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ARTICLE

A suitability model for viticulture in England and Wales: opportunities for investment, sector growth and increased climate resilience

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ABSTRACT

Despite continued investment and evidence of high quality wine production, English and Welsh wine grape yields remain low. To increase sector resilience to weather and climate risks we present the first combined terrestrial and climatic English and Welsh Viticulture Suitability (EWVS) model. Results show many existing vineyards (≥ 1 ha) are sub-optimally located. Limiting the model to the top 20% of suitable land in England and Wales resulted in 33,700 ha of prime viticulture land being identified, a scale just larger than the Champagne region of France. Beyond Kent and Sussex, large areas in Essex, with the warmest 30-year (1981–2010) Growing Season Average Temperature (13.9°C) on mainland Britain, and Suffolk, where few vineyards presently exist, appear especially suitable for viticulture. The EWVS model developed through this work allows, for the first time, a rapid assessment of land at local, regional and national scales to inform investment and policy related decisions.

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Bio-climatic indices; climate change; English viticulture; fuzzy logic; land use; Welsh viticulture

Introduction

Wine grape varieties (predominantly of *Vitis vinifera* L.) are generally suited to specific climatic conditions, historically found in narrow latitudinal (30–50°N and 30–40°S) bands in which growing season conditions are often characterised by a lack of extreme heat and cold (de Blij, 1983; Jones, 2006; Schultz & Jones, 2010; White, Diffenbaugh, Jones, Pal, & Giorgi, 2006). On a regional scale, suitability for viticulture is ultimately determined by the effects of mesoscale and local atmospheric processes (Carbonneau, 2003; Fraga, Malheiro, Moutinho-Pereira, & Santos, 2013a), which result in a global patchwork of grape varieties and wine 'types' that bring complexity and value to the wine market. However, the climatic sensitivity of *Vitis vinifera* L. exposes viticulture to threats and opportunities associated with climate change (Fraga, Malheiro, Moutinho-Pereira, & Santos, 2013b; Tóth & Végvári, 2016; Webb, Watterson, Bhend, Whetton, & Barlow, 2013). There is increasing evidence of new emerging cool-climate viticulture areas beyond 50°N, for example in Denmark, England and southern Sweden (Danskevingaarde, 2015; Nesbitt, Kemp, Steele, Lovett, & Dorling, 2016; Vinvagen, 2016). Their recent rapid growth and, particularly in the case of England, recognition for very high-quality wine (English Wine Producers, 2017; International Wine and Spirits Competition, 2017) suggests new investment opportunities.

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Supplemental data for this article can be accessed here.

Vineyard hectarage (ha) in England and Wales is estimated to have increased 246% (722 to 2500 ha) between 2004 (when sparkling wine started to dominate production – Nesbitt et al., 2016) and 2017 (Food Standards Agency, 2017; WineGB, 2018). Enhanced investor confidence, sector expansion, widening varietal suitability, and greater viticulture opportunity have been underpinned by climate change, evidenced through recent (1954–2013) warming of growing season (April–October) average temperatures (GSTs) (Nesbitt et al., 2016). However, notwithstanding *prima facie* opportunities associated with higher GSTs the UK is located between the mid-latitude westerly wind belt on the edge of the Atlantic Ocean and the continental influences of mainland Europe and is therefore sensitive to minor changes in the positioning of major atmospheric pressure systems. Resulting intra- and inter-annual weather variations can affect viticulture productivity at annual or longer time-scales. During the 2004–2013 period, UK-wide wine yield varied considerably (6–34 hectolitres per hectare (hL/ha)) with an average of 20.7 hL/ha, less than one third of the Champagne harvest base yield (66 hL/ha) – albeit due in part to a higher density planting structure, set by L'Institut National de l'Appellation d'Origine (Comité Champagne, 2017). Investments in English and Welsh viticulture therefore remain exposed to low and highly variable yields.

With weather and climate variability being significant contributors to this vulnerability, identifying areas in England and Wales that are both terrestrially (soil, topography and land use) suitable for viticulture and have enhanced climatic suitability is crucial to increasing sector resilience to weather and climate threats, and to inform investment decisions.

The spatial and varietal distribution of longer established wine producing regions of the world, often termed the 'old-world', largely results from centuries of trial and error, experience, learning and adaptation. For new regions touted as potentially having increased future suitability, including England and Wales (Fraga et al., 2013b; Kenny & Harrison, 1992; Nesbitt et al., 2016), decisions regarding terrestrial and climatic suitability cannot readily be established from empirical or regression-based predictions. Defined quantitative relationships between variables such as locality, topography, soil characteristics, seasonal weather profiles, inter-annual variability, grapevine yields and grape quality parameters for different varieties are not yet objectively established in England and Wales, and a trial and error phase is likely unpalatable to many due to investment risk. To date, the siting of vineyards in England and Wales has not been supported by an objective high-resolution local, regional or nation-wide assessment of climatic and terrestrial (soil, topography, land use) suitability. Site selection remains on an ad-hoc case-by-case basis lacking systematic spatial comparison and potentially exposed to value judgements around critical characteristics, their relative degrees of importance and the weightings that should be applied to them. However, the use of modern Geographic Information Systems (GIS) for data integration and spatial analysis provides a rapid means of identifying, quantifying, and grading land suitability for viticulture at high resolution, thus bypassing the decades or even centuries of exploration.

There has been some previous use of GIS to map suitability for viticulture, for example in Romania (Irimia, Patriche & Quénol, 2011) and Oregon (Jones, Duff, & Myers, 2006). However, land suitability assessments for viticulture have been commonly undertaken using a Boolean logic approach, i.e. logical true/false, rule-based methods that use a series of logical operators and, in some cases, weighting factors to define 'suitability'. Using a Boolean approach, the intersection operator 'and' can be very restrictive (risk averse) when overlaying multiple datasets because if a single criterion fails to meet its threshold an area is excluded. Conversely with the union operator 'or' there is the risk that an entire area could be chosen so long as a single criterion meets its threshold (Romano, Sasso, Liuzzi, & Gentile, 2015). In reality, climate and terrestrial factors that contribute to viticulture suitability are not discrete, but individually and collectively give a range of suitability without distinct boundaries. Furthermore, the risk of uncertainty (error and vagueness) in data regarding the natural environment, and ambiguity around precise relationships between viticulture and environmental variables relating to 'suitability' is not well accommodated in a Boolean approach, hence it may not fully elucidate opportunities, risks subjectivity and is unlikely to usefully grade land suitability (Joss, Hall, Sidders, & Keddy, 2008). In this study, where appropriate, we employ a different methodology, based on fuzzy logic. Fuzzy logic/fuzzy set theory is a precise logic of imprecision and approximate reasoning which allows for the conceptualization of uncertainty, in this case to help create an analytical tool which facilitates decision-making based on spatial information in a more valuable way than a 'narrow' Boolean approach would (Braimoh, Vlek, & Stein, 2004; Burrough, Macmillan, & van Deursen, 1992; Fisher, Comber, & Wadsworth, 2006; Robinson, 2003). Within fuzzy logic the concept of dataset membership is not absolute because all members have degrees of association between 0 (not a member) and 1 (definitely a member) (Malczewski, 2004), which are distributed according to the imposed membership function and spread value (see Materials and Methods). Where suitability parameters for viticulture are defined and delimited, fuzzy logic therefore presents a valuable tool for modelling risk and opportunities.

In this work we use GIS to deliver the first high-resolution (50 x 50 m) English and Welsh viticulture suitability (EWVS) model, spatially representative at local, regional and national scales to help direct investment, strategy, policy relevant actions and structural resilience to weather and climate risks. The study also presents the first 30-year (1981–2010) average climate maps (England and Wales) specifically relevant to the viticulture season (April–October) to deliver a comparative regional climate narrative. We also apply the EWVS model to the 13 largest (≥ 25 ha) vineyards in England and Wales to drive a model search for land with analogue characteristics and even higher fuzzified suitability values.

Materials and methods

Geographic information systems (GIS)

ArcGIS version 10.3 (ESRI, 2014) was used for data integration and analysis.

English and Welsh vineyard locations

No 'official' database of English and Welsh vineyard locations and sizes (ha) was publicly available so the UK Vineyards List (Skelton, 2015), although not independently verified, was deemed the most up-to-date (November 2015) source. However, postcodes from this list were often found to relate to premises and not precise vineyard locations, so to ensure model accuracy, individual vineyards (≥ 1 ha) were visually located utilising a combination of Google Earth (Google, 2015a), Google Maps Street View (Google, 2015b) and DigiMap Roam (Edina, 2015). Once located, coordinates (British National Grid) of approximate vineyard centres were imported as point features into ArcGIS to enable analysis of their spatial distribution and to quantify model parameters. Of the 384 ≥ 1 ha vineyards in England and Wales (2015), 4% (with a combined total of ~23 ha) could not be found using this visual identification process (possibly due to their newly planted status and therefore omission from the various base imagery used). They were therefore excluded from the mapping and analysis exercise.

