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Blurred Vines: A Fuzzy Logic-Based Terrestrial and Climate Suitability Model (DVSM) for Danish Viticulture with Spatial Autocorrelation and Vineyard Placement Analysis

By Patrick Tully

230242300

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Academic Supervisor: Dr. Jingxia Wang

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Signed____Patrick Tully____ Date______30/8/2024______

Preface

I would like to express my thanks to Dr. Ruth Hamilton and Dr. Andrew Sole from the Department of Geography, for their valuable technical guidance during this project. Their enthusiasm, including taking time out of their own summer holidays to support this research project, has contributed hugely. I would also like to thank my supervisor, Dr, Jingxia Wang, for her continued support and guidance. Her honest and insightful academic feedback during our dissertation supervision meetings was hugely appreciated.

This dissertation would not have been possible without the collective support of these three individuals; however, I would also like to thank the wider body of USP staff at the University of Sheffield. I am immensely appreciative to each member of the Applied GIS teaching staff for their commitment and enthusiasm during this period of study.

Abstract

Wine Grape cultivars *(Vitis Vinifera L.)* are traditionally grown within narrow latitudinal bands (30-50°N and 30-40°S). However, within Denmark the number of commercial growers increased 1100% between 2000 – 2017, supported by increasing mean Growing Season Temperatures during April – October. Despite increasing evidence that suggests viticultural suitability beyond 50°N, Denmark remains exposed to low and highly variable grape harvests. This investigation aims to develop and test a fuzzy logic-based Danish Vineyards Suitability Model (DVSM) to evaluate and mitigate risks associated with climate and terrestrial characteristics.

Open-source climate and terrestrial datasets were integrated within the DVSM using Fuzzy Membership and Overlay functionality in ArcGIS Pro to evaluate current suitability, spatial distribution of viticultural suitability and optimal Danish Vineyard site allocation at the national scale.

Results indicate that 70.7% of existing Danish vineyards meet observationally observed 'cool climate' thresholds during 2011-2023. Segmentation of the significantly warmer 2018 growing season suggests a high proportion (50.7%) of Danish vineyards meet threshold values for cultivation of Pinot Noir and Chardonnay varietals. These findings are tempered by statistically significant ($P < 0.05$) positive spatial autocorrelation of viticultural suitability at Local and Global spatial scales. Terrestrial, climate and combined suitability are highest throughout Hovedstaden and Sjælland, whilst low suitability clusters were positioned across Nordjylland, Midtjylland and Syddanmark. Growing Season Precipitation and Growing Season Temperature standard deviation showed increased stability at coastal margins compare to the Danish interior. Consequently, GST and GSP characteristics more favourably support existing and prospective vineyards at South-easterly oriented coastal margins beyond 10.8°E.

This investigation has successfully addressed the research objectives outlined, and developed and tested a high resolution (10m) Danish Vineyards Suitability Model to enable rapid identification and grading of suitable land, to support policy and investment decision-makers in Danish Viticulture.

Keywords *– DVSM, Fuzzy Logic, Danish Viticulture, Boolean Logic.*

Table of Contents

List of Tables and Figures

1. Introduction

Wine grape cultivars (Vitis Vinifera L.) are typically grown in narrow latitudinal bands (30-50°N and 30-40°S), characterised by growing season climatic conditions of low extreme heat and cold (Jones, Snead and Nelson, 2004). In each viticultural region the quality of wine produced is directly related to the quality of the grapes, with winemaking that has evolved through centuries of trial and error, resulting in long held cultural practices within the winery (Badr et al., 2018).

The interaction between cultural practices, local environment, and the vines is neatly summarized by the French concept of "terroir", which remains a fundamental consideration when cultivating grapes of high quality and yield (Nesbitt, Dorling and Lovett, 2018; Jones, Snead and Nelson, 2004; Vaudour, 2002). Growing season frost, wind exposure, inadequate solar irradiance and soil moisture and excessive growing season precipitation (hereby referred to as GSP) can damage grape quality (Nesbitt, Dorling and Lovett, 2018; Van Leeuwen and Seguin, 2006). The sensitivity of Vitis Vinifera to even small changes in growing season climatic indices indicates that climate change threatens the current spatial distribution of viticulturally suitable wine grape growing regions (Webb et al., 2013). Nesbitt et al (2022) report a ~1.0 °C increase in growing season average temperatures (GST) in the main viticultural regions of the UK between 1981-2000 and 1999-2018. Indeed, viticulture has expanded beyond regions traditionally bounded by the 10° and 20° isotherms (Schultz and Jones, 2010). There is increasing evidence to suggest new cool climate viticulture beyond 50°N, particularly in Denmark, England and Southern Sweden. Within Denmark, registered commercial producers increased from 8 to 96 (1100%) between 2000 to 2017 (Becker and Toldam-Andersen, 2021).

The significant increase in Danish vineyard hectarage, supported by increased Growing Season Temperature (hereby referred to as GST) during April – October has not been supported by high resolution, objectively quantifiable evaluation of variables including soil characteristics, seasonal weather profiles and interannual variability (Olsen et al., 2011). To date, vineyard site selection has occurred on a case-by-case basis, which leaves Danish viticulturists at risk of subjective judgements, in addition to exposure to low and significantly variable yields. The ability of modern GIS to integrate and process large quantities of geospatial data presents a compelling means by which to bypass centuries of 'old world' trial and error, learning and adaptation (Nesbitt, Dorling and Lovett, 2018). Defining quantitative relationships between significant environmental inputs will decrease the risk associated with weather and climate variability and increase investor confidence in Danish viticulture.

This investigation addresses three research questions. Research question 1 aims to determine the extent to which terrestrial and climatic conditions in Denmark support 'cool climate' grapevine production in Denmark. This is achieved via a review of the existing cool climate literature to define significant environmental variables. Research question 2 aims to evaluate the spatial distribution of viticultural suitability values derived from the Danish Vineyards Suitability Model (DVSM) in research question 1 using Global Moran's I and LISA statistical methods. Finally, research question 3 aims to evaluate whether existing Danish Vineyards are optimally located, through application of DVSM suitability values and variable inputs using Zonal Statistics in ArcGIS Pro.

The overarching purpose of this investigation is to address the existing deficit between 'cool climate' viticultural suitability analyses and current viticultural output in Denmark. Although a small number of studies have previously employed Analytical Hierarchy and Weighted Sum methodologies to site vineyards in Denmark, such studies are becoming increasingly outdated, relying on datasets which are increasingly unrepresentative of true climatic suitability in terms of GST and Growing Degree Day (hereby referred to as GDD) sums. This study will develop a novel fuzzy logic-based combined suitability model in Denmark, to more accurately conceptualise uncertainty in the context of suitable parameter values using Fuzzy Membership and Overlay functions in ArcGIS Pro. To provide the most accurate and valuable quantitative reference tool for Danish vine growers, this investigation will encompass Denmark at national scale, using open-source Danish Meteorological Institute observations of climate variables between 2011-2023. This temporal scale will not only contribute to the work of Olsen et al. (2011) who present Bioclimatic indices for Denmark for the period 1996-2006, but also provide contemporary insight into climatic conditions of recent growing seasons which continue to exhibit significant variability. Viticultural suitability outputs are presented are very high (10m) resolution such that viticultural suitability can be established on a cell-by-cell basis.

This investigation will break from traditional applications of GIS within viticulture, which typically employ Boolean (true/false) logical operators, often in tandem with user defined weighting factors to define 'suitability' (Wanyama et al., 2020; Jones, Duff and Myers, 2006; Tonietto and Carbonneau, 2004). This investigation employs Fuzzy set functionality in ArcGIS Pro to conceptualisation dataset i.e. suitability membership using a degree of association between 0 (non-member) and 1 (member). Although technically less established, fuzzy membership functionality has significant value for modelling risk and potential opportunities in a more nuanced way than 'narrow' Boolean approaches might. The methodology presented herein contributes to a growing body of Fuzzy logic-based cool-climate site suitability analyses in England, Wales and Southern Sweden (Nesbitt, Dorling and Lovett, 2018; Cepnioglu, 2021).

To answer the research questions and objectives stated in section 3, this investigation will be organised as follows. Initial context and background provided herein will inform a review of contemporary and relevant viticultural literature, present in section 2. Particular attention is given to fuzzy logic-based analyses particularly in emerging cool climate regions, to extract key modelling and parametrisation protocols. The methodology will describe and justify suitable parameter values used within DVSM development, particularly in terms of Fuzzy Membership and Overlay functions. Each research question is addressed separately within the methodology. Presentation of results by research question aims to clearly illustrate the distinct findings of each analytical process described in the methodology. The discussion section takes the opportunity to contextualise these findings within the broader literature, both in relation to previous fuzzy logic-based viticultural analyses and generic reference values for GSTs, GDD sums and GSP. The conclusion will summarise the key findings of DVSM and associated analyses to emphasise the utility of the analysis conducted herein.

2. Literature Review

2.1 Climate Change and the Emergence and Evolution of Cool-Climate Viticulture

Scandinavian viticulture can be dated to a small number of monasteries in medieval times; however, the resulting wines were of poor quality, owing to the unreliable and harsh bioclimatic indices (BCIs) (Olsen et al., 2011). Consequently, successful maturation of grapevines was uncertain, particularly during the Little Ice Age (1500-1800 A.D.), characterised by shorter growing seasons and increased prevalence of frost risk (Schultze, Sabbatini and Luo, 2016). Olsen et al. (2011) cite growing season length, volume and temporal distribution of rainfall, prevalence of frost risk, soil drainage and solar irradiance as relevant constraining factors within Danish viticulture. Anthropogenic climate change, bringing prolonged growing seasons and reduced prevalence of growing season frost (April – October) in the higher latitudes, combined frost resistant cultivars has led to an intensive development of Danish viticulture in the last 20-25 years (Becker and Toldam-Andersen, 2021). Génsbøl & Gundersen (2002) present an attempt to classify Danish vine-growing regions in, which ultimately failed to provide a suitably high resolution quantitative and objective measure of viticultural suitability.

Nesbitt et al. (2022) observe increases in growing season average temperatures (GST) between 1981-2000 and 1999-2018 of ~1°C in the UK, in tandem with rapid expansion of the UK viticultural sector. Vineyard hectarage (ha) in England and Wales has increased 246% (722 to 3800 ha) between 2004 and 2017. The authors cite “enhanced investor confidence, sector expansion, widening varietal suitability, and greater viticulture opportunity”, in addition to warming of GSTs (April – October) as underpinning this expansion (Nesbitt, Dorling and Lovett, 2018). The UK experienced it’s ten warmest years on record since 2002, making the 2018 record yield of 84 hL/ha 30 times more likely to occur, than would be expected without anthropogenic climate warming (Met Office, 2018). In contrast, a key theme relating to developing cool climate viticulture beyond 50°N in Denmark, England and Southern Sweden, concerns intra and inter-annual weather variations. All three nations are located between mid-latitude westerly wind belt on the edge of the Atlantic Ocean. They are therefore sensitive to fluctuations of major atmospheric systems, which has been demonstrated to impact viticultural productivity at annual or longer temporal scales. For example, Nesbitt, Dorling and Lovett (2018) report that between 2004-2013 period, UK wine yield exhibited considerable yields of 6-34 hectolitres per hectare (hL/ha), with a mean value of 20.7 hL/ha, less than one third of the Champagne harvest base yield of 66 hL/ha. Considering such variability, the authors conclude that cool climate viticulture remains exposed to low, and highly variable yields (Nesbitt, Dorling and Lovett, 2018). Considering the relevance of meteorological and climate variability to such vulnerability, identifying cool climate regions of requisite terrestrial and climatic suitability is critical to improving viticultural resilience in the face of predicted climate extremes, as a valuable tool for informing investment decisions.

