 8.0)	6.6 (3.9 - 8.7)	6.9 (4.2 - 9.1)	7.1 (4.8 - 7.4)	8.0 (5.7 - 8.3)
Herefordshire	West Midlands	31.0	1.8	3.6 (-0.7 - 6.9)	3.2 (-0.3 - 7.2)	3.0 (-0.5 – 7.0)	6.0 (2.9 - 8.4)	6.4 (3.4 - 8.8)	7.0 (4.4 - 7.9)	8.1 (5.5 – 9.0)
Hertfordshire	East of England	12.2	2.7	5.0 (2.0 - 8.1)	4.2 (1.0 - 7.8)	4.0 (0.9 - 7.7)	6.6 (3.9 - 8.5)	7.0 (4.3 – 9.0)	7.2 (5.0 - 7.4)	8.3 (6.1 - 8.5)
Isle of Wight	South East England	10.2	4.5	5.7 (3.5 - 7.8)	5.7 (3.4 - 8.5)	5.5 (3.2 - 8.3)	6.8 (4.9 – 8.0)	6.9 (5.1 - 8.1)	5.9 (4.6 - 5.4)	6.4 (5.1 - 5.9)
Kent	South East England	1012.9	3.4	5.2 (2.7 - 7.8)	4.9 (2.2 - 8.2)	4.8 (2.1 - 8.2)	6.9 (4.6 - 8.6)	7.6 (5.4 - 9.3)	7.0 (5.2 – 7.0)	8.6 (6.8 - 8.6)
Lincolnshire	East Midlands[d]	16.1	-0.2	2.8 (-1.0 - 6.6)	1.7 (-1.9 – 6.0)	1.6 (-2.1 - 5.8)	5.1 (1.9 - 7.8)	5.4 (2.2 - 8.1)	6.8 (4.0 – 8.0)	7.7 (4.8 - 8.8)
Monmouthshire	Wales	19.6	1.6	3.3 (-1.2 - 6.6)	2.8 (-0.8 – 7.0)	2.6 (-1.0 - 6.8)	5.6 (2.3 - 8.2)	5.9 (2.7 - 8.5)	6.7 (3.8 - 7.7)	7.6 (4.7 - 8.6)
Norfolk	East of England	52.0	2.4	4.8 (2.1 - 7.4)	3.9 (0.9 - 7.5)	3.8 (0.8 - 7.4)	6.3 (3.8 - 8.3)	6.9 (4.3 - 8.9)	7.0 (4.9 - 7.3)	8.3 (6.2 - 8.6)
North Yorkshire	Yorkshire and Humber[e]	10.7	-1.1	1.5 (-3.6 - 5.6)	0.7 (-3.3 - 5.1)	0.5 (-3.5 - 4.9)	4.3 (0.7 - 7.2)	4.4 (0.8 - 7.4)	6.3 (3.1 - 7.8)	6.8 (3.6 - 8.3)
Northamptonshire	East Midlands	14.4	0.4	3.3 (-1.0 - 7.4)	2.3 (-1.5 - 6.6)	2.2 (-1.6 - 6.4)	5.5 (2.2 - 8.2)	5.9 (2.6 - 8.5)	7.0 (4.2 – 8.0)	8.0 (5.1 – 9.0)