To facilitate an analogue approach to viticulture–climate suitability modelling, i.e. to enable the EWVS model to search for similar or better 'suited' land, the boundaries of the 13 largest (≥25 ha) vineyards in England and Wales were traced from an earth image base map (ESRI, 2014) using the ArcGIS Editor tool, and saved as polygon features.

Regional 'zoning'

Defining viticulture suitability through spatial zoning is not uncommon (Fraga et al., 2013b; Jones, Duff, Hall, & Myers, 2010) and the geo-political boundaries utilised in the process provide an artificial but useful means of depicting the appropriateness of relatively large areas. In the absence of multiple appellations or defined viticulture zones within England and Wales, except for West and East Sussex (which have a Protected Designation of Origin (PDO) geographic indication – Sussex)

(UKVA, 2017), Unitary Authority (UA) boundaries (limited to counties to exclude small borough pockets of suitability) (Ordnance Survey, 2015), were used as a means of representing spatial suitability for viticulture at a regional scale and to define model classifications.

Terrestrial and climate data

Elevation, aspect, slope angle, land cover, soil characteristics and land designations are key terrestrial factors when considering land suitability for viticulture. Weather and climate are critical as they play predominant roles in grapevine physiology and phenology (van-Leeuwen et al., 2004) and ultimately determine the commercial viability of viticulture. Data 'types', sources and EWVS model parameters are shown in Table 1. The basis for their inclusion in the model is outlined below.

Elevation

There is no stipulated 'ideal' elevation for vineyards in England and Wales but guidance suggested vineyards would be best sited below 100 and not above 150 m (Skelton, 2014), with between 25–80 m being the preferred range (English vineyard managers, personal communication, 2015). Elevation suitability is restricted by decreasing temperatures at higher altitudes and the greater potential for wind exposure.

Aspect

At higher latitudes south facing slopes (in the northern hemisphere) have greater direct solar radiation gain potential (Coombe & Dry, 2004; Jackson, 2014) particularly during the ripening period when the sun is higher in the sky. They are also conducive to reducing the lag phase during which a site heats up and dries out after a cold night (Jackson, 2014). All else being equal such slope aspects are favourable to both yield and grape berry quality parameters.

Slope Angle

Optimum slopes for viticulture are 5–10%. The potential for mechanical vineyard-management activity becomes limited on slopes greater than 10% (Jackson, 2014) and erosion risk increases. Below 1% there is an increased risk of cold air accumulation and potential frost damage (Jones, Snead, & Nelson, 2004).

Land cover

Potentially suitable areas for viticulture are limited in this work to those classified as arable, horticulture or grassland in the Centre for Ecology and Hydrology's (CEH) Land Cover Map (LCM) (Centre for Ecology and Hydrology, 2007) because they were deemed most likely to exhibit viticulture suitability parameters (Table 1).

Soil

Soil texture, drainage, pH, fertility, nutrient and organic matter content are all important attributes in determining viticultural suitability. Their influences on vine nutrient and water availability, soil temperature and humidity, the solubility of metal ions and the supply of nutrient cations and anions, the number of beneficial microbes, and contributions to soil chemical, physical and biological properties all impact vine health, growth and productivity (Davenport & Stevens, 2006; Field, Smith, Holzapfel, Hardie, & Emery, 2009; Lanyon, Cass, & Hansen, 2004; van-Leeuwen et al., 2004; Riches, 2013; White, 2010).

Although a range of desirable soil characteristics exist for viticulture, for example it is generally accepted that soil pH should be between 5.5–8.0 for optimum vine growth and soil microbial composition (Cass & Maschmedt, 1998; Lanyon et al., 2004; Riches, 2013), no one prescriptive 'ideal' set of soil properties exists. Rather a broad and generalised range is presented as being suitable

Table 1. Suitability model terrestrial and climatic constraints, data source, type and resolution, and model membership types.

Variable	Suitable parameter values	Original data type, resolution and source	Suitability model membership type
Elevation	1–150 m	10 x 10 km ASCII tiles with a resolution of 50 × 50 m. Derived from the OS Digital Terrain Model 50 (DTM) for England and Wales (Edina, 2015). OS Terrain 50 has been compared with GPS points to provide a Route Mean Square Error (RMSE) value for the height points in a range of sample areas. The RMSE was verified to be 4 m (Ordnance Survey, 2017).	Membership: Fuzzy Type: Near Mid-point: 52.5 m Spread: 0.001
Aspect	The azimuth angle of the slope: East – West (90–270°)	Derived from elevation using the D8 algorithm (ESRI, 2015a), maintaining a resolution of 50 × 50 m (ArcGIS Spatial Analyst).	Membership: Fuzzy Type: Near Mid-point: 180° Spread: 0.001
Slope gradient	1–15%	Derived from elevation maintaining a resolution of 50 × 50 m (ArcGIS Spatial Analyst).	Membership: Fuzzy Type: Near Mid-point: 5% Spread: 0.001
Land cover	• Arable & horticulture • Improved grassland • Rough grassland • Neutral grassland • Calcareous grassland	25 x 25 m raster layer (CEH Land Cover Map, 2007). Selected for use in this work as, when validated by Morton et al. (2011), it was found to have a high level of correspondence between ground reference points and classifications.	Membership: Boolean Type: Boolean AND
Soil	(1) Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils (2) Slowly permeable seasonally wet acid loamy and clayey soils (3) Slightly acid loamy and clayey soils with impeded drainage (4) Shallow lime rich soils over chalk or limestone (5) Freely draining soils: (a) very acid sandy and loamy soils (b) slightly acid sandy soils (c) slightly acid loamy soils (d) slightly acid but base-rich soils (e) sandy Breckland soil (f) lime-rich loamy soils (g) acid loamy soils over rock	1:250,000 scale provided as delineated polygons (Farewell et al., 2011; LandIS, 2015).	Membership: Boolean Type: Boolean AND

(Continued)

Table 1. (Continued).

Variable	Suitable parameter values	Original data type, resolution and source	Suitability model membership type
Designated areas	• Registered battlefields • Registered parks and gardens • Country parks • World heritage sites • Local and national nature reserves • Sites of special scientific interest • Special areas of conservation • Special protected areas	Shapefiles (Historic England, 2015; Natural England, 2015; Natural Resources Wales, 2015).	Membership: Boolean Type: Boolean AND
GST	• Higher values to higher temperatures. GST equation: $\frac{\sum_{d=1}^{n}[Tmax+Tmin]/2}{n}$	Gridded 5 × 5 km txt. files of monthly data obtained from the UK Climate Projections 2009 (Met Office, 2015a) 5 × 5 km gridded dataset. Data are derived from station daily means ([Tmax + Tmin]/2). The station data had been subjected to multiple regression and inverse-distance weighted interpolation techniques to generate values on a regular grid (5 x 5 km), taking into account factors such as latitude, longitude, elevation, terrain shape, coastal influence and urban land use (Perry & Hollis, 2005). The 1981–2010 period is a commonly used climatological averaging period (Met Office, 2015b) and encompasses the period in which English and Welsh vineyard area started to increase (Nesbitt et al., 2016).	Membership: Fuzzy Type: Linear Classifications: • Cool = 13–15°C • Intermediate = 15–17°C • Warm = 17–19°C • Hot = 19–24°C (Jones, 2006)
Mean growing season total precipitation	Higher values to lower growing season rainfall totals	Gridded 1 × 1 km NetCDF files derived from monthly (1981–2010) 1 × 1 km Gridded Estimates of Areal Rainfall (CEH GEAR) which itself is derived from a national database of historical Met Office weather and rain-gauge observations (Centre for Ecology and Hydrology, 2014; Keller et al., 2015; Tanguy, Dixon, Prosdocimi, Morris, & Keller, 2014).	Membership: Fuzzy Type: Small Mid-point: 634.5 mm Spread: 5
June precipitation	Higher values to lower June rainfall totals	Gridded 1 × 1 km (1981–2010) NetCDF files (CEH GEAR).	Membership: Fuzzy Type: Small Mid-point: 64 mm Spread: 5
GST and precipitation inter-annual variability	Higher values to lower levels of variability	Gridded 5 × 5 km (1981–2010) txt. files (Met Office, 2015a; Perry & Hollis, 2005).	Membership: Fuzzy Type: Small GST SD Mid-point: 6 Growing season precipitation SD Mid-point: 25 Spread: 5
Days of air frost (≤ 0°C) in April – May	Higher values to lower air frost days	Gridded 5 × 5 km (1981–2010) txt. files (Met Office, 2015a; Perry & Hollis, 2005).	Membership: Fuzzy Type: Small Mid-point: 3.8 Spread: 5
Bright sunshine	Higher values to higher sunshine hours	Gridded 5 × 5 km (1981–2010) txt. files (Met Office, 2015a; Perry & Hollis, 2005). Whilst solar radiation can be estimated in ArcGIS v10.3, accurate cloud cover data is required to extend the model beyond the theoretical.	Membership: Fuzzy Type: Linear