2.2 Evaluation of Conventional GIS Applications in Viticulture

GIS-based analyses within the literature have been applied to map viticultural suitability both in 'old' and 'new' world grape growing regions, specifically England and Wales, Romania, Oregon and Southern Sweden (Jones, Snead and Nelson, 2004; Irimia and Patriche, 2011; Nesbitt, Dorling and Lovett, 2018; Cepnioglu, 2021). Early approaches typically favour Boolean (true/false) logical operator, 'AND' and 'OR' union operators combined with user defined weighting factors to define 'suitability'.

Jones et al. (2004) aimed to evaluate climate and landscape suitability of the relatively young growing region Umpqua Valley, Oregon. Topography, soil type, land use and climate suitability were used to model suitability. Climatic suitability was defined using a GDD calculation, further refined using GSP and observed frost risk, specifically length of frost-free growing season (days between last and first frost within the growing season). Weighted overlays were calculated to determine relative importance of input variable both when developing composite indices of soil and climatic characteristics and during final model development. Although this investigation identified 3000 acres of 'nearly ideal' sites, additional suitable land may have been 'masked' out due to the overly restrictive intersection operator 'and' used when combining multiple datasets which may exclude an area if a single criterion fails to meet its Boolean threshold value. The methodology presented is somewhat limited by the inability to appropriately model membership 'uncertainty' in this context. It is likely that terrestrially and climatically marginal areas, which may be improved through vineyard amelioration techniques will be entirely excluded within this methodology and overall viticultural suitable area underestimated.

Similar, although technically distinct research by Kurtural et al. (2007) aimed to develop and apply a GIS for Illinois, to mitigate economic risk associated with biotic and abiotic stressed which threaten grape quality and crop yields. Spring frost and low growing season air temperature are cited as being particularly impactful to vine health. This was achieved via a weighted sum calculation, which incorporated macro and mesoclimate indices from 1969 and 2002, soil properties and land use attributes to model viticultural suitability. Weighted sum analyses, which rely on user defined weighting values to quantify variable influence within the model, are commonplace within crop suitability analyses. In this case, an index scale (0-100) determined the suitability value which is categorically defined as 'best', 'good', 'fair', 'risky', 'unsuitable'. The 0-100 suitability scale was weighted according to perceived importance, with 40 points available for macro and meso-scale climate variables each, and a further 10 points each available for soil properties and current land use. Although the implication that macro and micro-scale climate variables are of relatively high importance in moderating grapevine quality and yield is supported by the literature, the implication that such influences are four times greater than soil or land use characteristics is not. User defined weighting values are partial to user bias, resulting in skewed model outputs. Moreover, the sorting of suitability in categorical bins of 20 points width introduces further uncertainty whereby a suitable score of 1 point may result in each land area being assigned a significantly different categorical suitability classification.

An emerging trend towards additional temporal nuance specifically in terms of intra annual GSP and GST trends, is supported by increasing resolution of spatial and temporal datasets and desktop GIS computational efficiency. Wanyama et al. (2020) refined Jones et al'. 2004 study in Michigan by segmenting early and late season precipitation, both of which are increasingly understood to influence grape development and quality parameters as well as flavour profiles in the weeks prior to harvest (Nesbitt, Dorling and Lovett, 2018). This investigation aimed to provide a quantitative decision support tool to support the expansion of Viticulture in Michigan and contributes the first data driven approach to viticultural site suitability in the state. The authors emphasise the importance of the following BCIs: frequency of cold days, number of frost-free days, GDDs and segmented precipitation (for growth, disease and rot) as fundamental driving forces of vinifera production. This contention is widely supported within the academic literature (Jones, Duff and Myers, 2006; Hellman et al., 2011; Perry, Sabbatini and Burns, 2012).

To summarise, conventional applications of GIS in viticultural site selection have been driven by the growing requirement for a cost-effective means of retrieving, managing and analysing relevant geospatial datasets to inform viticulturalists and offset the financial risk associated with centuries of trial and error, learning and refinement associated with traditional 'old-world' viticulture. Contemporary advances in desk-based GIS computational efficiency and high-resolution spatiotemporal datasets continue to improve upon the 'benchmark' site suitability analyses discussed. The following section discusses the utility of fuzzy set membership in combatting restrictive Boolean (true/false) logical operators which may have skewed early quantitative evaluation of viticulturally suitable land (Chrobak, Chrobak and Kazak, 2020).

2.3 Recent Fuzzy Logic-Based GIS Site Suitability Analyses

The overwhelming majority of site suitability analyses have favoured multi-criteria decision analysis methods, particularly analytical hierarchy process and weighted overlay methods (Jones, Snead and Nelson, 2004; Irimia and Patriche, 2011). In the last 10 years a small number of studies have employed fuzzy logic within the context of viticulture, focussing specifically on the relationship between vintage quality and environmental parameters (Grelier et al., 2007; Paoli et al., 2005; Perrot et al., 2015). Fuzzy membership functions have been applied to evaluate the impacts of agronomical practices and organic viticulture on the environment (G. Fragoulis et al., 2007); evaluation of the impact of micrometeorological conditions on pesticide application in vineyards (Gil et al., 2008), and delineation of vineyard management within vineyards (Morari, Castrignanò and C. Pagliarin, 2009; Tagarakis et al., 2013). Since 2018, several benchmark analyses, discussed below served to evaluate site suitability within viticulture, with improved ability to manage uncertainty, creating more realistic outputs in comparison to contemporary Boolean logic-based approaches.

Badr et al. (2018) successfully implements an array of fuzzified biophysical characteristics derived from historical (1983-2012) climate datasets within Idaho, USA. It is significant to note, 11 distinct BCI methods were incorporated within each model, however, both GST and GDDs, with a base temperature of 10°C were cited among the most reliable BCIs within the literature. GDD Estimates ranged from 850 – 2700, 850 was assigned the fuzzy logic membership value 0 (non-member) and 2700 of 1 (member). GST membership values ranging from 13°C (0) to 18°C (1) were assigned. This study characterises GSTs of <13°C and GDD < 850 as being too cold to support grapevine cultivation, however, it fails to account for emerging cool climate cultivars particularly Aurora, Frontenac and Leon Millot, which Gąstoł (2015) demonstrates exhibits favourable yield volumes, with only minimal detrimental impact to frost damage, sugar content and acidity under similar climatic conditions in Krakow, Poland. Despite this, ground truthing revealed that 97% (38,979.45 ha) of existing vineyards were in ‘high potential’ areas. An additional 3% of vineyards were located within ‘moderate potential’ areas. This is highly significant. Firstly, as proof that highly viticulturally suitable land is found at 49°N, the upper margin of the commonly cited 30-50°N latitudinal band (Schultz and Jones, 2010; de Blij, 1983). Secondly, the high degree of modelling accuracy (100% of existing vineyards were either ‘high’ or ‘moderate’) confirms that fuzzy logic-based analyses can accurately determine viticultural suitability, which traditionally is the result of centuries of trial and error, experience and adaptation.

Within England and Wales, a 246% increase in vineyard hectarage (722 to 2500 ha) (2004-2017) has been supported by sustained increases in growing season average temperatures (April-October) (Food Standards Agency, 2023). Nesbitt, Dorling and Lovett (2018) provide valuable insights into the nature of evolving viticultural suitability in England and Wales by presenting a multi-criteria combined terrestrial-climate based fuzzy logic model at national scale. 33,700 ha of prime viticultural land, larger than the Champagne region of France (33,500 ha) was identified, of which the Isle of Wight, Suffolk and West Sussex were found to exhibit the highest mean suitability score (0.46, 0.45, 0.44 respectively). Although Climatic suitability, a function of GST, Rainfall, frost risk and precipitation and temperature interannual variability, was heavily skewed towards regions in the South and Southeast of England, spatial distribution of terrestrially suitable land was more uniform. North Yorkshire (162,393ha), Cumbria (108,288ha), Lincolnshire (98,095ha) and Northumberland (95,947ha) were all found within the top 10 most suitable Unitary Authorities in terms of terrestrial suitability. These findings contribute fundamentally to developing an objective and quantitatively defined decision support system for winegrowers in England and Wales, a system which, the authors argue, will offset existing concerns regarding grapevine yields, which have varied significantly during 2004-2013 (6-34 hL/ha, mean = 20.7 hL/ha). Inclusion of GST/ GSP inter-annual standard deviation with fuzzy membership type of small, effectively penalises regions of high magnitude GST and GSP variability, which detrimental effects grapevine yield and quality (Ashenfelter and Storchmann, 2014).

2.4 Fuzzy Logic-Based Site Suitability in Denmark and Southern Sweden

Having defined the climatic context in which Danish viticulture is evolving, in addition to ‘Conventional’ and Fuzzy Logic-based viticultural suitability analyses, previous GIS-based investigations within Denmark and South Sweden are now considered.

Olsen et al. (2011) present compelling insights into emerging Danish viticultural suitability. Sum of Growing Degree Days (SDD), Risk of frost damage, Number of sunshine hours during growth season and Soil drainage, are of particular significance to Danish viticulture, determined through personal communication with Danish Viticulture academics and 150 Danish Vine growers.

Several Cool climate viticulture investigations have called to include a wind exposure parameter, both wind direction and speed are significant contextual factors for viticultural suitability, particularly direction, which at broader spatial scales influence air temperature and air moisture (Olsen et al., 2011; Nesbitt, Dorling and Lovett, 2018; Gurwicz, 2020). Within Denmark, windblown salt deposition and mechanical damage due to wind exposure are particularly relevant at coastal margins, particularly the western coast of Jutland which is most strongly impacted by westerly Atlantic and Southerly continental air masses from Mainland Europe (Nesbitt et al., 2022). Despite this, both Olsen et al. (2011) and Nesbitt, Dorling and Lovett (2018) excluded wind direction and speed parameters from modelling attempts, the former arguing that salt associated vine damage is constrained to the saltier and windier Western Jutland coastal margins, while the later argues that inclusion of fuzzified slope aspect and elevation datasets, favouring southerly facing sites of low elevation (20-80m AMSL) elevation, exposure to south westerly winds will be minimized. In the same study, Olsen et al. (2011) calculated and reported GDD estimations from 10 x 10 km gridded minimum and maximum temperature datasets. This investigation utilised a base temperature of 10°C over the 213-day growing season between 1999 to 2016. GDD values of 690 to 964 were found. Such values, although practically unheard of in 'old world' winegrowing regions, show certain promise in the context of emerging cool climate cultivars (Becker and Toldam-Andersen, 2021).

Cepnioglu (2021) Applies Fuzzy Logic-based methods to find that 0.13% (0.58km^2) of cultivated land in Skåne County, Southern Sweden exhibits viticultural suitability greater than 70%, according to their combined topographic, soil, climate suitability model. Considering SMHI predictions of a 1-2°C increase in mean air temperature by 2050, GDDs were recalculated to reflect 1°C, 1.5°C and 2°C warming scenarios. Under such conditions minimum suitability remains constant (12.6%) however mean and maximum suitability increase significantly by 22.6 pp and 31.9 pp respectively.

3. Research Questions and Objectives

3.1 Research Questions

1. To what extent do terrestrial and climatic conditions across Denmark support cool climate wine grape production according to the DVSM?

2. What are the global and local spatial clusters and distributions of viticultural suitability in Demark?

3. Are existing Danish Vineyards optimally located according to DVSM analysis?

3.2 Research Objectives

- Utilise open-source meteorological data to establish Growing Season Temperature and growing degree day sum estimates for Denmark between 2011-2023.

- Apply fuzzy membership and overlay methods to determine to what extent climate and terrestrial datasets support grapevine development.

- Apply spatial statistics (Global Moran's I, Local Anselin I) to ascertain global and local clustering of viticultural suitability scores within Denmark.