Nottinghamshire	East Midlands	9.0	1.7	4.0 (-0.1 - 7.6)	3.4 (-0.3 - 7.5)	3.2 (-0.5 - 7.3)	6.1 (2.9 - 8.7)	6.4 (3.2 - 8.9)	7.2 (4.5 - 8.1)	7.9 (5.3 - 8.9)
Oxfordshire	South East England	41.8	1.5	3.8 (-0.1 - 7.8)	3.4 (-0.1 - 7.4)	3.3 (-0.2 - 7.3)	6.3 (3.3 - 8.6)	6.9 (3.9 - 9.2)	7.3 (4.8 - 7.9)	8.7 (6.2 - 9.2)
Shropshire	West Midlands	18.5	-0.6	1.6 (-3.0 - 5.3)	1.0 (-3.1 - 5.6)	0.7 (-3.3 - 5.4)	4.6 (1.0 - 7.6)	4.9 (1.2 - 7.9)	6.5 (3.3 - 7.9)	7.3 (4.0 - 8.7)
Somerset	South West England	19.9	1.9	3.7 (-0.4 - 7.2)	3.4 (0.2 - 7.4)	3.1 (0.0 - 7.1)	5.9 (3.1 - 8.2)	6.2 (3.4 - 8.5)	6.7 (4.2 - 7.2)	7.6 (5.1 - 8.1)
Staffordshire	West Midlands	20.1	0.7	2.8 (-1.8 - 6.8)	2.2 (-1.8 - 6.6)	1.9 (-2.1 - 6.3)	5.4 (2.0 - 8.2)	5.8 (2.3 - 8.5)	6.9 (4.0 – 8.0)	7.9 (4.9 - 8.9)
Suffolk	East of England	48.8	2.9	5.1 (2.3 - 7.9)	4.3 (1.1 - 7.9)	4.2 (1.0 - 7.8)	6.6 (3.9 - 8.5)	7.1 (4.5 – 9.0)	7.1 (5.0 - 7.3)	8.4 (6.3 - 8.5)
Surrey	South East England	126.9	1.7	3.9 (0.5 - 7.9)	3.6 (0.2 - 7.6)	3.5 (0.1 - 7.5)	6.4 (3.4 - 8.7)	7.0 (4.0 - 9.3)	7.4 (4.8 - 7.8)	8.8 (6.3 - 9.3)
West Sussex	South East England	456.6	2.9	4.5 (1.3 - 7.8)	4.5 (1.4 - 8.4)	4.3 (1.2 - 8.2)	6.8 (4.0 - 8.9)	7.2 (4.4 - 9.3)	7.2 (4.9 - 7.4)	8.2 (5.9 - 8.5)
Wiltshire	South West England	31.8	1.2	3.3 (-0.8 - 7.3)	2.9 (-0.7 - 7.1)	2.6 (-1 - 6.8)	5.8 (2.6 - 8.3)	6.1 (2.9 - 8.6)	7 (4.3 - 7.8)	7.9 (5.1 - 8.6)
Worcestershire	West Midlands	23.3	3.5	4.9 (1.0 - 7.9)	4.7 (1.4 - 8.4)	4.5 (1.2 - 8.1)	6.8 (4.1 - 8.9)	7.2 (4.5 - 9.3)	7.1 (4.9 - 7.6)	8.2 (6.0 - 8.7)

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

[b] Figures in brackets are the 2010-19 range, from lowest scoring vintage (2012) to best scoring vintage (2018).