under different environmental circumstances and for different rootstocks, clones, varieties, planting densities and training systems. It should also be noted that many soil characteristics, particularly nutrient availability, can be ameliorated via soil management activities to achieve desired traits. However, to best represent the range of soil characteristics deemed desirable for viticulture, within the EWVS model, three soil datasets were evaluated for their suitability in reflecting soil properties in English vineyards. Results from this initial data trial (see supplementary material) led to the selection of the Soilscapes (Farewell, Truckell, Keay, & Hallett, 2011; LandIS, 2015) dataset (11 of 27 simplistic soil descriptors) for inclusion in the EWVS model.

Designated areas

It was assumed that where land areas had been awarded a special designated status, for example, Site of Special Scientific Interest, and were therefore 'protected', that they would not be available for viticulture.

Temperature and bioclimatic indices

Temperature plays a major role in viticulture viability, grapevine growth, and in modulating the final content of compounds in grape berries such as sugars, acids, phenolics, flavour compounds and proteins (Gladstones, 1992; Kliewer & Torres, 1972).

In viticulture-climate research temperature is often presented through bioclimatic indices (BCIs), metrics which provide simplistic illustrations and assessments of present or future viticulture or varietal suitability (Anderson, Jones & Tait, 2012; Duchêne & Schneider, 2005; Hall & Jones, 2010; Kenny & Harrison, 1992; Tonietto & Carbonneau, 2004). These BCIs commonly place numerical or descriptive envelopes around summed or averaged daily or monthly growing-season temperatures to express varietal suitability ranges. Various indices exist, for example Growing Degree Days (GDD) and modifications thereof (Amerine & Winkler, 1944; Gladstones, 1992), the Growing Season Average Temperature (GST) indices (Jones, 2006) and others as discussed in Tonietto and Carbonneau (2004) and Malheiro, Santos, Fraga, and Joaquim (2010). They have been applied in different regions, for different timescales, using different spatial resolutions, and driven by both observed and modelled climate data which does not necessarily resolve the range of climatic processes, intra-annual variability, or critical daily or hourly time-scale events which threaten productivity and which are likely to influence sub-regional climate-viticulture relationships (Jackson & Cherry, 1988; Jones, Moriondo, Bois, Hall & Duff, 2009; White et al., 2006). BCI classification envelopes are restricted to observed establishment which may not adequately illustrate varietal 'potential' or the adaptive capacity of viticulture through vineyard management techniques (Jones & Storchmann, 2001; Tomasi, Jones, Giust, Lovat, & Gaiotti, 2011; Webb, Whetton, & Barlow, 2008). They are in essence crude measures of suitability that may mask or overstate true viticulture potential in a specific location. As such, in this work the employment of BCIs is limited to GST (Jones, 2006) for a 30-year (1981–2010) period with the sole aim of representing spatial and temporal variability, an approach also adopted by Hall and Jones (2010) in Australia. Where GST is applied to model viticulture potential in England and Wales it is used as an analogue with the assumption that larger bioclimatic values present increased opportunity when the bottom end of 'cool-climate' is being explored. It was also selected for this work because of the availability of observed monthly averaged daily temperature data, from which it is calculated (Table 1), and because it has previously been widely used in inter- and intra-regional comparisons of viticulture climates and suitability (Anderson et al., 2012; Hall & Jones, 2010; Jones et al., 2009; Montes, Perez-Quezada, Pena-Neira, & Tonietto, 2012; Neethling, Barbeau, Bonnefor, & Quénol, 2012; Schultze & Sabbatini, 2014; Webb, Whetton, & Barlow, 2007; and Xu, Castel, Richard, Cuccia, & Bois, 2012).

Whilst average growing season thermal characteristics are generally applied to determine varietal suitability, intra-season temperature variability and extremes commonly influence the quantity and quality of grapes produced (Ashenfelter & Storchmann, 2014). Vintage variation is not a new concept in wine production, in fact it is one of the vagaries of wine that feeds into its marketing and its value.

However, where the magnitude of weather variability is large viticulture may be unviable. Areas with higher long-term GST variability in England and Wales (expressed in this work through inter-annual standard deviation (SD)) were deemed to be less viticulturally stable.

Spring air frosts that injure developing buds and shoots are among the most common detrimental effects of minimum temperature extremes on *Vitis vinifera* L. grapevines. Notwithstanding frost protection, they pose a significant economic risk to vineyards (Trought, Howell, & Cherry, 1999). Cool-climate wine producing regions are particularly exposed to the risk of early season frost events when the advancement of budburst occurs in response to increased spring air temperatures (Molitor, Junk, Evers, Hoffmann, & Beyer, 2014; Mosedale, Wilson, & Maclean, 2015).

Rainfall

Wine grape quality and quantity are affected by precipitation and water availability (Makra et al., 2009; Moutinho-Pereira et al., 2007). High levels of rainfall, usually accompanied by reduced sunlight, can negatively affect vine growth, berry quality and quantity through associated issues such as increased disease pressure, overstimulated vegetative growth, reduced flowering, millerandage (where grape bunches contain berries that differ greatly in size and maturity, sometimes referred to as 'chicken and hen'), coulure (flowers fail to set and are shed at or after flowering) and a sugar/acidity imbalance. In this work, for suitability modelling purposes, areas with lower growing season (April–October) rainfall and lower rainfall variability were favoured as a shortage of rainfall is not presently deemed to be a significant risk to viticulture in England and Wales.

High rainfall during June, when grapevine flowering commonly occurs in the UK, has been previously shown to have a negative impact on flowering and subsequent grape yield (Nesbitt et al., 2016). As such, areas within England and Wales with lower average June rainfall (1981–2010) were also awarded higher levels of viticulture suitability within the model.

Sunshine and solar radiation

Solar radiation at the earth's surface, insolation, provides energy through photosynthetic processes for grapevine growth and plays a particularly beneficial role during berry ripening and maturation when sugar and phenolic contents are determined (Gladstones, 1992).

One additional meteorological variable that could be limiting to viticulture is wind speed. Whilst wind data were not incorporated into the suitability model, site aspect and elevation were. Where suitable topographic conditions (southerly facing sites and elevations of 20–80 m) exist, exposure to easterly winds and dominant south-westerly winds should be minimised, although further site amelioration may be required to offer greater protection.

Table 1 summarises these variables, their suitability parameters, data type, source, resolution, and model membership type which are integrated into the EWVS model. The fuzzy logic model membership 'type' and spread is described below.

Fuzzification

Fuzzy logic, when employed using ArcGIS, allows for different model/fuzzy membership types. These different 'types' can represent the data distribution according to a user-imposed 'optimum' mid-point and spread value. The spread value defines the width and character of the transition zone and directs the distribution of the data over a range of association from 0 (not a member) to 1 (definitely a member) (Malczewski, 2004). In the model a number of different membership functions were used to represent different ways in which changes in factor values were thought to influence suitability.

For elevation a 'Near' fuzzy membership type (ESRI, 2015b) was imposed on the data with a mid-point of 52.5 m (25–80 m mean value) and a spread value of 0.001 (Table 1 and Figure S1 – see supplementary material). The midpoint defines the centre of the set, identifying definite membership and is therefore assigned a value of 1 within the EWVS model. As values move from the midpoint, in both the positive and negative directions, membership decreases until it reaches 0, defining no membership, in this case for cells below 1 or above 150 m. The 0.001 spread was selected for this model to allow a wide transition zone, illustrated in Figure S1 (supplementary material). Doing so gave a broader spread of values across all grid cells than say a spread of 0.1 which would assign much lower values to cells only marginally outside of the 52.5 m mid-point. The broad spread in this model indicates that an elevation of 25 or 80 m may not be significantly less suitable than 52.5 m.

Slope aspect and angle datasets were also transformed and integrated into the fuzzy model using the Near function, with spread values of 0.001. Slope was imposed with a mid-point 'optimisation' of 5%, and aspect with 180°, see Table 1.