- Apply statistical methods to establish the extent to which existing Danish vineyards are optimally located according to DVSM analysis.

4. Materials and Methods

Study Area

This investigation is conducted at national scale in Denmark. Commercial wine production was legally established in 2000 (Becker and Toldam-Andersen, 2021). The number of registered commercial producers increased 1100% between 2000 and 2017 from 8 to 96 (Becker and Toldam-Andersen, 2021). The Danish Vineyard Association reported 1,230 members, including 1,096 hobbyist growers, 3.3% of which originated from other Scandinavian countries in 2017. The top 10 largest producers occupy 52% of total viticultural area with mean vineyard hectarage being 5-10 hectares. Smaller vineyards of 500-2,000 plants are common, with predominant cultivars including Solaris (42%), Rondo (30%), Orion (12%) and Regent (12%) (The Association of Danish Wine, n.d.).

Denmark has a mild coastal climate of relatively warm winters and cool summers. Precipitation is uniformly distributed throughout the year (Olsen et al., 2011). Growing season average temperatures suggest a trend toward increasing suitability for several cool climate cultivars, notwithstanding the uncharacteristically cool 2010-2013 growing seasons. Yield volumes have shown promise in recent years, particularly in 2014, 2016 and 2018 (figure 3-4) (Becker and Toldam-Andersen, 2021). Traditionally dominant red cultivars have recently given way to white, rosé and sparkling varieties. This study will use Regioner (Region), Kommuner (Municipality) and Sogn (Parish) administrative boundaries in multiple cases during statistical analyses to aggregate and standardise terrestrial and climatic suitability.

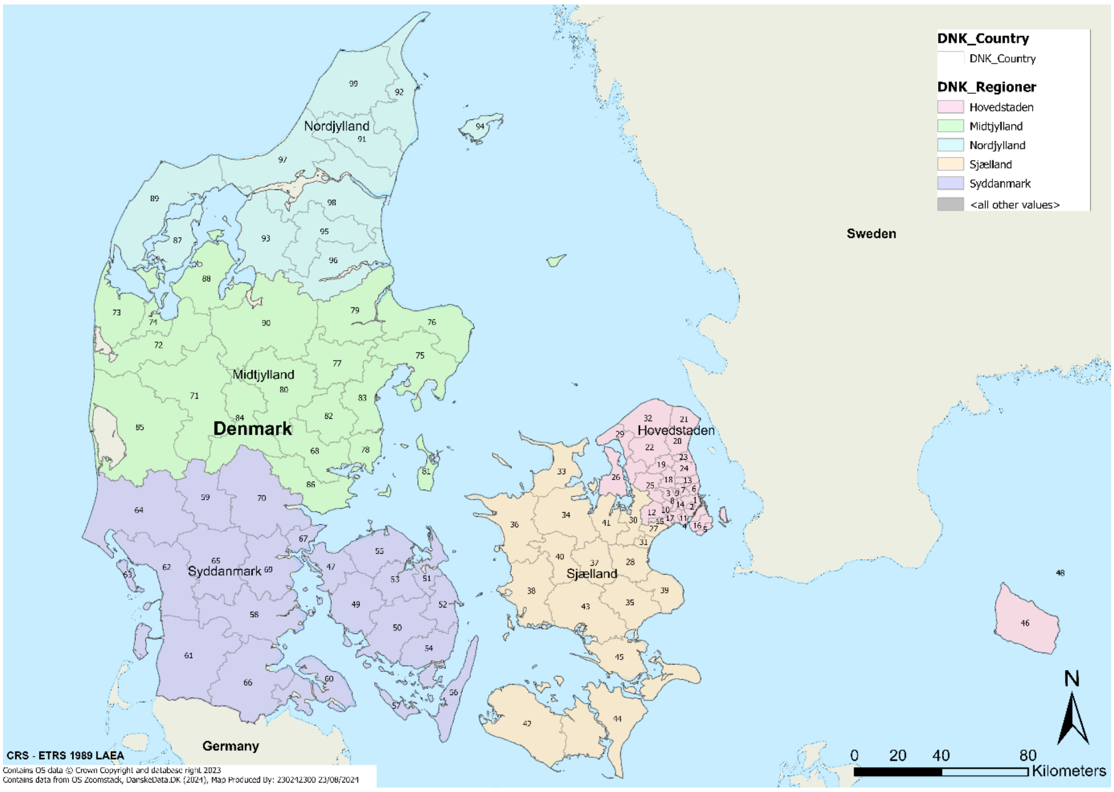

Figure 1 - The study area of the research with Regioner and Kommuner boundaries overlaid.

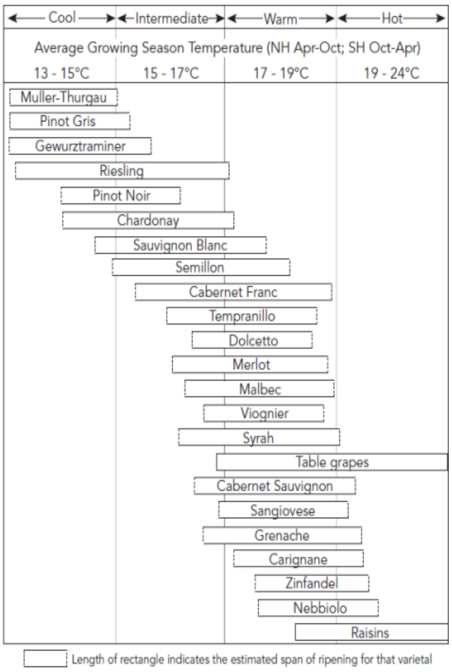

Figure 2 – Climate/Maturity groupings by Grape varietal (Jones, 2006).

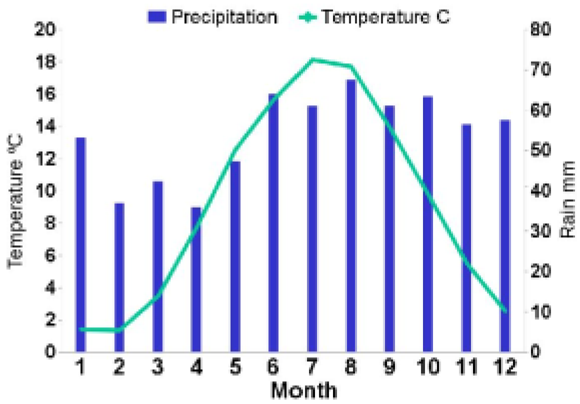

Figure 3 - 1980 - 2010 Mean accumulated precipitation and temperature data for Roskilde, Denmark (Becker and Toldam-Andersen, 2021).

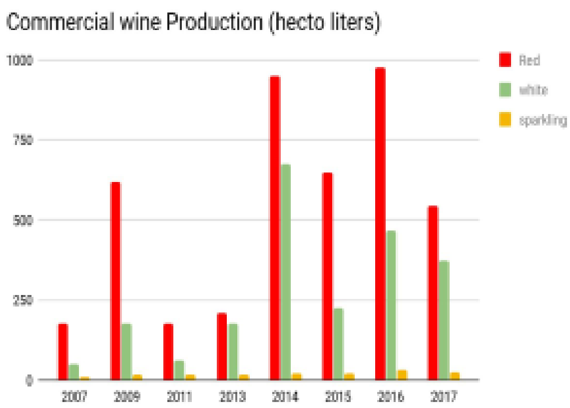

Figure 4 - Danish commercial wine production by varietal (hL) (2007-2017) (Becker and Toldam-Andersen, 2021).

Terrestrial and Climate Data

Variable	Accepted parameter values	Source data type, resolution and source	Model membership type
Elevation	1-150 m	30 x 30m resolution Digital Terrain Model (DTM) for Denmark derived from GEDI, ICESat-2, AW3D, GLO-30, EUDEM, MERIT DEM and background layers (OpenTopography, 2022).	Membership type: Fuzzy Near Mid-point: 52.5 m Spread: 0.001
Aspect	Azimuth angle of slope (90-270°)	Derived from Digital Terrain Model (see above) via ArcGIS Pro Aspect tool at 30 x 30 m resolution.	Membership type: Fuzzy Near Mid-point: 180° Spread: 0.001
Slope gradient	1-15%	Derived from Digital Terrain Model (see above) via ArcGIS Pro Slope tool at 30 x 30 m resolution.	Membership type: Fuzzy Near Mid-point: 5% Spread: 0.001
Land cover	• Agriculture, intensive, temporary crops • Agriculture, intensive, permanent crops • Agriculture, extensive • Agriculture, not classified • Nature, dry • Nature, dry, Agriculture, extensive • Nature, wet, Agriculture, extensive	Basemap04 (Aarhus University - Department of Environmental Science, 2023)	Membership: Boolean Type: Boolean AND
Soil	• Clay, Silty Clay, Silty Clay-Loam, Sandy Clay, Sandy Clay-Loam, Clay-Loam, Silt, Silt-Loam, Loam, Sand, Loamy Sand, Sandy Loam	provided as 3 (500 x 500m resolution) .tif Raster tiles representing Silt, Clay and Sand as percentage of overall soil content. ArcGIS Pro (spatial analyst) Combine tool used to generate a composite soil classification raster. Soil type classified according to US Department of Agriculture Unified Soil Classification System (United States Department of Agriculture, 1987; (Pappas, 2022) (See Appendix).	Membership: Boolean Type: Boolean AND
Designated areas	• Management plans for Defence sites • Management plans for state forests • Protected habitat types • Natura2000 habitats	Basemap04 (Aarhus University - Department of Environmental Science, 2023)	Membership: Boolean Type: Boolean AND

GST	• Higher values to higher growing season temperatures. • GST: = Σ((Tmax + Tmin) ⁄ 2) ⁄ n	Monthly Growing season Average Temperature (Tmax + Tmin) / 2 (mean of daily values) (2011-2023) .geojson files for growing season months (April-October) (Danish Meteorological Institute, 2023). Converted to shapefiles (JSON to feature) and rasterized to 10 x 10 km .tif raster layers.	Membership: Fuzzy Type: Linear
Growing Degree Days (GDD)	• Higher values to higher growing degree days • GDD= ((Tmax+Tmin) ⁄ 2) - 10	Mean of summed daily minimum and maximum temperature observations for each growing season day (April 1st - October 31st) (2011-2023) minus base temperature (10°C)	Membership type: Fuzzy Linear
Mean growing season total precipitation	Higher values to lower growing season precipitation totals	Monthly Growing season Accumulated Precipitation (Σ daily values) (2011-2023) .geojson files for growing season months (April-October) (Danish Meteorological Institute, 2023). Converted to shapefiles (JSON to feature) and rasterized to 10 x 10 km .tif raster layers.	Membership type: Fuzzy Small Mid-point: 6050.3 Spread: 568.74
June Rainfall	Higher fuzzy membership awarded to lower June precipitation total.	Derived for Monthly accumulated precipitation for July only (Danish Meteorological Institute, 2023). Converted to shapefiles (JSON to feature) and rasterized to 10 x 10 km .tif raster layers.	Membership Type: Fuzzy Small Mid-point: 764.1 mm Spread: 81.72
GSP and GST standard deviation	Higher fuzzy membership to areas of lower variance.	Interannual Standard Deviation of Growing Season Temperature and Growing Season Precipitation. Derived from DMI observations of monthly mean temperature and accumulated precipitation.	Membership Type: Fuzzy Small GST SD Mid-point: 0.62 GST Spread: 0.35 GSP SD Mid-point: 12.51 GSP SD Spread 1.44
April – May air frost	Higher fuzzy membership in areas of fewer spring frosts	Monthly frost days (minimum temperature ≤ 0°C) count from 59 Danish weather stations (April and May only). Interpolated via Inverse Distance Weighted (IDW) methods (ArcGIS Pro Spatial Analyst)	Membership Type: Fuzzy Small Mid-point: 77.42 Spread: 21.42
Solar Irradiance	Higher values to greater solar irradiance	April - October monthly Solar Irradiance (MJ/m^2) .geojson files derived from sum of underlying hourly bright sunshine values within a day ($10*10/10^6$). (JSON to feature) and rasterized to 10 x 10 km .tif raster layers (Danish Meteorological Institute, 2023).	Membership Type: Fuzzy Linear

Table 1 - DVSM terrestrial and climate variables with dataset, resolution, source and suitable parameter value.