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

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

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

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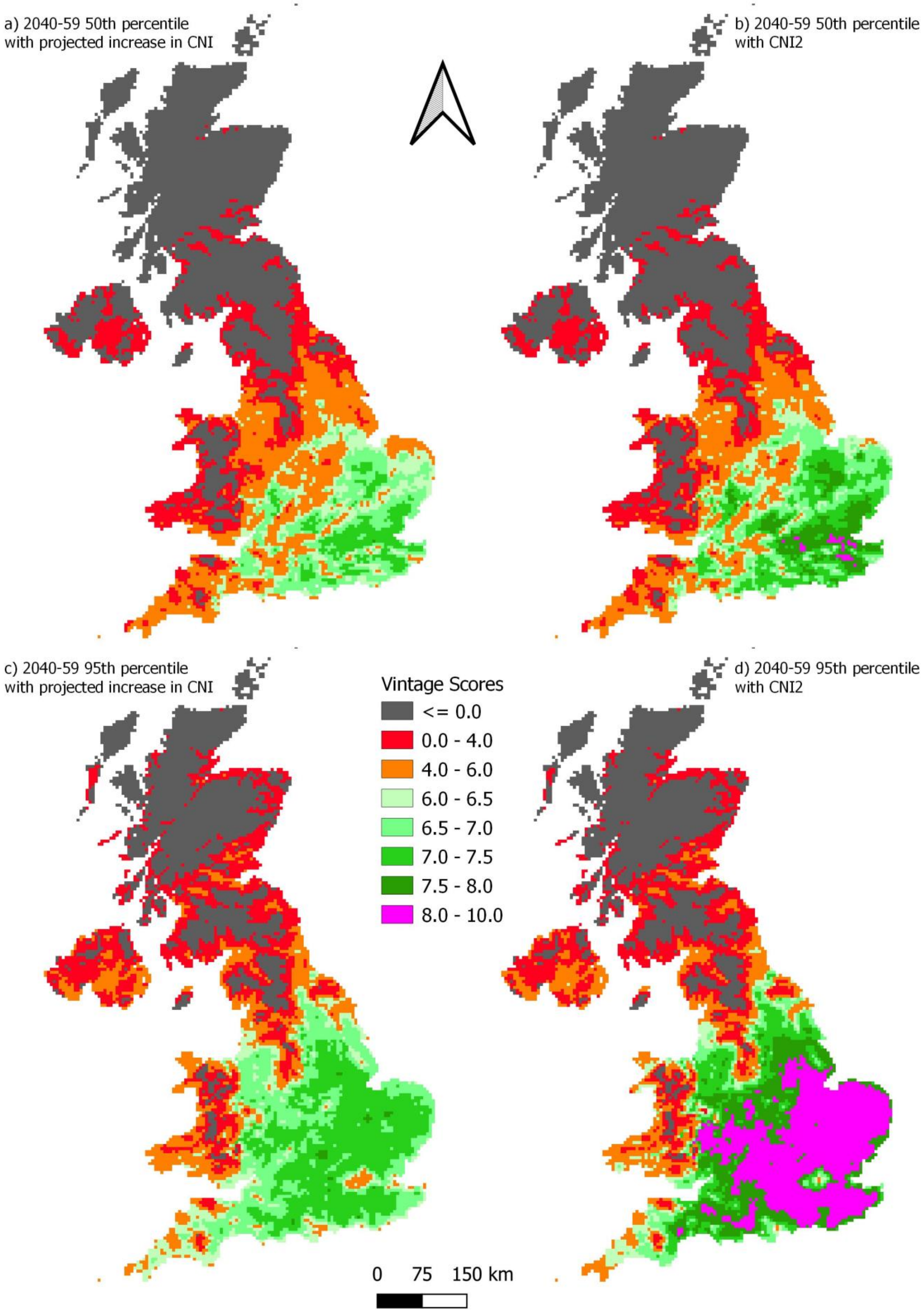
a) 2040-59 50th percentile with projected increase in CNI
b) 2040-59 50th percentile with CNI2
c) 2040-59 95th percentile with projected increase in CNI
d) 2040-59 95th percentile with CNI2
Vintage Scores
<= 0.0
0.0 - 4.0
4.0 - 6.0
6.0 - 6.5
6.5 - 7.0
7.0 - 7.5
7.5 - 8.0
8.0 - 10.0
0 75 150 km

453

Figure 6. Variation in Model predictions for the vintage score of Chardonnay still wine across the UK under RCP 4.5 (mean and 95th percentile): (a) 2040-49 using the median RCP 4.5 projection (UK area rated *Good* 20.7%, *Excellent* 0.0%); (b) 2040-49 using the median RCP 4.5 projection but with *CNI2*, a smaller increase than *CNI* projections (*Good* 24.5%, *Excellent* 0.3%); (c) 2040-49 using the 95th percentile RCP 4.5 projection (*Good* 39.1%, *Excellent* 0.0%); (d) 2040-49 using the 95th percentile RCP 4.5 projection but with *CNI2* (*Good* 24.5%, *Excellent* 17.9%). Green is *Good*, purple is *Excellent*.