Mean growing season total precipitation and precipitation inter-annual variability, June precipitation and days of air frost (≤ 0°C) in April–May were incorporated into the climatic suitability model using a 'Small' fuzzy membership function with spread values of 5 (Table 1). The Small membership function awards higher model membership suitability to cells with lower values, as demonstrated in Figure S2 (see supplementary material), with a spread value of 5 assigning increasingly steep fuzzification around the mid-point.

GST and hourly sunlight data (1981–2010) were integrated into the climatic suitability model using a Linear fuzzy membership function (Table 1). No spread values were applied because the fuzzy Linear transformation applies a straight line between the minimum and maximum values of the dataset. Grid cells with the highest GST or Sunshine hours were awarded a value of 1, and those with the lowest a value of 0.

Where layers were overlain and fuzzified, towards the ends of the terrestrial, climate, and combined EWVS model developments (see Figure 1), a fuzzy Gamma overlay method was applied with a gamma parameter of 0.5 to combine the data. This had the effect of producing an outcome that was a compromise between a fuzzy SUM operation (an increase function used when the combination of multiple evidence is more important than any of the inputs alone) and fuzzy PRODUCT (a decrease function used when the combination of multiple evidence is less important or smaller than any of the inputs alone). Alternative fuzzy overlay options of 'And' or 'Or' would have produced the minimum or maximum value respectively, of the raster inputs being overlain.

EWVS model construction

Two suitability model sub-sets (terrestrial and climatic) were constructed and subsequently combined to produce the EWVS model (see Figure 1). Some viticulture-climate studies present bioclimatic values for zones or regions which in reality may not be entirely terrestrially suitable for viticulture, for example Kenny and Harrison (1992), White et al. (2006), Hall and Jones (2010), and Malheiro et al. (2010). In this work, by creating the terrestrial (soil, topography, and land use) suitability model first and then delimiting the climatic and combined EWVS model criteria to it, regional and localised suitability can be more accurately determined. Key steps in the model construction process are shown in Figure 1.

Model results extraction

The model outputs were overlain with Unitary Authority (UA) boundaries, the location of existing vineyards (≥ 1 ha), and the boundaries of the 13 largest vineyards (≥ 25 ha). Using the ArcGIS Map Algebra and Spatial Analyst tools the terrestrial, climatic and combined EWVS model values for existing vineyards, and regional and national land areas were then extracted for different model parameters, along with fuzzified/graded viticulture suitability.

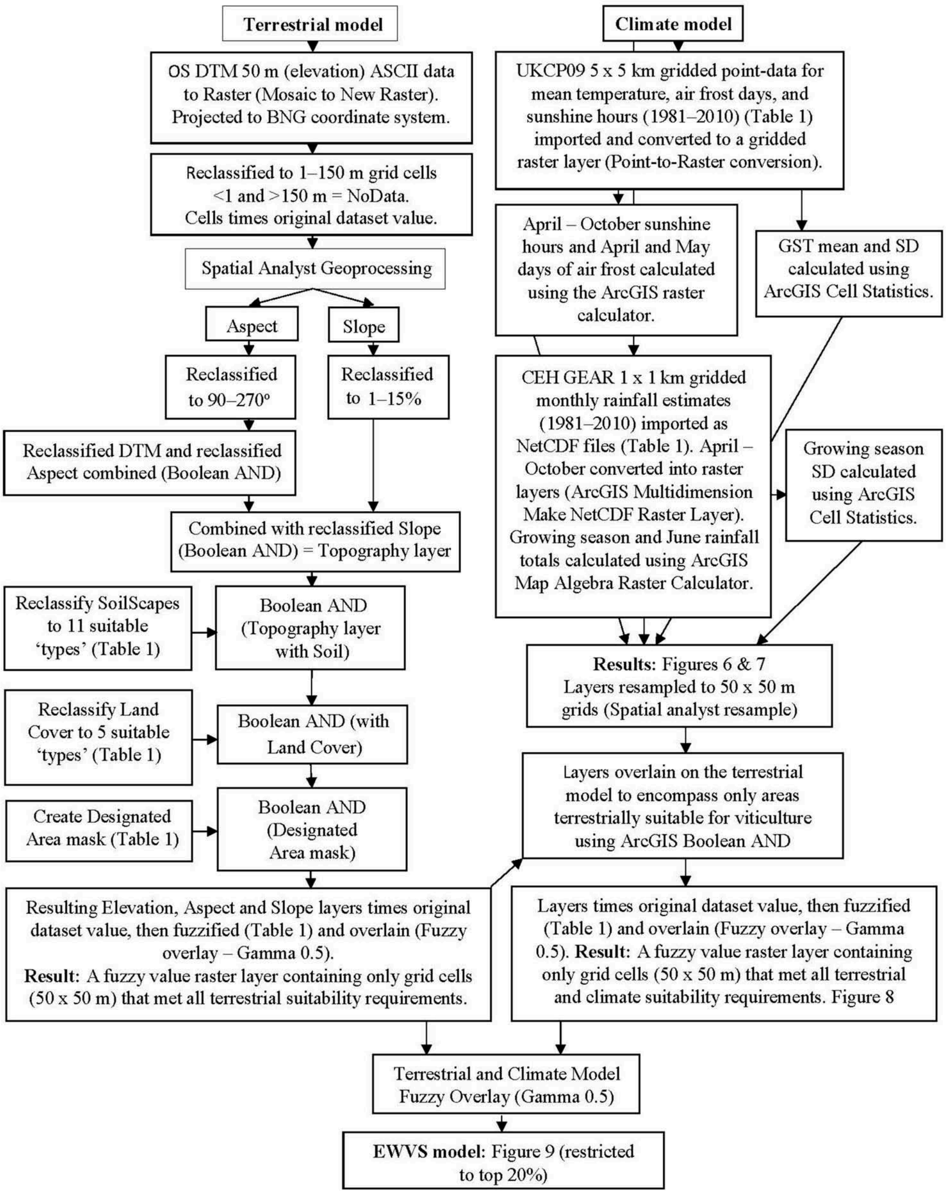

Figure 1. Viticulture suitability model construction flow-diagram of key steps and ArcGIS tools employed.

Results and discussion

Existing vineyard locations

The 2015 spatial distribution of vineyards can be seen in Figure 2 to be orientated towards south-east and south-central England, a structure that has emerged over-time possibly as a result of local vineyard suitability assessments and/or investor momentum built on observed occurrence of high-quality wines being produced in these areas. The 2015 overall hectarage by Unitary Authority is presented in Table 2.

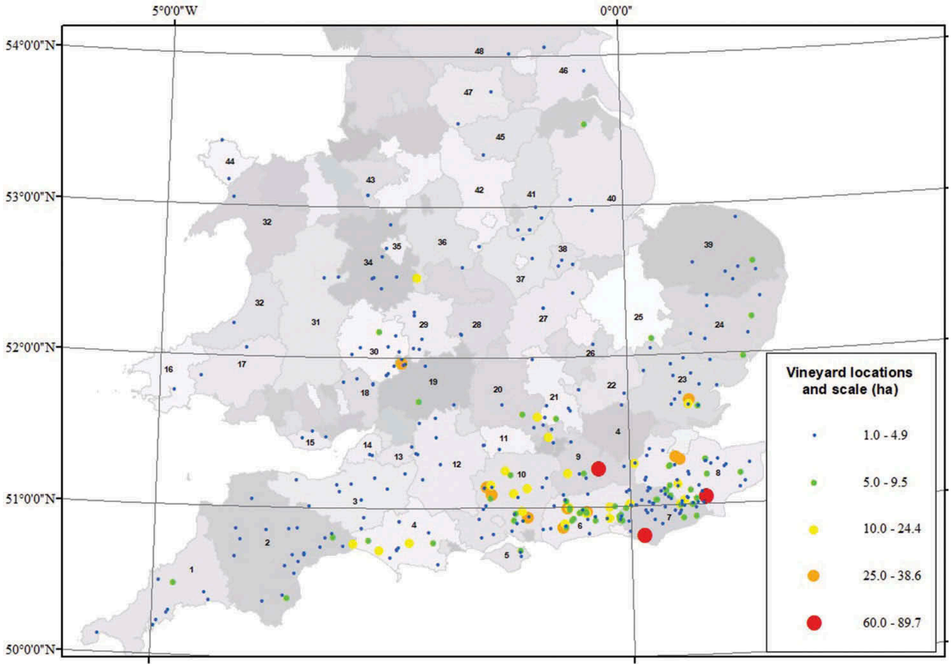

Figure 2. English and Welsh vineyard (≥ 1 ha) distribution and scale (ha) in 2015. Numbers denote Unitary Authorities identified in Table 2.