Terrestrial

Elevation

Elevation suitability is largely determined by decreasing temperatures and increased risk of wind exposure at higher altitudes (Nesbitt, Dorling and Lovett, 2018; Olsen et al., 2011). Despite this, 'idealised' elevation parameters for Northern Hemisphere cool climate vineyards are poorly defined. Skelton (2014) suggests vineyard elevation of below 100m and not above 150m (AMSL) for Great Britain.

Aspect

In the Northern Hemisphere vineyards, south facing slopes have greater solar irradiance potential (Coombe and Dry, 2006), especially during the ripening season when the sun is directly overhead. Increased heat accumulation reduces lag times for soil warming and drying following cold nighttime temperatures in the early growing season. This investigation defines suitable aspect values as 270° ≥ x ≥ 90 ° (*x = Suitable aspect values).*

Slope

Optimal slopes for viticulture are between 5-10% incline (Bennie et al., 2006; Unwin, 2010). Above 10%, mechanised viticulture becomes uneconomical. Although high quality wines have originated from regions of terraced viticulture particularly the Douro Valley, Portugal, The Cinque Terre and Valtellina regions, Italy, diminished yields volumes and higher labour costs due to the necessity of manual labour are ubiquitous. Slopes below 1% risk increased cold air accumulation and frost damage. Low relief slopes (<1%) typically found in Danish coastal margins were excluded from DWVS analysis.

Land Cover

Seven land use classes were extracted from basemap04, an open-source 10 x 10m resolution raster layer of land uses within Denmark (Aarhus University - Department of Environmental Science, 2023). 'Suitable' types only included Agricultural and Natural classes. Urban development and infrastructure, including resource extraction, rail, air and road infrastructure were excluded from further analysis. Suitable land use classes area shown in table 1. Only classes most likely to exhibit suitable viticultural parameters were included via a Boolean AND calculation in Raster Calculator.

Soil

Recent viticultural research has emphasises the significant influence of soil texture, drainage, pH, fertility and organic matter on viticultural suitability by influencing vine nutrient and water availability, soil temperature and humidity. Although certain desirable soil properties are specified within the literature, no single 'ideal' soil or bedrock type exists. pH levels for vine development and microbial health are commonly specified between 5.5 – 8.0 (White, 2015; Badr et al., 2018; Jackson, 2008). A range of soil properties may support vine development, depending on environmental circumstances, rootstock typology and planting density. Soil management strategies have proven successful in ameliorating many soil characteristics, particularly nutrient availability, such that previously marginal soil types may successfully support grapevine development. Three 500m resolution soil rasters representing Sand, Silt and Clay by percentage were retrieved from the ESDAC (2018). The ArcGIS Combine tool and a soil classification script, based on the USDA soil classification triangle was developed and applied, identifying 12 unique soil classes within Denmark (Appendix 2).

Protected Areas

Four classes of protected areas were identified and extracted from the basemap04 dataset. Four protected area classes were reclassified, and raster calculator with the Boolean AND excluded areas with 'protected area' status from further analysis.

Designated Area		Area (ha)	% of Designated Areas
Management plans for Defence sites		22871.7	4.4
Management plan for state forests		179759.4	34.8
Protected habitat types		241012.1	46.7
Natura 2000 habitat types		72216	14.0
	Total	515859.2	100

Table 2 - Basemap04 Designated area types by total area and proportion of overall protected land area.

Climate

Temperature and bioclimatic indices

Mean air temperature and its variability throughout the growing season (April-October) is fundamental to viticultural suitability. Mean air temperature affects sugar content, acid, phenolics, flavour compounds and protein density within grape berries (Crippen and Morrison, 1986). Northern Hemisphere growing season average temperatures of 12-22°C are considered commercially suitable, although high quality commercial production is traditionally association with GSTs of 13-23°C (Coombe, 1987). This investigation calculated monthly mean GST from gridded mean monthly temperature observations (2011-2023), which is derived from and IDW interpolation of 59 Danish weather station datasets. GST interannual variation was calculated by taking the standard deviation of each year from the mean.

Growing Degree Days (GDD)

Daily minimum and maximum GSTs were retrieved from the Danish Meteorological Institute Climate Data API. Temperature observations in 10 x 10 km gridded format, are derived from 59 Danish weather stations. Weather station point data is interpolated via a modified IDW algorithm, considering Denmark's proximity to the sea as a significant factor (Danish Meteorological Institute, 2020). A 10°C base temperature defines the threshold at which grapevine growth and pest risk becomes active. Below 10°C grapevine growth and risk of pests are considered negligible (Olsen et al., 2011). GDD sums were calculated for each growing season day between April 1st – October 31st using the formula:

$$GDD = \left({}^{Tmax + Tmin}/_{2} \right) - 10$$

The highest and lowest hourly temperature observation per day is shown by Tmax and Tmin variables. On days where the average temperature was less than 10°C the daily GDD sum is calculated at 0. Previous studies typically incorporate a maximum temperature threshold (~30°C) at which point heat damage may threaten grapevines, however this was not deemed to be a threat in Denmark, so is omitted (Oliveira, 1998).

Rainfall

GSP, in addition to diminished solar irradiance via increased cloud cover, negatively impacts vine growth, grape quality and grapevine yield (Makra et al., 2009). Increased disease pressure, reduced flowering and Millerandage are associated with increased growing season rainfall which reduce viticultural suitability (Jackson, 2008). Monthly 10 x 10km accumulated precipitation grids (Danish Meteorological Institute, 2023) (2011 – 2023) were retrieved. June precipitation, mean growing season (April-October) precipitation and interannual GSP variability were segmented to separate raster datasets. Timing of rainfall events in addition to volume of accumulated precipitation was shown by Nesbitt et al. (2016) to detrimentally impact flowering and subsequent grape yield in English viticulture. Interannual precipitation variability was calculate by taking the standard deviation of yearly rainfall against the study period mean.

Solar Irradiance

Solar radiation provides energy for photosynthesis during berry growth and maturation, particularly during berry ripening when solar irradiance enhances sugar and phenolic concentrations (Crippen and Morrison, 1986; Gladstones, 1992). Not only is direct sunlight critical to develop natural flavouring and colourants, but high GSTs are more likely to occur where direct sunshine is abundant (Oke, 1987). Research in Røsnæs, Denmark, emphasised the role of solar radiation in grape acid digestion (Olsen et al., 2011). Mean monthly and annual solar irradiance during each growing season month between 2011 and 2023 was calculated from 10 x 10 km gridded .geojson files retrieved from the Danish Meteorological Institute.

Spring Frost

Specific cultivars of Vitis Vinifera L. may tolerate dormant period temperature lows up to -20°C (Davenport, Keller and Mills, 2008). However, spring air frosts (April-May) during shoot and bud development and following budburst can significantly reduce grape yields across multiple growing seasons, leading to crop loss during the current and following harvest years (Trought, Howell and Cherry, 1999). Cool climate wine producing regions (GST 13-15°C) are particularly vulnerable to late season frost events (Mosedale, Wilson and Maclean, 2015). Total days of spring air frost (April-May) were calculated between 2011-2023, from 10 x 10km gridded Danish Meteorological Institute observations (Danish Meteorological Institute, 2023b)

Research Question 1

Fuzzification

Fuzzy membership and overlay functionality include several membership types, each representing a different frequency distribution based on user-defined 'optimum' mid-point and spread values. These parameters determine the width and nature of the transition zone from 0 (not a member) to 1 (a member) (Malczewski, 2004; Nesbitt, Dorling, and Lovett, 2018). Several membership types to were incorporated with the DVSM to conceptualise how changes in variable inputs impact climatic and terrestrial suitability within Danish viticulture. Details on membership type, mid-points and spread values are shown in table 1.

When parametrising Elevation, a fuzzy 'Near' membership type was used with the previously mentioned 'preferred range' midpoint of 52.5m ((25+80)/2) and spread value of 0.001. The midpoint of 52.5m defines the centre of the set which is assigned (1) with membership gradually decreasing to 0 for elevation values greater than 150m or below 1m. The spread value of 0.001 defines a broad membership transition which penalises raster cells with cell values (elevation) which deviate from 52.5m. Slope angle and aspect also used the 'Near' type membership, with spread values of 0.001 and mid-point values of 5% and 180° respectively.

GSP, Interannual variability, accumulated June precipitation and days of spring air frost, have an 'optimum' value of 0 within this investigation. Consequently, fuzzy 'Small' membership was used to assign higher membership values to cells of lower value. Unique midpoint and spread values for each variable were used to determine membership of 0.5 and to set the shape of the membership gradient on either side of 0.5 membership. The midpoint was calculated as 50% of the variable range and the spread value was calculated as 15% of the midpoint value (ESRI Ltd., 2024).

In contrast Higher GDDs, GST and Solar irradiance are beneficial to grape quality and yield. Therefore Fuzzy 'Linear' membership, which assumes a linear relationship between input variable values and fuzzy set membership, was selected. Membership of '1' is given to higher cell values, and '0' to lower cell values. Where terrestrial and climate fuzzy layers are combined using fuzzy overlay, a Gamma value was applied. The gamma value in figure 5 was used to produce a fuzzy overlay raster layer which is a combination of fuzzy SUM and fuzzy PRODUCT operations (ESRI Ltd., 2024).

DWVS Model Presentation

The results of the DWVS presented within this investigation are the result of a combining terrestrial and climate suitability models. Significant steps within the model analysis are shown in table 1. Climatic suitability outputs are spatially delimited by the terrestrial suitability mode Previous studies frequently present climate suitability for regions which fail to meet terrestrial pre-requisites for commercial viticulture. Delimiting allows increased accuracy when aggregating fuzzified viticultural suitability to Regioner and Kommuner scale. ArcGIS Pro Map algebra, zonal and spatial statistics toolboxes were used to extract terrestrial, climate and combined model values to Danish Regioner and Kommuner boundaries.