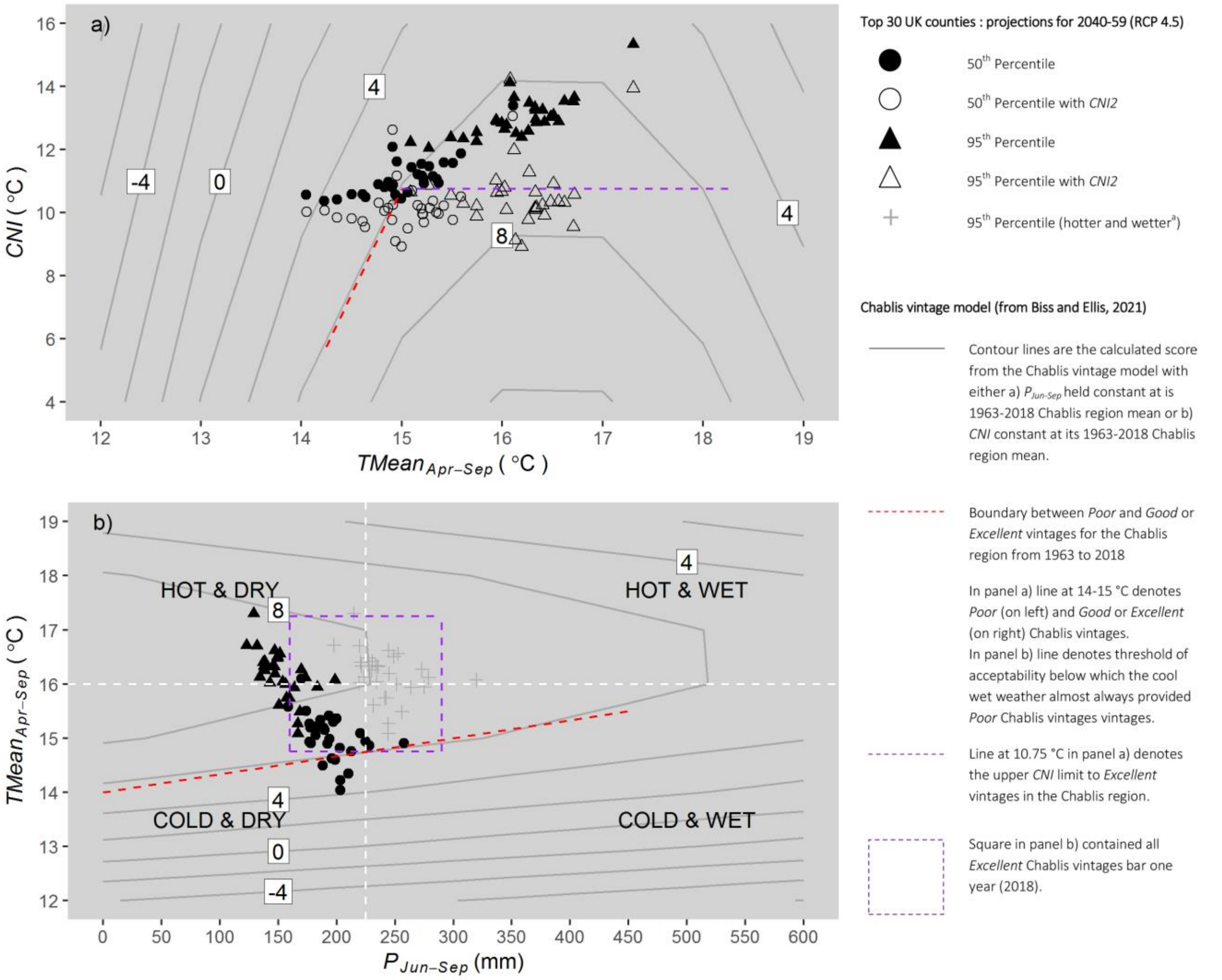

Figure 7. Comparison of climates between the top 30 UK counties (Table 4) in 2040-59 and the Chablis region, France, from 1963 to 2018. Contours (vintage score) and dashed lines from Biss and Ellis (2021).

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

4.3 95th percentile projection

The 95th percentile RCP 4.5 projections (Figures 6c and 6d) led to a substantial area of UK land with high-quality ratings (39.1 % *Good*, 0 % *Excellent*). There was also a noticeable expansion over the median projection of areas predicted to produce the highest-quality wine, moving beyond the South East and East of England into the Midlands and parts of the South West (compare Figure 6c with 5a). Estimated vintage scores for the Isle of Wight (Table 4) and London (Figure 6), however, were noticeably lower than those provided by the median projection.

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

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

5. Medium-term projections for the UK in 2040-59 with *CNI2*

If *CNI* were to continue to rise at a slower rate than $Tmean_{Apr\text{-}Sep}$, as generally occurred throughout the UK between 1981-2000 and 2010-19 (Figure 2), then the vintage scores for the 50th percentile and 95th percentile would increase. Using the alternative projection for *CNI* (i.e. *CNI2*), which extrapolates the relationship between *TmeanApr-Sep* and *CNI* into 2040-59 (see Method section 2.3), the area of land deemed climatically suitable under the 50th percentile projection would be 24.8% (up from 20.7% with *CNI*) (Figure 6b).