Terrestrial viticulture suitability in England and Wales

The model threshold for terrestrial suitability is any 50 × 50 m grid cell that meets all the soil, land cover, land use, elevation, aspect and slope criteria identified in Table 1. Following interrogation of the terrestrial suitability model (shown in Figure 3) using ArcGIS Map Algebra and Spatial Analyst tools:

- 1,435,867 ha of existing arable or horticulture land (Centre for Ecology and Hydrology, 2007) in England and Wales was identified as terrestrially suitable for viticulture. 549,270 ha of this was on soil classified as freely draining, and 179,852 ha on shallow lime-rich soils over chalk or limestone.
- At a regional scale:
  - Large areas of terrestrially suitable land were identified in Devon (206,776 ha), North Yorkshire (162,393 ha), and Cornwall (118,502 ha), see Table 3. To compare scale with an established wine producing region, Hampshire alone (Area 10, Figure 2) was found to have 27,384 ha of suitable land on shallow lime-rich soils over chalk or limestone. This is slightly less than the Champagne viticultural area (33,500 ha), which is also predominantly over chalk (Johnson & Robinson, 2001). It is also over 10 times the existing vineyard hectarage (2,500 ha (2017)) in the whole of England and Wales (WineGB, 2018).
  - Norfolk has the highest terrestrial mean fuzzy value (0.54) over 117,231 ha (21.3% of its land area), followed by Essex and Suffolk (both 0.52 – Table 3). However, they contain only 1, 5.3 and 1.6% respectively of current English and Welsh vineyard (≥ 1 ha) area (2015). In contrast, Kent, with 16.6% of vineyard area (≥ 1 ha) has a lower mean fuzzy terrestrial value of 0.47.

The weak relationship between terrestrial suitability and viticulture establishment in England and Wales is most likely due to constraints related to climate, i.e. although topographic, soil and land use criteria are met in many areas commercial viticulture viability is restricted due to unfavourable

Table 2. English and Welsh vineyard (≥ 1 ha) area (ha) by Unitary Authority (2015).

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

climatic conditions. Nevertheless, these results for terrestrial suitability alone are indicators of viticulture potential in England and Wales under future climate change scenarios.

Climatic viticulture suitability in England and Wales

Identification of climatically suitable viticulture areas (5 x 5 km) is presented here through grid cells (50 x 50 m) that encompass terrestrially suitable land. By combining data layers of different scales, the output, at 50 m resolution, is the result of spatial averaging. Therefore, whilst the results for terrestrial suitability are representative at field or meso-scale, subsequent integrated outputs for climatic and combined (EWVS model) suitability are likely to be less accurate at such scales and more indicative of wider local conditions.

The overall distributions of 1981–2010 mean GST, April and May air frosts, growing season bright sunshine, growing season rainfall and June rainfall within England and Wales, were calculated and mapped (Figure 4 (a–e)). Results show:

- In general, highest GSTs (14–15°C) occurred in London, south-central, south-east and eastern England, particularly on the south coast and coastal regions of Essex and south Suffolk.
- At Unitary Authority scale the highest spatially averaged GSTs were in Essex and the Isle of Wight (both 13.9°C), followed by Cambridgeshire (13.8°C), then West Sussex, East Sussex and Kent (13.6°C), all relatively highly populated with existing vineyards (Figure 2). However, Suffolk also had a 13.6°C GST but only hosted 17 vineyards in 2015.
- Essex had the lowest growing season rainfall (346 mm), followed by Cambridgeshire (356 mm) then Suffolk (362 mm).
- During the month of June (a critical period for grape vine flowering where high levels of rainfall have been shown to negatively affect UK wine yields (Nesbitt et al., 2016)), the Unitary Authority with the lowest rainfall was the Isle of Wight (47 mm), followed by the Isles of Scilly (49 mm), Kent (49 mm) and Surrey (50 mm).

- Lower April and May (combined) air frost risk occurred in coastal areas of England and Wales and in urban conurbations such as London (Figure 4(b)).

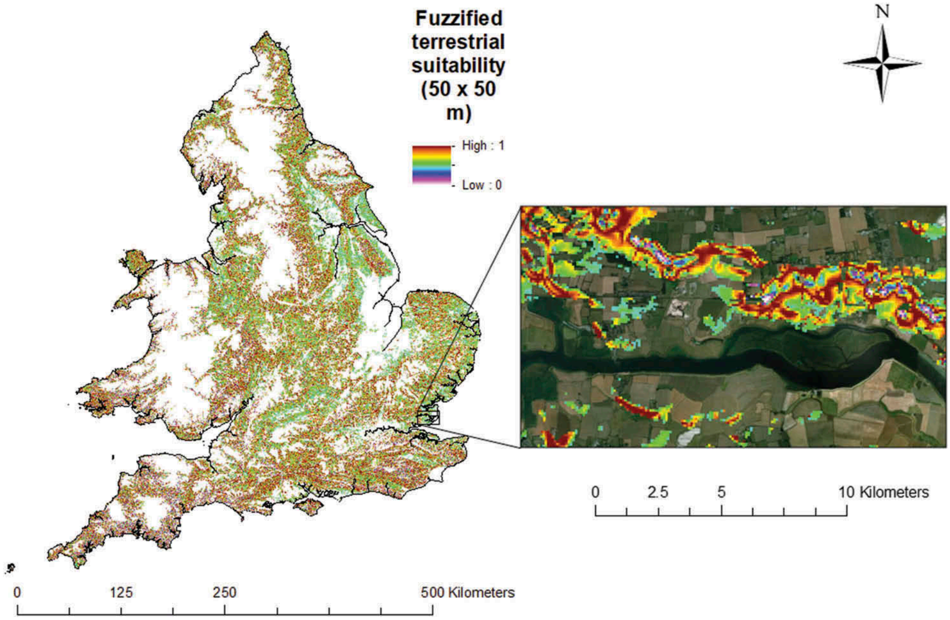

Figure 3. Terrestrial fuzzified viticulture suitability at national and local scales.

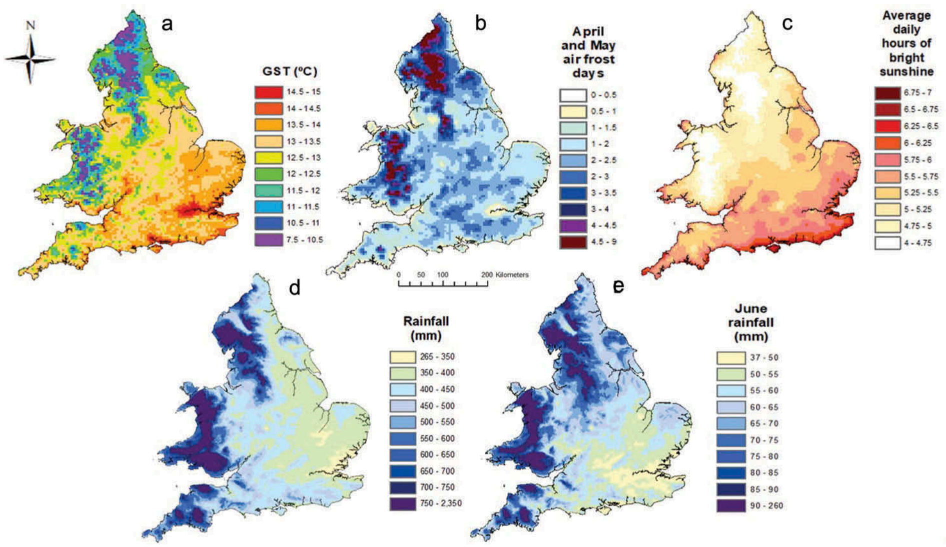

Figure 4. 1981–2010 mean viticulture climate conditions in England and Wales. A – GST (°C) (5 x 5 km); B – April and May air frost days (5 x 5 km); C – Growing season average daily hours of bright sunshine (5 x 5 km); D – Growing season rainfall (mm) (1 x 1 km), and E – June rainfall (mm) (1 x 1 km). Data sources: Centre for Ecology and Hydrology (2014) (Rainfall) and Met Office (2015a) (Temperature, Air Frost and Sunshine).

- The majority of East Anglia experienced on average (1981–2010) 1–2 days of air frost in April and May, whilst the viticulturally dominant areas of south-central and south-east England had slightly higher frequencies of 2–3 days. Areas in Dorset, Cornwall, the Severn Estuary, and Anglesey also had lower levels of April and May air frost.

Table 3. Top 10 (ranked) Unitary Authorities (UA) by terrestrial suitability, their fuzzy values according to the EWVS model, terrestrially suitable area (ha) and its proportion of UA land (mean fuzzy suitability = the average fuzzy suitability values of 50 × 50 m grid cells in the UA).