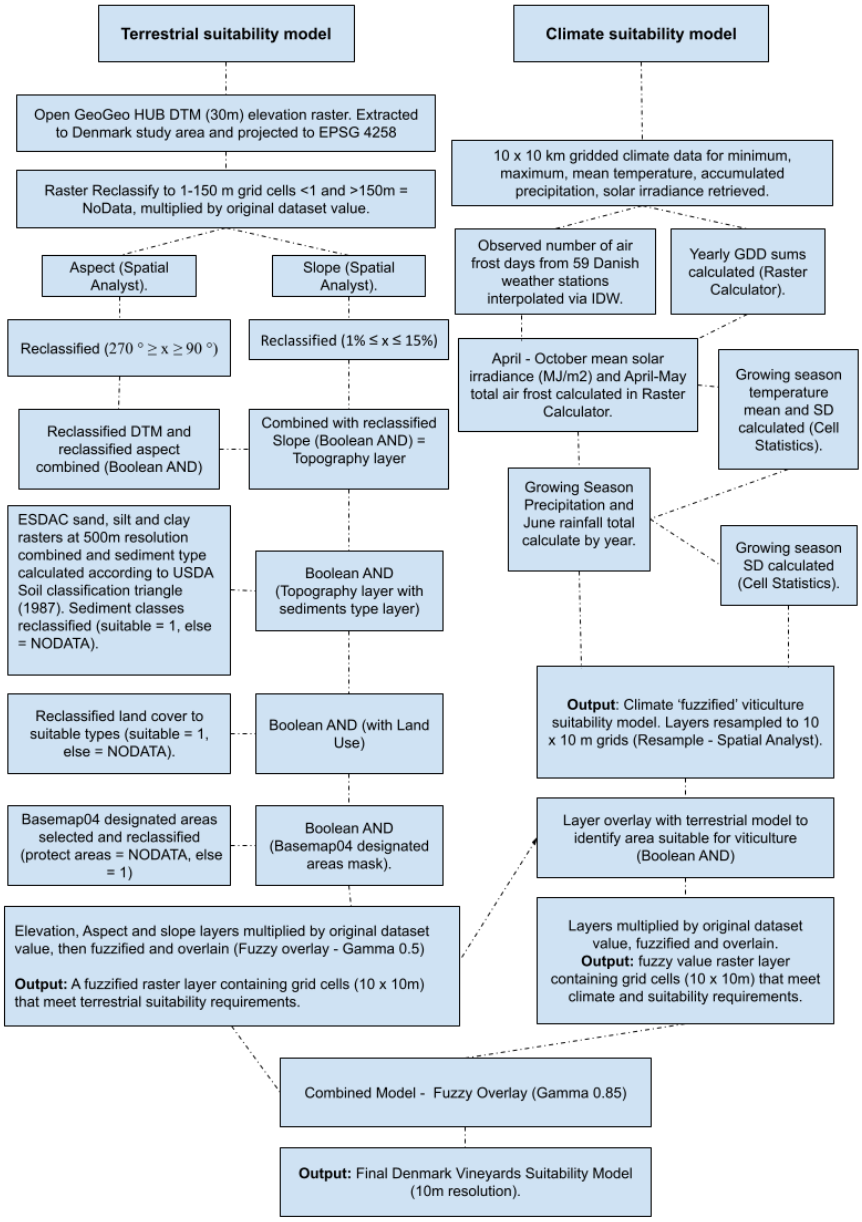

Figure 5 - DVSM key model construction phases and ArcGIS Pro tools.

Research Question 2

To identify where combined terrestrial and climatic suitability results exhibit spatial clustering, two measures of spatial autocorrelation were utilised, Global Moran's I and Local Anselin Moran's I. Preprocessing of viticultural suitability involved calculation of mean fuzzified suitability at the Sogn administrative level. Zonal statistics extracted mean fuzzy suitability across 2,144 Sogn features. To assess spatial autocorrelation at the global scale, three iterations were calculated of climatic, terrestrial and combined viticultural suitability. For each iteration, the null hypothesis that 'fuzzy suitability values are randomly distributed across Sogn features' is assumed. Global Moran's I calculates spatial autocorrelation based on both feature locations and feature values simultaneously.

Therefore, the spatial relationship between Sogn was conceptualised via a K nearest neighbours operation (neighbours = 15). Denmark is comprised of many islands. Therefore, many Sogne share no contiguous boundaries. A k-nearest neighbours' relationship was selected over a contiguity-based or fixed distance relationship to evaluate spatial distribution of fuzzy suitability in isolated regions, ensuring that each target feature will be considered in the spatial context of 15 neighbours.

An Anselin Local Moran's I was conducted to identify localised 'high' and 'low' clusters of fuzzy suitability at the individual Sogn scale. Anselin Local Moran's I analysis assumes a similar null hypothesis that 'the observed spatial pattern of fuzzy suitability is the result of random spatial processes', which implies that fuzzy suitability at a given feature is not influenced by suitability values at neighbouring features. A K-nearest neighbours' conceptualisation method was used (neighbours – 15).

Research Question 3

Danish Vineyard Locations

Academically verified open-source datasets for Danish viticulture are piecemeal, despite ongoing research efforts to quantify the location and size of existing Danish Vineyards (Becker and Toldam-Andersen, 2021). Therefore, The Association of Danish Wine list of Danish Commercial Wineries was referenced, which contains 177 spatially referenced descriptions of existing wineries. This investigation exclusively concerns grape wine production, therefore wineries exclusively producing fruit wine were removed from further analysis. Longitude and Latitude coordinates were extracted from postcode information by applying a geocoding script (Appendix 3). One vineyard observation, which contained a corrupted postcode reference was excluded from further analysis. Winery postcode information typically relates to premises or administrative buildings. To ensure model accuracy, Postcode point features were cross-referenced with a Danish Vineyards polygon dataset, acquired through the OpenStreetMap Overpass API. Visual inspection and selection of Danish Vineyard Polygons which fall within 2km of a Commercially registered vineyard point feature ensured model accuracy by excluding vineyards 'not associated' within a commercial winery according to the 2km exclusion buffer. 77 vineyard polygons were included within further statistical analyses.

Assessment of viticultural suitability, according to measures of central tendency, including mean and median fuzzy suitability values, STD, area and range was achieved on a vineyard-by-vineyard basis. Zonal statistics were calculated at the Vineyard polygon scale and standardised to enable pairwise comparison of vineyard parcels of differing hectarage, which in Denmark is considerable (standard deviation = 3.82 ha).

5. Results

Research Question 1

Terrestrial Viticultural suitability in Demark

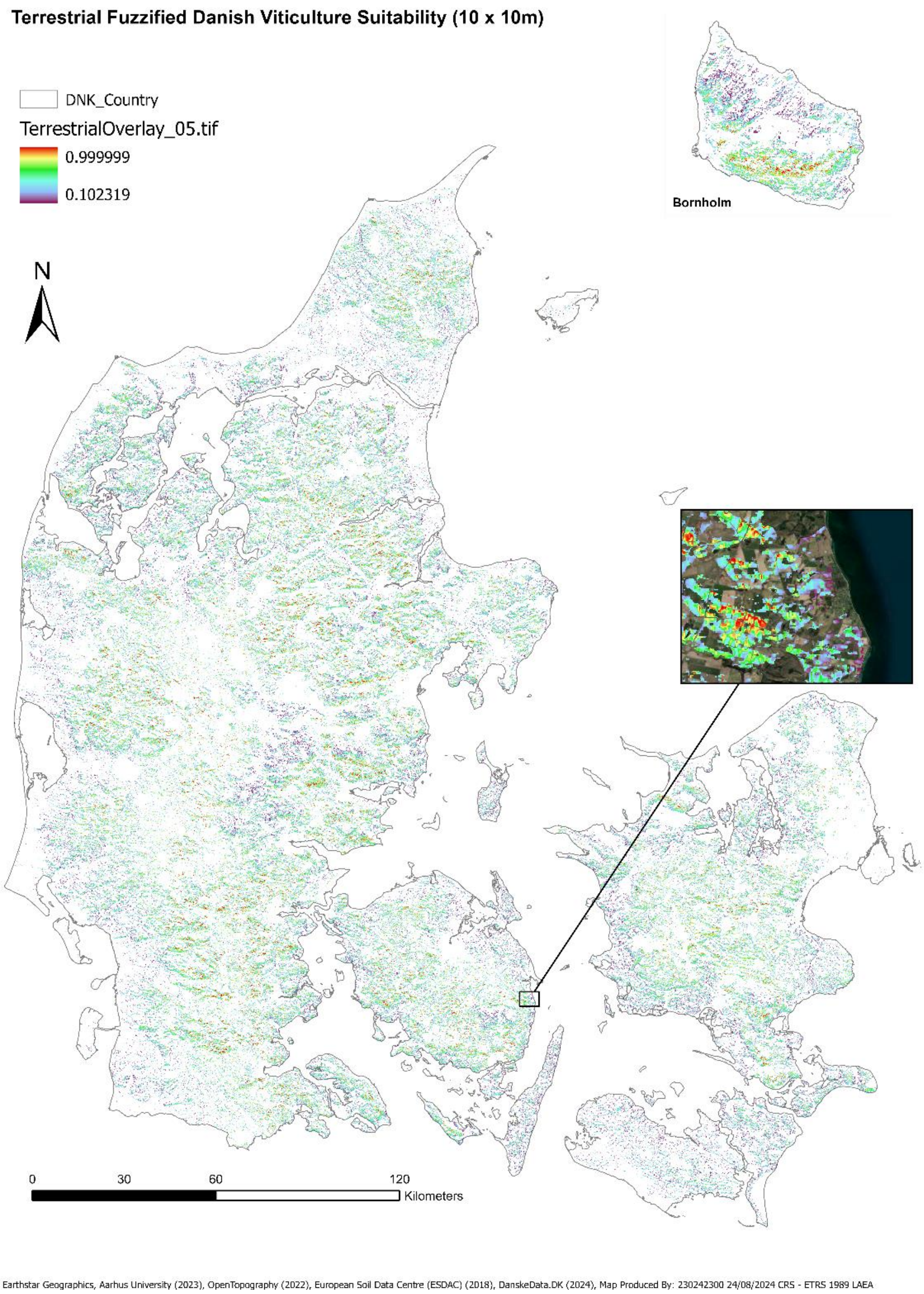

Figure 6 - Terrestrial fuzzy viticultural suitability at national scale, high resolution and Bornholm inset maps shown.

The model threshold for terrestrial suitability shown in figure 6, is any 10 x 10m cell which met all elevation, slope, aspect, land use, soil and restricted area criteria set out in table 1. Terrestrial suitability is defined according to fuzzy set membership where 0 represents the lowest likelihood of viticultural suitability and 1 the highest.

At national scale, terrestrial suitability appears to be evenly spatially distributed across the study area. 10 Kommuner were found to contain total suitable vineyard hectarage of 218,129.9 ha, which is 5.07% of Danish total land area. Regionally, Viborg has 29,115.4 ha (20.47% of total area) classified as terrestrially favourable for viticulture. Ringkøbing-Skjern and Vejle contain 25,281.98 (16.91%) and 23,695.57 ha (22.0%) respectively. High proportions of viticulturally suitable land were found in Haderslev (24.56%), Vesthimmerlands (25.09%) and Vejen (24.26%). Allerød and Vejen show the highest terrestrial suitability (0.58) closely followed by Ringsted, Billund and Herning (0.57), indicating relatively high although slightly less consistently suitable area by comparison. In certain instances, high mean terrestrial suitability coincides with high volume suitable hectarage, particularly in the case of Vejen in which mean terrestrial suitability of 0.58 was found across 19,754.95 ha.

Terrestrial Suitability

Rank Order	Id	Kommuner	Suitable Hectarage	% of Kommuner Area	Id	Kommuner	Mean Suitability
1	88	Viborg	29115.40	20.47	18	Allerød	0.58
2	83	Ringkøbing-Skjern	25281.98	16.91	63	Vejen	0.58
3	68	Vejle	23695.57	22.30	36	Ringsted	0.57
4	69	Herning	21304.74	16.09	57	Billund	0.57
5	87	Thisted	20940.12	19.10	69	Herning	0.57
6	62	Varde	20402.72	16.49	67	Kolding	0.56
7	56	Haderslev	20003.53	24.56	17	Furesø	0.56
8	63	Vejen	19754.95	24.26	39	Sorø	0.55
9	91	Vesthimmerlands	19283.44	25.09	64	Aabenraa	0.55
10	97	Hjørring	18347.45	19.79	84	Hedensted	0.55

Table 3 - Ranked terrestrial mean and total fuzzy suitability by Kommune.