The difference between applying *CNI* and *CNI2* showed great effect under the 95% projection, with a mean difference in predicted mean scores of 1.0 compared to only 0.4 for the 50% projection. High-quality ratings vintage scores were provided for 42.4% of the UK land area for 2040-59 under *CNI2* (Figure 6d), up from 39.1 % for *CNI* (Figure 6c), with *Excellent* scores when using *CNI2*

(Figure 6d, 17.9 % of land area), but not *CNI* (Figure 6c, 0.0 %). Overall, the (cooler) *CNI2*-based projections showed greater potential for *Excellent* Chardonnay wine (open circles and triangles, Figure 7a). Of the top 30 counties with the largest area of vineyards (Table 4), 17 counties provided scores in the *Excellent* category when using *CNI2*-based projections, which were close to or below 10.75 °C (open triangles, Figure 7a).

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

Discussion

1. Assessing results and model performance against existing research

1.1 Historical periods

Though the amount of UK land area deemed capable of producing *Good* wine by the Model (Biss and Ellis, 2021) was generally lower (by 0.1 to 9.2%) than that suggested by using the simple 14 °C GST threshold (Jones, 2006) for 1981-2000, 2010-19, 2012 and 2018, the two methods produced similar distributions of land with suitable climates (compare Figures 3 and 4).

We maintain the Model has added value over the GST threshold approach in two regards. First, the scoring is continuous and not threshold-based, this being a more realistic assessment for viticultural suitability (Nesbitt *et al.*, 2018). Second, the Model is specific to the production of still Chardonnay wine. Moreover, closer inspection of the distributions highlights some important differences. For example, 11.0% of UK land (compared to only 1.8% for the Model) is deemed capable of producing still Chardonnay wine for the 2010-19 period on average according to the 14 °C GST threshold, with suitability concentrated in the South East and East of England, and along the Severn estuary. Even in the East of England (the region with the highest GST outside of London), GST was only just, on average, above 14 °C for the period (14.1 °C). Still Chardonnay wine requires berries grown under slightly warmer conditions than 14 °C, probably around 14.4 °C GST assuming a minimum threshold of 14.75 °C for $Tmean_{Apr\text{-}Sep}$ (approximate position of red dashed line to the right of solid circles cluster in Figure 4a). This value is based on the calculation that $Tmean_{Apr\text{-}Sep}$ is typically around 0.4 °C higher than the equivalent GST (mean difference for 2010-19 was 0.36 °C). Moreover, inter-annual variation would have resulted in many vintages being below the required GST threshold (see Discussion section 6). Certainly, very few major producers were making still Chardonnay wine until the 2018 vintage (Robinson, 2019).

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

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

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

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

One implication of our findings, particularly considering inter-annual variability (Table 4), is that new vineyards planted henceforth in areas that are expected to be suitable for good-quality still Chardonnay wine in 2040-59 could be planted with Chardonnay clones that can be used to produce sparkling wine (either as a blend or as a blanc de blanc) but will also work well for still wine in the future. For example, clones 75, 76, 95, 121, 131 and 548 are good for both types of wine (Skelton, 2020a). Moreover, it may be possible to use the May to July period to plan ahead within year regarding whether to produce still or sparkling wine (Biss and Ellis, 2021).

1.2 Projections with Climate Change

Georgeson and Maslin (2017) projected forward to 2100 by applying known thresholds for GST, annual precipitation and harvest precipitation (October), using RCP 6.0 (+2.2 °C GST and +5.6% increase in annual rainfall from 1981-2005), for several grapevine varieties, including Chardonnay. Their projection is comparable to the 95th percentile RCP 4.5 projection for 2040-59 used in this study in terms of temperature increase (Table 2) though they assume a wetter season and harvest period. They concluded that large areas of the UK will be especially suitable for Chardonnay, but with a risk that current wine-producing areas in the South of England may become too wet or too warm for Chardonnay (and Pinot Noir) and that the sparkling wine industry in the South of England may be threatened. They highlight that one limitation of their research is that the harvest may move forward into September.

Georgeson and Maslin’s projections are broadly similar to ours for the 95th percentile RCP 4.5 projection in Figures 6c and 6d, but in ours the South of England provides a larger area of suitable land than Georgeson and Maslin. It is notable that the projections presented here are based on a reduction in $P_{Jun\text{-}Sep}$, but even with a 6% increase rather than a decline, 95th percentile projections for 29 of the top 30 counties remain within the ideal range for $P_{Jun\text{-}Sep}$ and all 30 counties remain above the *Poor* threshold when compared to Chablis vintages from 1963 to 2018 (grey plusses, Figure 7b).