	Terrestrial suitability				
Rank order	Unitary Authority	Suitable hectarage	% of UA land area	Unitary Authority	Mean fuzzy suitability
1	Devon	206,776	31.2	Norfolk	0.54
2	North Yorkshire	162,393	14.8	Essex	0.52
3	Cornwall	118,502	32.8	Suffolk	0.52
4	Norfolk	117,231	21.3	Kent	0.47
5	Hampshire	110,172	29.5	North Yorkshire	0.45
6	Wiltshire	108,692	33.4	Lincolnshire	0.45
7	Cumbria	108,288	15.1	Dorset	0.44
8	Lincolnshire	98,095	16.0	Hampshire	0.42
9	Northumberland	95,947	18.9	Cornwall	0.41
10	Shropshire	94,240	29.5	Cumbria	0.41

- High levels of growing-season mean daily hours of bright sunshine occurred along the south-coast, particularly in south-central and south-east England, with decreasing sunshine levels northward and westward (Figure 4(c)).

Inter-annual variability (SD) of GST and growing season rainfall in England and Wales has previously been identified as a risk to wine yields (Nesbitt et al., 2016). Results in Figure 5 for the 1981–2010 period show:

- Higher GST inter-annual variability through central England and west Norfolk, and lower in Suffolk, north Essex, the south west, and west Wales including Anglesey. In general, proximity to the coast will reduce the SD because sea surface temperature varies less from year to year. Further inland, the less influence the sea has and then temperature can vary more according to sunshine and wind direction anomalies.

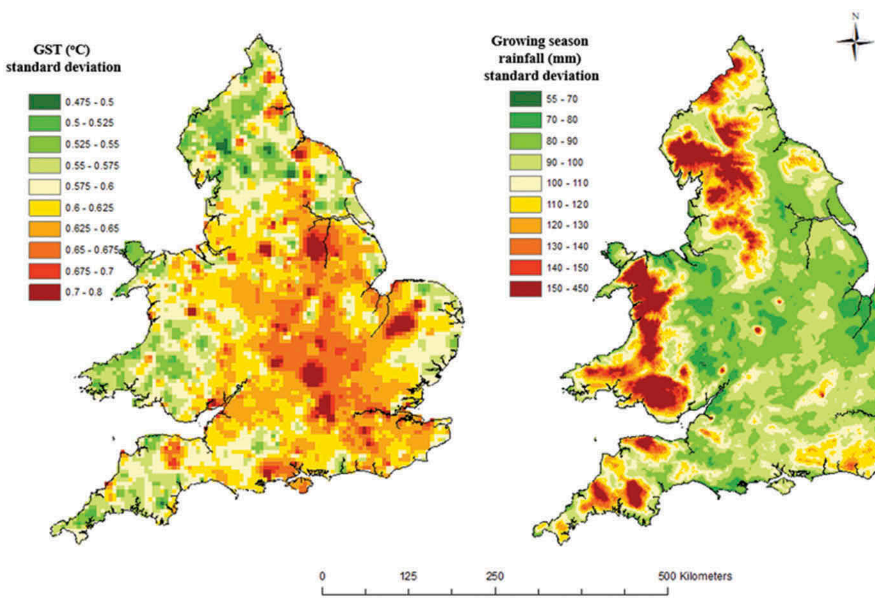

Figure 5. 1981–2010 GST (°C) (5 x 5 km) and growing season rainfall (mm) (1 x 1 km) inter-annual variability (expressed as SD) across England and Wales. Data sources: Centre for Ecology and Hydrology (2014) (Rainfall) and Met Office (2015a) (GST).

- Areas within East and West Sussex and Hampshire had a rainfall standard deviation of 110–140 mm, higher than the majority of East Anglia and Essex (55–90 mm) during the growing season. The latter areas and others in east Wales, the Severn estuary, and Dorset have much greater levels of growing-season rainfall 'stability'.

Figures 4 and 5 show, for the first time, the broad spatial variability of viticultural relevant climatic variables which require assessment when determining optimal viticulture locations. Climatic suitability for viticulture in England and Wales is however not dependent on any one single variable, rather it is the combination of factors that is important. When 1981–2010 mean GST, GST SD, April and May air frost days, growing season bright sunlight hours, growing season rainfall, growing season rainfall SD, and June rainfall values are individually fuzzified, and then combined (Fuzzy Overlay), the resulting climatic suitability model can be visualised to help identify spatial suitability at national and local scales.

Figure 6 shows the spatial distribution and fuzzification of climatic suitability for viticulture across terrestrially suitable areas in England and Wales at 5 × 5 km resolution. White areas in Figure 6 are not suitable. At a local level (0–5 km) when previously identified terrestrially suitable land (Figure 3) is overlain with the model climatic suitability layer, results determine whether climate may be a limiting suitability factor or, as in the case illustrated in Figure 6, that there is indicative viticulture opportunity. The highest maximum cell-value for climatic suitability was found in West Sussex, but at UA scale the Isle of Wight had the highest mean fuzzy climatic suitability (see Table 4), followed by West Sussex and Suffolk. These results suggest an apparent correlation between climatic suitability and the current distribution of viticulture in the south-east of England, but also indicate a high degree of mean climatic suitability in Suffolk, which hosts only eight vineyards (≥ 1 ha) equating to only 1.6% of vineyard area (ha) in England and Wales (2015). Suffolk and Essex had both relatively high mean terrestrial suitability values and area, and relatively high combined climatic suitability (Table 4). Within these Eastern counties it can also be seen (Figure 5) that in general there is lower GST and growing season rainfall inter-annual variability (1981–2010) than in the south-east and south-central areas which currently dominate production. This suggests these areas have greater temperature and rainfall stability from one season to the next.

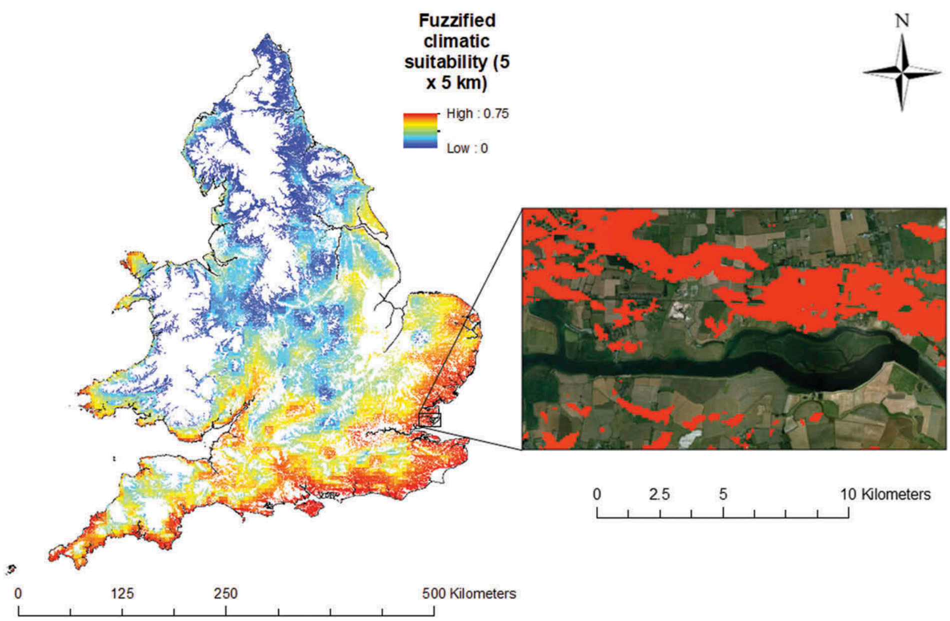

Figure 6. Climatic fuzzified viticulture suitability at national and local scales.

Table 4. Top 10 (ranked) Unitary Authorities (UA) by climatic suitability and their fuzzy values according to the EWVS model (mean fuzzy suitability = the average fuzzy suitability values of 50 × 50 m grid cells in the UA; maximum fuzzy suitability = the highest fuzzy suitability value of a grid cell in the UA).