The highest terrestrial suitability by soil type includes Alternating till beds (0.69), Selandian sand (0.66), Eocene Marl (0.58) and Freshwater Peat (0.56). 20 sediment classes contained terrestrial suitability values greater than 0.5, of which 40% were predominantly composed of gravel, sand or clay. Clay and Sandy till sediments underlay 447,804.4 ha of terrestrially suitable land. The top 10 sediment classes by viticultural area have a terrestrial suitability mean of 0.48 and range of 0.11. Traditionally successful Chalk and limestone substrata are sparse, containing 3,221.8 ha of terrestrially suitable land at a mean value of 0.41.

Climate Viticultural Suitability in Demark

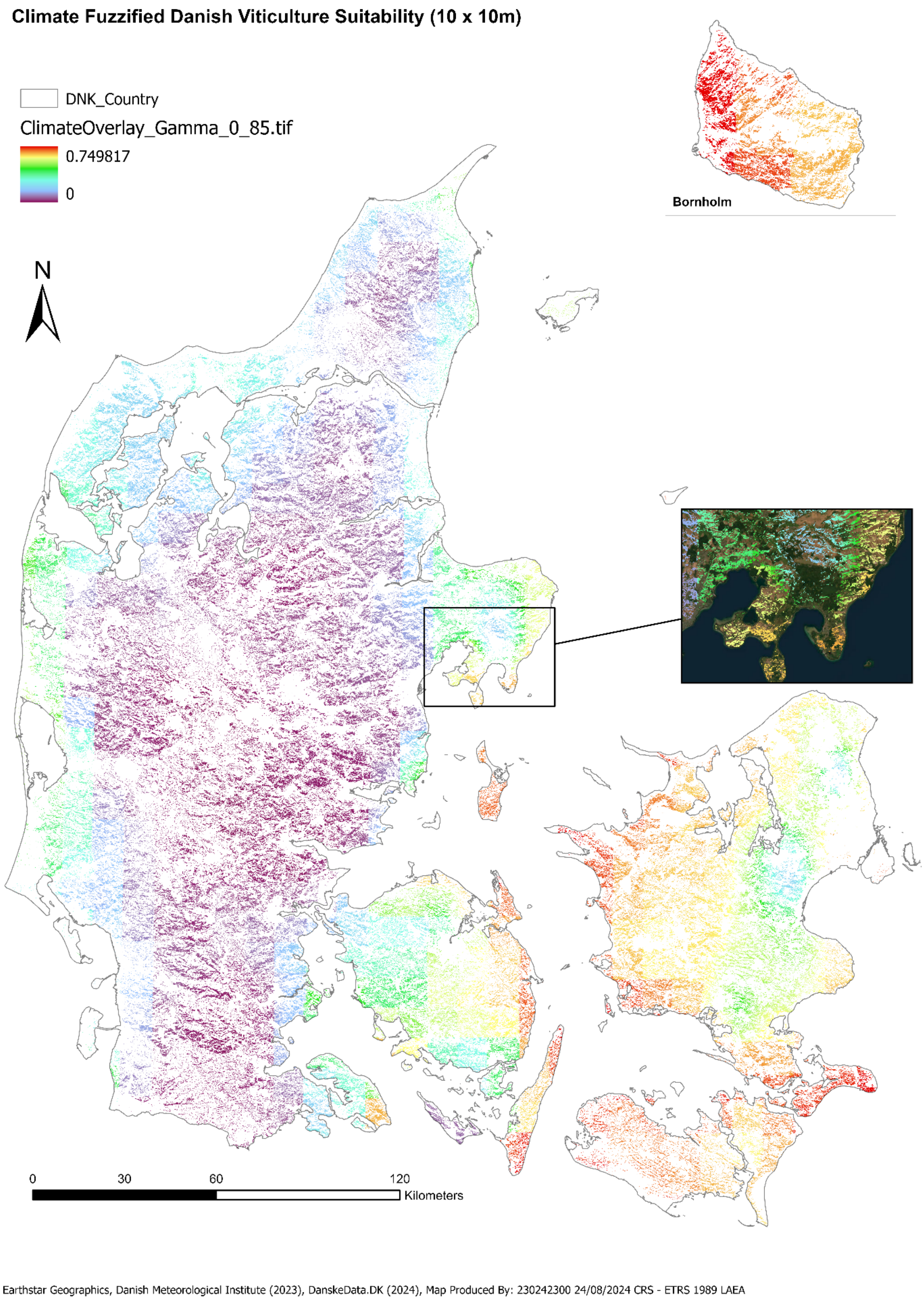

Figure 7- Climate fuzzy viticultural suitability at national scale, high resolution and Bornholm inset maps shown.

Climatic Suitability						
Rank Order	**Id**	**Kommuner**	**Mean Suitability**	**Id**	**Kommuner**	**Maximum Suitability**
1	4	Dragør	0.68	41	Lolland	0.75
2	15	Tårnby	0.68	45	Bornholm	0.75
3	41	Lolland	0.67	37	Slagelse	0.73
4	79	Samsø	0.67	54	Langeland	0.73
5	45	Bornholm	0.67	35	Kalundborg	0.73
6	44	Vordingborg	0.66	44	Vordingborg	0.71
7	35	Kalundborg	0.65	49	Kerteminde	0.71
8	54	Langeland	0.64	43	Guldborgsund	0.70
9	32	Odsherred	0.64	32	Odsherred	0.70
10	10	Hvidovre	0.64	4	Dragør	0.68

Table 4- Mean and maximum fuzzy climatic suitability ranked by Kommune.

Climatic suitability (figure 7) is a function of 8 variables shown in figures (8 to 11). Highest GSTs were restricted to Southeast Hovedstaden and Northwest Sjælland. 9 Kommuner had mean GST > 14°C. Frederiksberg (14.21°C), København (14.15°C), Tårnby (14.05°C) and Hvidovre (14.05°C) exhibited the highest mean GST in Demark and all share contiguous borders and are located on the coastal margin of Eastern Denmark. 29.3% of Kommuner had GST < 13 °C, all of which shared contiguous borders. 93% of Nordjylland and Midtjylland Kommuner failed to achieve GST of > 13°C. Mean Solar Radiation (figure 9) shows a similar East-West divide. Bornholm, the sunniest Kommune, received 14.3% more solar radiation (MJ/m^2) than the least sunny Kommune Christiansø (507.45 and 443.91 MJ/m^2 respectively). 9 of the 10 least irradiated Kommuner are contained within a large cluster within Central Midtjylland, shown in figure 9 as a large red mass. Figure 9 shows a striking decrease in days of air frost experienced in coastal regions. Indeed, 100% of Kommuner experiencing fewer than 20 days of April and May air frost were in coastal margins, although skew toward eastern of western coastal areas is less clear.

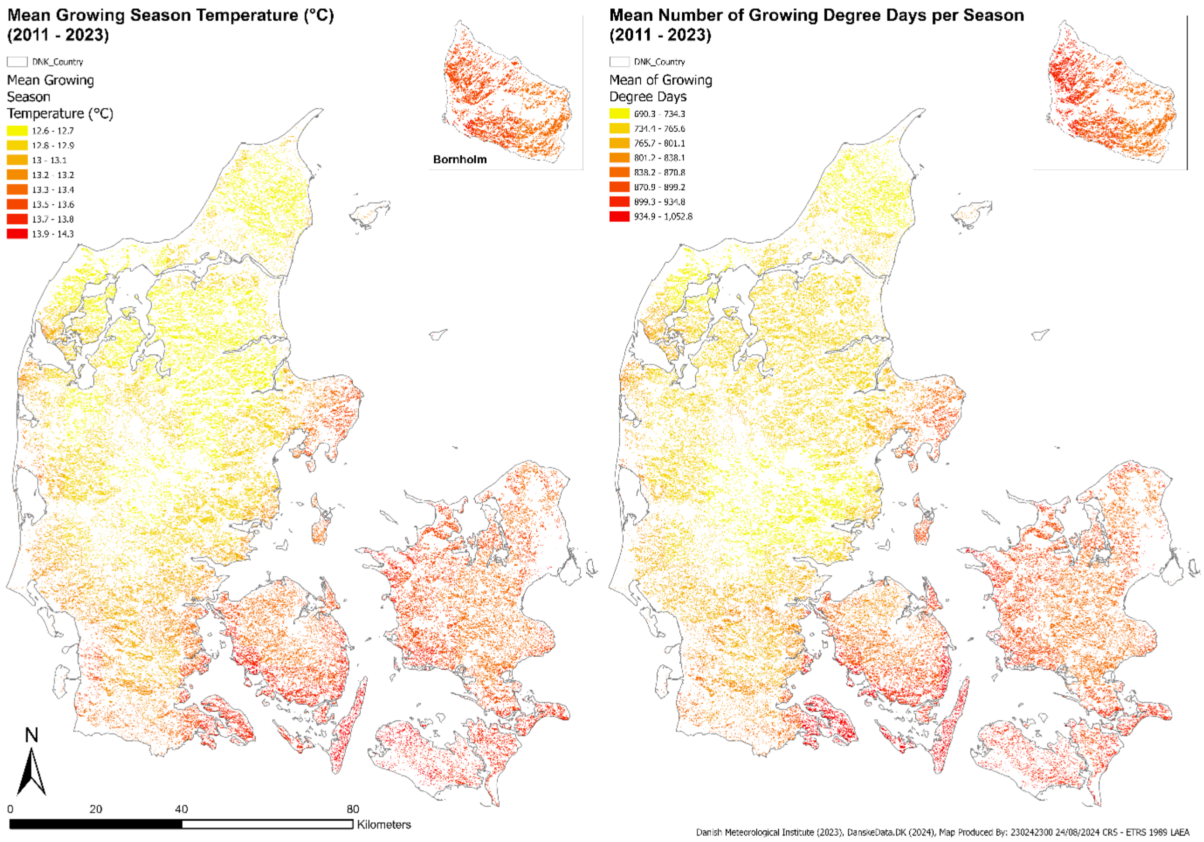

Figure 8 - Mean GST and GDD count in Denmark (2011-2023).

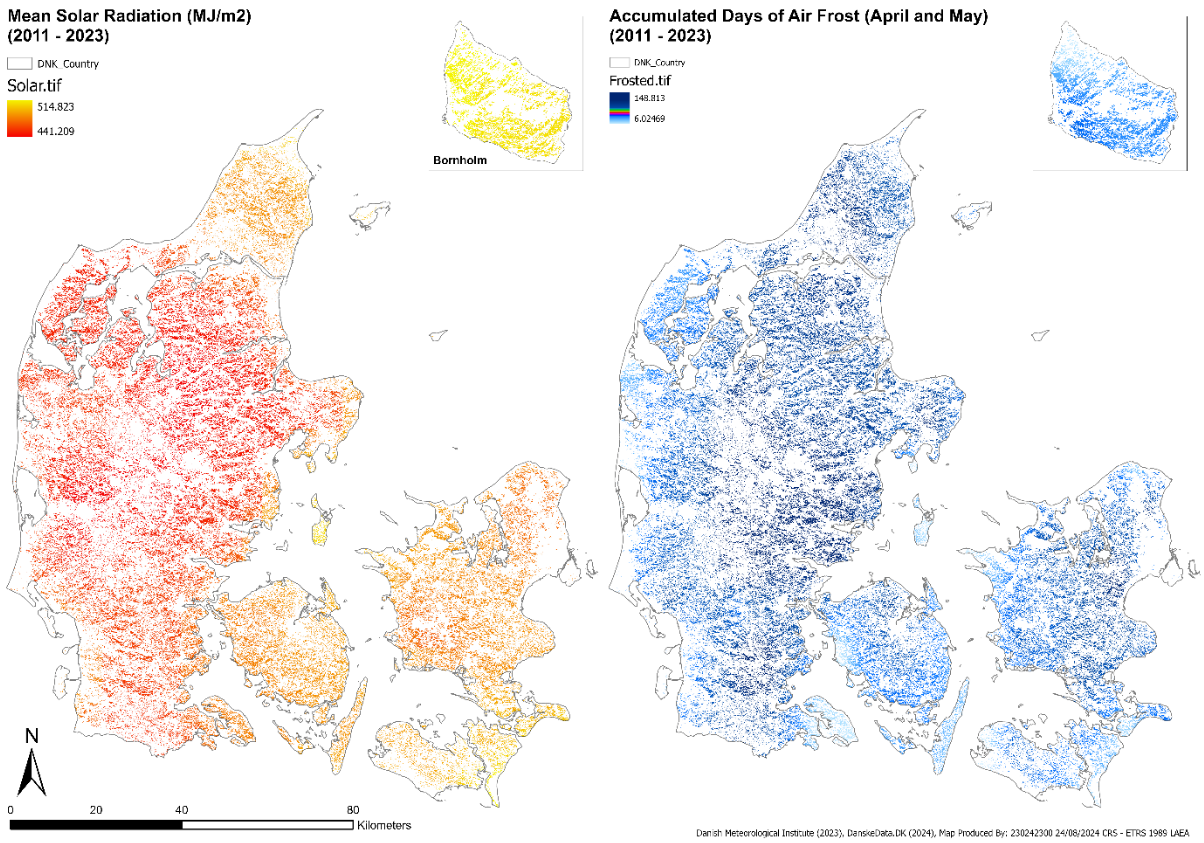

Figure 9 - Mean solar radiation and air frost days April - May count (2011-2023).