2. Uncertainties

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

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

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

Another source of uncertainty particularly relevant to this study is how each of the three variables in the Chablis vintage model will change in relation to each other. The projections presented here for 2040-59 assume that as $Tmean_{Apr\text{-}Sep}$ rises (from 5th to 50th to 95th percentile), precipitation will decrease. This is consistent with research that suggests Britain will have warmer and drier summers (Harkness *et al.*, 2020; Vinescapes, 2021). It is also consistent with the weak inverse relationship (*r*

= -0.34) between $Tmean_{Apr\text{-}Sep}$ and $P_{Jun\text{-}Sep}$ *for* the 3000 model sample runs. Thus 95th percentile projections for $Tmean_{Apr\text{-}Sep}$ and *CNI* were used in conjunction with the 5th percentile projections for $P_{Jun\text{-}Sep}$, and vice versa. It is possible, however, that growing seasons will become hotter and wetter. Nonetheless, total precipitation from June to September seems unlikely to be a limiting factor, on average, to making good Chardonnay wine at the 95th percentile, even if precipitation levels were modelled the other way around (grey plusses, Figure 7b).

It is also the case that $Tmean_{Apr\text{-}Sep}$ and *CNI* may not move in the same direction or with the same magnitude from year-to-year. The 2018 vintage was notably hotter than the 2010-19 average, yet its *CNI* remained below the 10.75 °C threshold in all but two of the top 30 counties (Figure 4a). The 2018 UK vintage was exceptionally good (Olsen, 2021; WineGB, 2021) and the low CNI may have been an important driver of this.

Finally, whether *CNI* increases as projected by UKCP18 is also questionable. Our observation that *CNI* did not increase as uniformly (spatially) between 1981-2000 and 2010-19 compared to $Tmean_{Apr\text{-}Sep}$ was checked against Met Office weather station data (Met Office, n.d.[c]) and substantially verified. A similar observation has also been made for Chablis, the Côte de Beaune and the Loire Valley regions in France (Biss and Ellis, 2021; Neethling *et al.*, 2012). However, whether the observed relationship between $Tmean_{Apr\text{-}Sep}$ and *CNI* can be extrapolated into the future, as assumed with *CNI2*, is also uncertain – but may be highly relevant to future UK viticulture.

3. Is Chablis an appropriate analogy?

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

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

When applied to the UK, the Model may suffer from "blind spots". For example, it may be that prior autumn and winter precipitation (not accounted for by the Model) may be more important for UK viticulture (or certain regions of the UK) than it is for the Chablis region, as is the case for the Bordeaux region (Byron and Ashenfelter, 1995). Moreover, the Model only goes to September, whereas the month of October may be crucial for UK viticulture especially in the earlier years of the 2040-59 period when phenology may not have yet advanced to the same extent as it has already in Chablis. The UK is an emerging wine region where temperatures are currently marginal and harvests typically go well into October versus the long-established Chablis region where harvests typically occur from late August to September (Biss, 2020).

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

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

4. The importance of CNI

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

5. Improving projections and further research

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

6. Inter-annual variation

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

As such, an increase in GST (or $Tmean_{Apr\text{-}Sep}$) from now until 2040-59 should result in improved wine quality, greater yields, *and* lower sensitivity to interannual variation, at least until GST rises above the ideal curvilinear peak value for Chardonnay (Jones *et al.*, 2005; Kurtural and Gambetta, 2021).

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

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

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

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

Conclusions

This study suggests:

1. The production of high-quality Chardonnay still wine was rarely possible throughout most of the UK in recent times (1981-2000 and 2010-19). This would remain to be the case under the 5th percentile projection for climate change (RCP 4.5).
2. Considerable areas of England and Wales, particularly the South East, East of England, and Central England, should be able to produce high-quality still Chardonnay wine, on average, in 2040-59, with the 50th and 95th percentile projections for climate change (RCP 4.5).
3. The average climate in 2040-59 (RCP 4.5, 50th percentile projections) should be sufficiently above the threshold for Chardonnay viticulture to allow ripening even in relatively cool years in the South East and East of England, especially Essex, Kent, and the Isle of Wight, extending to Central England under the 95th percentile projection, provided inter-annual variation remains similar to, or less than, recent times.
4. If *CNI* rises less than that projected by UKCP18 and instead continues along its current path (*CNI2*), the potential quality of wine may increase further.

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

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

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