Climatic suitability			
Unitary Authority	Mean fuzzy suitability	Unitary Authority	Maximum fuzzy suitability
Isle of Wight	0.59	West Sussex	0.75
West Sussex	0.52	Kent	0.69
Suffolk	0.51	East Sussex	0.66
East Sussex	0.50	Essex	0.65
Kent	0.50	Isle of Wight	0.65
Essex	0.49	Cornwall	0.65
Cornwall	0.47	Dorset	0.64
Dorset	0.47	Suffolk	0.64
Hampshire	0.46	Hampshire	0.63
Greater London Authority	0.46	Devon	0.63

Combined viticulture suitability in England and Wales: EWVS model results

By combining terrestrial and climatic models, through an overlay fuzzification process, a comprehensive viticulture suitability model for England and Wales was generated – as presented in Figure 7 (including the highest 20% of fuzzified suitable land) at regional and local scales. Viticulture suitability, through the EWVS model, is defined as any 50 × 50 m grid-cell that encompasses all the prescribed suitability parameters set out in Table 1. The higher the EWVS model fuzzy score (0–1) the greater the cell's viticultural suitability. From this it is possible to assess collective suitability by Unitary Authority and gain an understanding of the amount of potential viticultural land under different model fuzzified classifications.

Table 5 shows, for each of the most suitable 10 Unitary Authorities in England and Wales, the mean and highest fuzzy value of all suitable 50 × 50 m cells as well as the total (summation of all suitable cell values) within those Unitary Authorities.

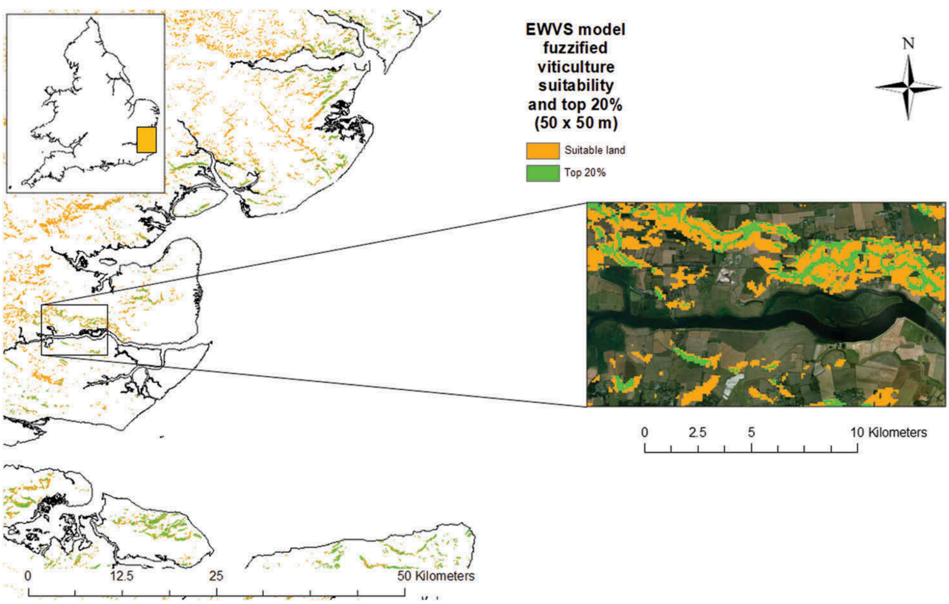

Figure 7. Combined (EWVS model) fuzzified viticulture suitability at regional and local scales, including the highest fuzzified 20% of land.

Ranking viticulture suitability by Unitary Authority resulted in:

- The Isle of Wight, followed by Suffolk, West Sussex and Essex having the highest mean suitability (the mean of all suitable grid cells within those UAs). In Wales, the Vale of Glamorgan 'scored' particularly well, perhaps surprisingly as it only currently has 6.3 ha of vineyards (Figure 2, reference 15/Table 2).
- Kent having the highest (0.82) single viticulture suitability grid cell (50 x 50 m)
- Norfolk topping overall suitability, when land area is taken into consideration (all suitable grid cell values summed).

Limiting the EWVS model to identify only the highest 20% of suitable viticultural areas in England and Wales (Figure 7) results in:

- The identification of 33,700 ha of prime viticulture land. This is slightly larger than the Champagne region in France (33,500 ha) (Johnson & Robinson, 2001). Kent, West and East Sussex, Essex and Suffolk have the largest share of this land area.

When the EWVS model was even further restricted to show the top 5% of suitable land the results, by hectarage, stretched across 25 Unitary Authorities with West Sussex having the largest area (911 ha), followed by East Sussex (503 ha), Kent (468 ha), Suffolk (343 ha) and Cornwall (341 ha). Approximately 300 ha were identified in both Dorset and the Isle of Wight, 150 ha in Devon and 100 ha in both Hampshire and Essex.

Interestingly Sussex (West and East combined), is the only region within England and Wales to have its own PDO status which specifically refers to Sussex as 'one of the driest and warmest areas in England … with average rainfall typically between 600–850 mm per annum …'. Although through this work Essex was found to be the warmest and driest region during the growing season (over the 1981–2010 period) in overall suitability classifications, East and West Sussex also 'performed' well.

This assessment illustrates the significant scale of opportunity for English and Welsh viticulture in highly suitable areas and demonstrates viticulture potential well beyond the previously defined latitudinal 'norms' (40–50°N – de Blij, 1983; Jones, 2006; Schultz & Jones, 2010; White et al., 2006), up to circa 51.5°N. The local identification and targeting of these prime locations can be achieved through the EWVS model. As illustrated in Figure 7 the EWVS model can be used to rapidly 'grade'

Table 5. Ranked viticulture suitability by Unitary Authority.

Summed fuzzy suitability ranked by UA						
Rank Order	Unitary Authority	Mean suitability	Unitary Authority	Maximum suitability	Unitary Authority	Summed suitability
1	Isle of Wight	0.46	Kent	0.82	Norfolk	194,276
2	Suffolk	0.45	East Sussex	0.81	Devon	147,161
3	West Sussex	0.44	Isle of Wight	0.80	Hampshire	136,290
4	Essex	0.44	West Sussex	0.80	Essex	130,377
5	Vale of Glamorgan	0.43	Dorset	0.79	Kent	128,564
6	East Sussex	0.42	Cornwall	0.78	Lincolnshire	128,232
7	Norfolk	0.42	Devon	0.77	North Yorkshire	127,623
8	Kent	0.41	Pembrokeshire	0.75	Suffolk	125,546
9	Greater London Authority	0.40	Hampshire	0.75	Cornwall	116,559
10	Isle of Anglesey	0.39	Suffolk	0.74	Dorset	105,472

any 5 × 5 km area for suitability and within those grid-cells, identify terrestrial suitability at field scale (50 x 50 m).

The distribution pattern of the combined resulting fuzzy scores for cells in the EWVS model is skewed left, as shown in Figure S3 (supplementary material). The distribution indicates that most of the viticulturally suitable land has a score higher than the mean and a larger proportion of suitability grid-cells have a fuzzy score of > 0.5, perhaps indicative of the restrictions/suitability envelopes imposed on suitability criteria (Table 1).

Viticulture suitability of existing English and Welsh vineyards

By applying the EWVS model to existing English and Welsh vineyards (≥ 1 ha) their fitness and model alignment can be determined to assess existing suitability. Here, it should be noted that these results are based on only one 50 × 50 m visually prescribed grid cell closest to the centre of each vineyard (see Materials and Methods). Although such a small area may not be indicative of mean elevation, slope angle or aspect throughout a vineyard, the coarser resolution Soilscapes data layer and spatially averaged 5 × 5 km 1981–2010 climate layers used in model development are likely to provide more appropriate results when extracted from a single grid-cell.

The top five soil 'types' in existing vineyards were classified as: 'Slightly acid loamy and clayey soils with impeded drainage' – 92 (25%), 'Freely draining slightly acid loamy soils' – 85 (23%), 'Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils' – 70 (19%), 'Shallow lime-rich soils over chalk or limestone' – 32 (9%), 'Freely draining lime-rich loamy soils' – 19 (5%). A further five vineyards were positioned on soils classified as being 'Slowly permeable seasonally wet acid loamy and clayey soils'. These results suggest that of the approximate centres of the 367 vineyards identified and analysed, 45% are positioned on soils classified by the Soil scapes (Farewell et al., 2011; LandIS, 2015) data as having impeded drainage or being slowly permeable and seasonally wet, factors that are not deemed 'ideal' for viticulture due to their negative association with disease pressures and impact on vine health (Lanyon et al., 2004). However, despite the *prima facie* unsuitability of such soil 'types' they were included within the EWVS model because such a considerable number of vineyards were located on them. Potential soil amelioration activities (including land drainage), rootstock selections, and analysis of vineyard performance from vineyards on these soil types fell outside of the scope of this study but it is accepted that such activities can mitigate otherwise negative effects of these soil parameters.

Overlaying ≥ 1 ha vineyards with 1981–2010 climate outputs, presenting these conditions in bands and calculating the number of vineyards that fell within each band highlighted the potential for spatial optimisation of viticulture to areas with higher degrees of climatic suitability, as presented in Table 6.