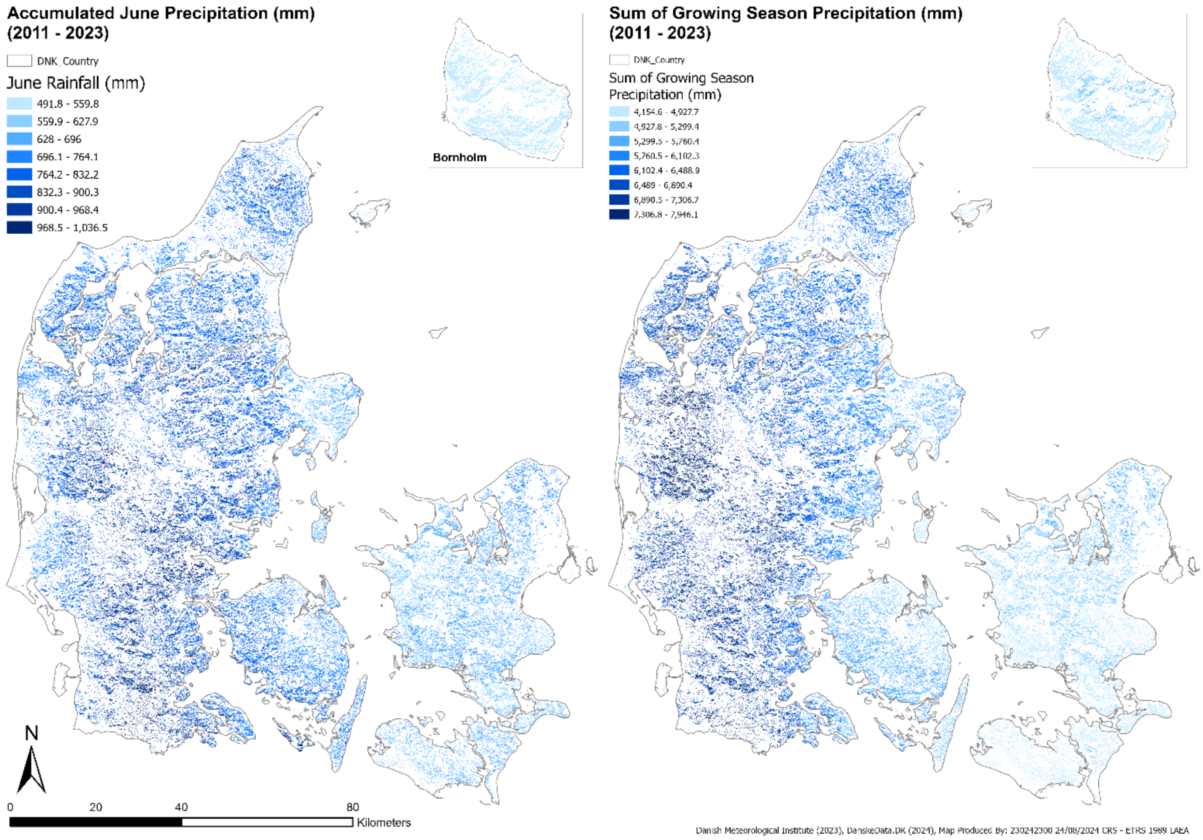

Figure 10 - Accumulated June and growing season precipitation (2011-2023).

Volume and timing of precipitation are both fundamental to successful flowering and vine development. Figure 10 shows the spatial distribution of June and Growing Season precipitation. The role of topography in ceding orographic rainfall becomes apparent. 14 Kommuner experienced > 800mm of June precipitation, equivalent to 30.77 mm per each month across the data. Spatial clustering of high precipitation kommuner is apparent. The 10 rainiest June Kommuner received 19.83% of June precipitation, despite accounting for just 17% of land area. Bornholm (503.32mm), Vordingborg (613.93mm), and Kalundborg (619.57mm) experienced the lowest June precipitation, all of which are coastally located and fall East of 10.8° of longitude. Total GSP exhibits similarities with June precipitation. Lolland (4685.27 mm), Bornholm (4782.13) and Vordingborg (4819.66 mm) experience the driest growing seasons. The 10 wettest kommuner accounts for 71,678.39 mm (12.65%) of total Danish precipitation, the driest 15 contribute 73,496.17 mm (12.97%)

Interannual variability of GST and GSP was identified previously as a potential source of damage to grapevine yields (Nesbitt, Dorling and Lovett, 2018). Figure 11 below suggests that higher GST variability occurs through Nordjylland and Northern Midtjylland up to 0.7°C on both Eastern and Western coastal margins. Lower variability ~0.5°C is increasingly frequent beyond 10.5° East, particularly on eastern coastlines. Temperature variability increases marginally inland, particularly through Central Syddanmark. In coastal margins, where sea surface temperature exhibits lower interannual deviation, temperature is increasingly stable. Deviation from the coastal margins increases solar variation and wind direction anomalies. Areas within central and Southwestern Syddanmark had Precipitation standard deviation in the range of 15-17mm, in comparison to Sjælland and Bornholm (~7-10mm). Low lying coastal regions in Western Nordjylland comprise 80% of the most 'settled' GSP Kommuner.

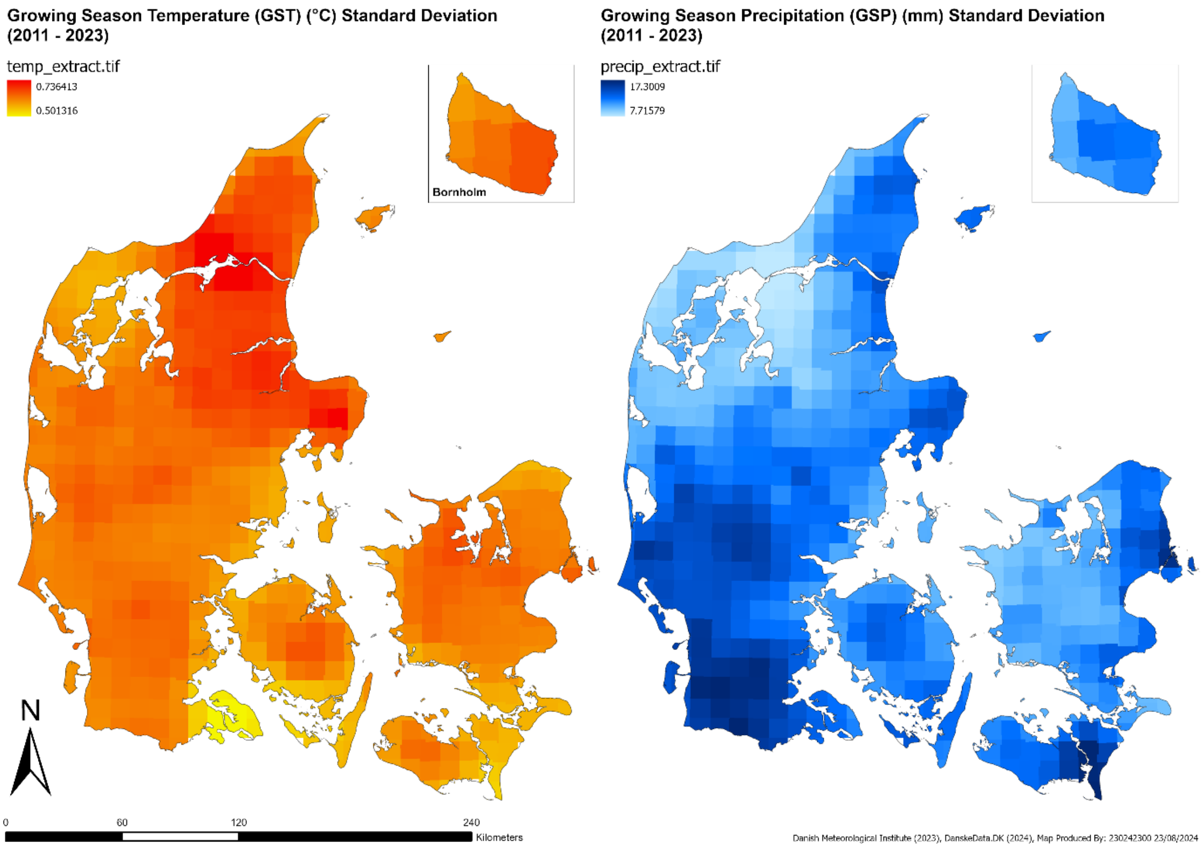

Figure 11 - Gridded 10 x 10km mean GST and GSP standard deviation from 2011 - 2023.