These results demonstrate:

- 85% of vineyards (≥ 1 ha) in England and Wales are positioned in locations (within 5 × 5 km grids) with a 30-year (1981–2010) mean GST above the 13°C climate/maturity threshold for cool-climate viticulture (Jones, 2006).
- Only 10% are in regions with a mean GST > 14°C, the observationally driven climate/maturity threshold for Chardonnay and Pinot Noir (Jones, 2006), the dominant grape cultivars in England and Wales (Nesbitt et al., 2016).
- Only 4% of vineyards were in areas with the highest level of sunshine hours, with the majority experiencing 5.5–6 hours per day on average during the growing season.
- All vineyards were positioned within 5 × 5 km grid-cells with April and May air frost occurrence. These results suggest that without site positioning that allows adequate cold air drainage or frost risk mitigation capacity, all vineyards are exposed to a degree of threat.
- The largest proportion of vineyards (≥ 1 ha) were in locations with 400–450 mm of rain (1981–2010) during the growing season and 50–55 mm in June. However, there were vineyards positioned in areas with lower rainfall (seasonally and in June when high levels of rainfall have

Table 6. Ranked (Top 6) percentage of English and Welsh vineyard locations (from 367 ≥ 1 ha) with imposed 1981–2010 mean climatic bands.

Rank order	Vineyards (%)	GST (°C)	Vineyards (%)	Daily mean hours of bright sunshine	Vineyards (%)	April & May air frost days	Vineyards (%)	Growing season total rain-fall (mm)	Vineyards (%)	June rainfall (mm)	Vineyards (%)	GST (°C) SD	Vineyards (%)	Rainfall (mm) SD
1	10	> 14	4	> 6.25	3	< 0.5	4	< 350	16	< 50	11	< 0.575	5	< 80
2	40	13.5–14	21	6–6.25	3	0.5–1	21	350–400	34	50–55	15	0.575–0.6	28	80–90
3	35	13–13.5	26	5.75–6	13	1–1.5	39	400–450	27	55–60	32	0.6–0.625	26	90–100
4	12	12.5–13	27	5.5–5.75	38	1.5–2	23	450–500	13	60–65	30	0.625–0.65	19	100–110
5	2	12–12.5	14	5.25–5.5	35	2–2.2.5	6	500–550	5	65–70	11	0.65–0.675	17	110–120
6	1	< 12	8	< 5.25	8	> 2.5	7	> 550	5	> 70	1	> 0.675	5	> 120

been shown to negatively affect wine yields in England and Wales (Nesbitt et al., 2016)), demonstrating potential for improved climatic positioning.

- All vineyards (≥ 1 ha) were in areas with a GST SD above 0.53°C, and growing season rainfall SD > 73 mm. As illustrated in Table 4 there is potential for vineyards to be positioned in areas with lower levels of inter-annual variability than most currently are. Lower levels of inter-annual variability indicate greater growing season climatic stability which in turn, when all else is equal, is conducive to greater yield consistency.

Although detailed analysis of terrestrial suitability across each of the existing 367 vineyards (≥ 1 ha) in England and Wales was beyond the scope of this work, modelled terrestrial suitability was calculated for the entirety of each of the 13 largest (≥ 25 ha) English vineyards, accounting for 29.8 % (523 ha) of English and Welsh vineyard hectarage (≥ 1 ha) included in this study. Results were as follows:

- A mean aspect averaged across all 13 vineyards of 158° (south-south-east) and slope 5.6 %.
- A dominant soil type of 'Shallow lime-rich soils over chalk or limestone' followed by 'Freely draining slightly acid loamy soils'.
- Ten of the 13 vineyards predominantly established on land classified as Arable or Horticulture, two on land classified as improved grassland and one on rough grassland.
- A mean fuzzy suitability of 0.6 and a range of individual vineyard mean values from 0.34–0.74.
- An elevation range of 3–124 m across the 13 vineyards with the average of all elevation means being 50 m, within the 'optimal' model criteria.

Using an analogue approach to viticulture-terrestrial suitability modelling an analysis of terrestrially suitable land with greater fuzzy suitability values (> 0.74) across England and Wales was subsequently undertaken, resulting in a total 1,592,749 ha of land being identified, i.e. land with a greater suitability value rating than the highest of the existing 13 largest vineyards in England and Wales. Perhaps of greater significance was that 284,110 ha were in the counties of East and West Sussex, Kent, Surrey, Hampshire and Wiltshire, where the majority of the 13 large vineyards were located, suggesting potential climatic as well as terrestrial suitability.

Discussion

The prospect of future climate change impacts on viticulture, specifically risks to appellations in 'old world' regions, potential changes to existing cool-climate regions, and opportunities for additional 'new world' regions to emerge was raised almost 30-years ago (Smart, 1989). Smart (1989) noted the potential for a global re-distribution of wine-grape growing and recognised the social and economic implications that such shifts could cause. Whilst large-scale viticulture migration from 'hot' areas has not been realised to-date, potentially as a result of adaptive capacity building, a greater body of evidence has been collected to demonstrate potential opportunities for new 'new world' regions to emerge (Fraga et al., 2013a; b; Kenny & Harrison, 1992; Nesbitt et al., 2016; Tesic, Woolley, Hewett & Martin, 2001; Tóth & Végvári, 2016). As yet, however, there are few impact studies that producers or investors can extract decision making value from, not least because most do not align climate suitability models with the terrestrial landscape that is paramount to commercial viticulture potential. Furthermore, whilst viticulture-climate studies to-date have predominantly focused on climate change impacts in the hotter viticulture regions of the world, few have paid attention to emerging 'cool-climate' regions.

This work has concerned itself with two new regions, England and Wales. Multi-criteria datasets were overlain using ArcGIS and subjected to fuzzification processes to develop the first viticulture suitability model for England and Wales – the EWVS model. This somewhat novel approach to viticulture suitability modelling enables, in our opinion, a more valuable and informative grading of land suitability than can be derived from a Boolean approach. Applying the model to existing vineyards in England and Wales, through an overlay and analysis process, the sub-optimal positioning of most vineyards was found in relation to GST (only 10% of vineyards were currently located in areas with highest GST values) sunshine hours, April & May air frosts, and rainfall (seasonally and in June). Furthermore, restricting the EWVS model outputs to only the top 20% of combined terrestrial and climatic area resulted in 33,700 ha of prime land being identified, an area larger than the existing Champagne region of France, and on similar terrain. As well as opportunities for expansion within the currently dominant regions of Kent and Sussex, new areas such as Essex and Suffolk in particular, where relatively few vineyards currently exist, have been shown to have highly suitable land, express high degrees of climatic suitability and greater levels of stability from season to season than areas currently populated with vineyards. The lack of viticulture practiced within these authorities is therefore somewhat surprising and may result from successful cropping in other forms of agriculture or horticulture. However, it could also be partly explained through a prior lack of nationwide suitability analysis and investment momentum regarding establishment of vineyards in the south-east. Under future climate change scenarios suitable land area could increase further, potentially beyond the ~51.5°N latitude of suitability identified in this work, as terrestrially suitable land in England and Wales far outweighs that which is currently considered to be climatically suitable. Using existing larger vineyards as analogues and interrogating the model to uncover areas with higher terrestrial suitability resulted in significant new areas of high value land being exposed for potential viticulture investment.

Several studies have modelled future climate change impacts on viticulture in Europe, for example Moriondo et al. (2013), and Fraga, Garcia de Cortazar Atauri, Malheiro & Santos (2016). Modelled projections of future viticulture suitability by Tóth and Végvári (2016) implied that post-2050 large areas of southern England may be suitable for viticulture, but evidence of existing and rapidly increasing viticulture activity in England and Wales has been largely overlooked in research to date. Although rapid recent sector growth in England and Wales does not necessarily reflect viticulture 'suitability' or economic sustainability, a closer examination of the spatial variability of terrestrial and climatic suitability generates knowledge from which informed investment decisions can be made about where best to establish vineyards.

Near-surface wind speed data, higher-resolution soil data, historic vineyard varietal yield and quality parameters, and the ability to incorporate inter-annual variability expressed as coefficient of variation would all enhance model functionality. Nonetheless, through reference to the EWVS model presented in this study, the regional distribution of viticulture could be adapted to better match apparent terrestrial, weather and climate suitability.

Acknowledgments

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Disclosure statement

This research may lead to the development of products which may be licensed to Climate Wine Consulting Limited and/or Weatherquest Limited, in which Dr Alistair Nesbitt and Professor Steve Dorling respectively have business and financial interests. They have disclosed those interests to Taylor & Francis.

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