Combined Viticultural Suitability in Denmark

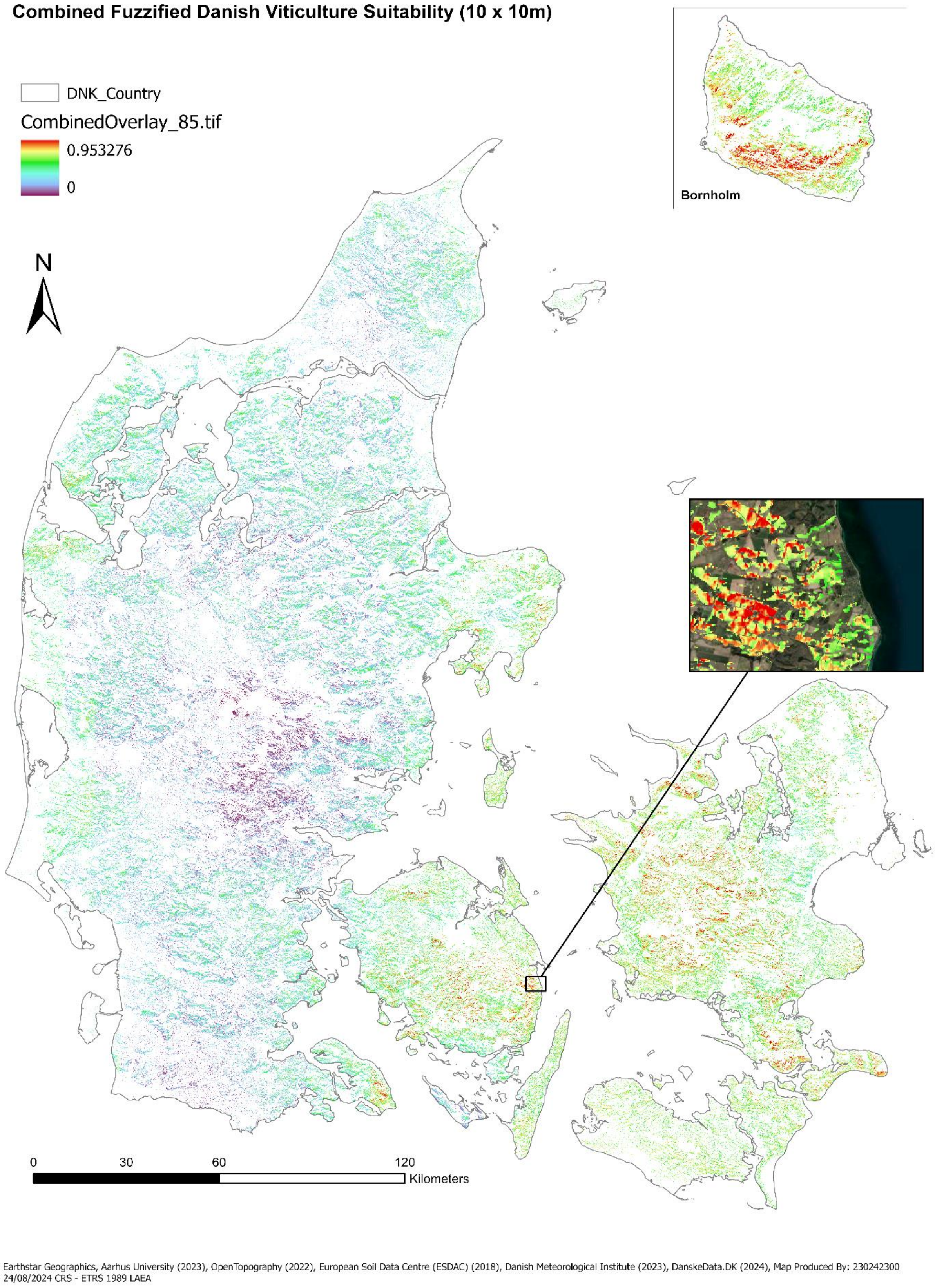

Figure 12 - Combined viticultural suitability in Denmark (10m) with high resolution and Bornholm inset shown.

Combined Viticultural Suitability

Rank Order	Id	Kommuner	Mean Suitability	Id	Kommuner	Maximum Suitability	Id	Kommuner	Summed Suitability
1	45	Bornholm	0.711527	45	Bornholm	0.953	42	Næstved	1194874
2	39	Sorø	0.71106	35	Kalundborg	0.953	45	Bornholm	1110718
3	36	Ringsted	0.702897	44	Vordingborg	0.950	48	Faaborg-Midtfyn	1044614
4	12	Lyngby-Taarbæk	0.699986	50	Nyborg	0.942	44	Vordingborg	1022665
5	32	Odsherred	0.69601	32	Odsherred	0.938	43	Guldborgsund	1019400
6	44	Vordingborg	0.692334	33	Holbæk	0.937	83	Ringkøbing-Skjern	968349
7	50	Nyborg	0.687758	52	Svendborg	0.935	88	Viborg	953845
8	33	Holbæk	0.686252	58	Sønderborg	0.931	87	Thisted	944731
9	35	Kalundborg	0.684355	28	Halsnæs	0.929	37	Slagelse	924853
10	37	Slagelse	0.668258	48	Faaborg-Midtfyn	0.928	35	Kalundborg	881589

Table 5 - Ranked mean, maximum and summed viticultural suitability by Kommune.

Geovisualisation of combined fuzzy viticultural suitability (figure 12) reveals several striking insights, supported by table 5. Bornholm performs particularly strongly, with a mean value = 0.71, maximum suitability = 0.95 and summed suitability = 1,110,718, The highest mean and maximum suitability within the study area. Mean suitability across the 10 most suitable Kommuner is 0.69, with median maximum suitability of 0.931. Kommuner that exhibit high mean and maximum suitability scores are moderately positively correlated with summed suitability. Increased GST and GSP variance, lower GST and more frequent April- May frosts continue to damage viticultural suitability of the Danish interior relative to coastal margins which appear in figure 11 to perform strongly, relative to interior regions. The influence of Solar irradiance and GST continues to skew combined viticultural suitability southwards. Although viticultural suitability > 0.5 is observed in Nordjylland, the highest combined suitability (>0.8) remains constrained to Sjælland and Hovedstaden, particularly in low lying coastal zones, which exist within the rain shadow of Nordjylland and Syddanmark. Combined fuzzy suitability scores of >0.8 are seldom found 56.53°N. At a national scale, mean suitability of 0.52 indicates moderate suitability of Danish Kommuner when considering both terrestrial and climate determinants of viticultural viability.

Research Question 2

Global Moran's I

A. Climate Suitability

Global Moran's I Summary

Moran's Index	0.842151
Expected Index	-0.000489
Variance	0.00006
z-score	108.714871
p-value	0

B. Terrestrial Suitability

Global Moran's I Summary

Moran's Index	0.446294
Expected Index	-0.000489
Variance	0.00006
z-score	57.652501
p-value	0

C. Combined Global Moran's I Summary

Moran's Index	0.815738
Expected Index	-0.000489
Variance	0.00006
z-score	105.313893
p-value	0

Table 6 - Global Moran's I test statistics for climatic, terrestrial and combined Viticultural suitability.

Fuzzified Climate, Terrestrial and Combined fuzzy suitability was first determined at the global scale (Sogne). In each case, the null hypothesis that 'Fuzzified suitability values are evenly randomly distributed among Sogn features' is assumed, implying that terrestrial and climatic processes governing fuzzy suitability are entirely random. Global Moran's I statistics are show in Table 6. A Moran's index value of 0.84 indicates Climatic Fuzzy suitability values have a strong positive spatial autocorrelation. A z-score of 108.7 (>1.96) indicates that the observed spatial pattern is significantly different from a random distribution (p <0.05). Fuzzified terrestrial suitability exhibits moderate positive spatial autocorrelation (0.45) i.e. high and low terrestrial suitability values tend to be located near each other. A z-score of 57.65 (>1.96) ($p < 0.05$) indicates that the observed spatial pattern differs significantly from a random distribution. A Moran's I index of 0.82 suggests a strong positive spatial autocorrelation of combined fuzzy suitability scores. This value is supported by a z-score of 105.31 (> 1.96) indicating that the observed spatial pattern is statistically significant ($p < 0.05$). This investigation rejects each null hypothesis at the 95% confidence level, concluding that in all three instances, fuzzified suitability values are spatially autocorrelated, at Sogn scale.

Local Anselin Moran's I

Spatial autocorrelation at local (individual Sogn) scale is shown in figures 13 – 15. In each figure, mean fuzzified suitability by Sogn is shown. Clustering of both high and low climatic suitability is evident at the Sogn level. Clustering of climatic suitability continues to follow topographical features outlined previously, represented as a broad "Low-Low" cluster across Midtjylland, Nordjylland and Syddanmark. Similarly, "High-High" clustering throughout Sjælland and Hovedstaden is evident, indicating Sogne of high climatic suitability, surrounded by Sogne of similarly high climatic suitability. What is visually striking in figures 13-15 are Sogne of both high and low suitability, surrounded by Sogne of contrasting suitability, shown in bold red and blue colours. Local clustering of Combined viticultural suitability strongly resembles spatial distribution patterns of climate suitability clustering. A striking East-West divide is particularly evident in figures 13-14. Combined suitability remains high within Hovedstaden and Sjælland, where climatic suitability is consistently higher than much of Nordjylland and Syddanmark.

Fuzzified terrestrial suitability, although spatially autocorrelated appears more evenly distributed, with high and low terrestrial suitability clusters found disperse across the study area. Sogne of "High-Low" and "Low-High" are therefore more common, being found at transition zones between high and low terrestrial suitability. The spatial clustering observed supports the more even distribution of terrestrial fuzzified suitability observed in figure 6.

Label	Description
HH	Positive, statistically significant clusters of fuzzified suitability values by Sogn, surrounded by high fuzzy suitability Sogne.
HL	Positive, statistically significant clusters of fuzzified suitability values by Sogn, surrounded by low fuzzy suitability Sogne.
LH	Low fuzzy suitability Sogne surrounded by high fuzzy suitability Sogne, negative and statistically significant.
LL	Sogne of low fuzzy suitability surrounded by low fuzzy suitability Sogne, statistically significant.

Table 7 - LISA cluster and outlier acronyms and associated definition. Sogn is equivalent to a Parish.

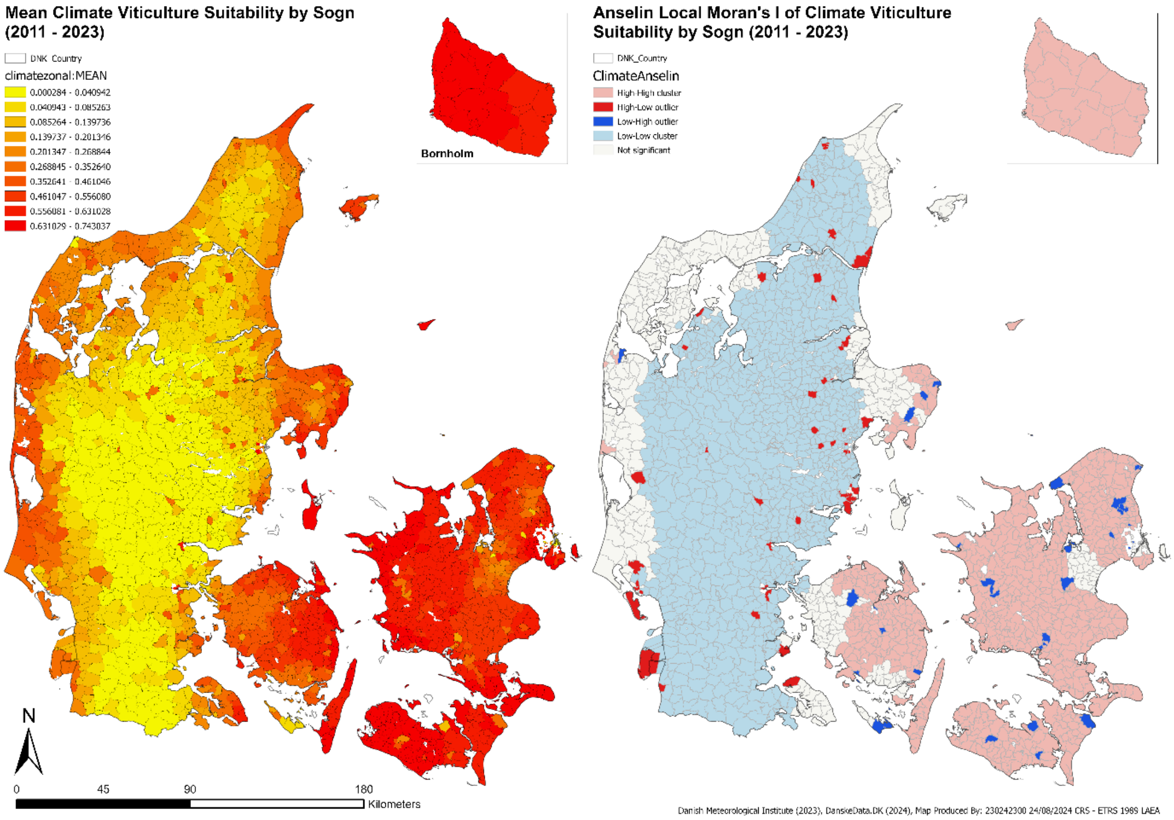

Figure 13 - Mean climate suitability by Sogn with LISA cluster and outlier spatial autocorrelation shown.

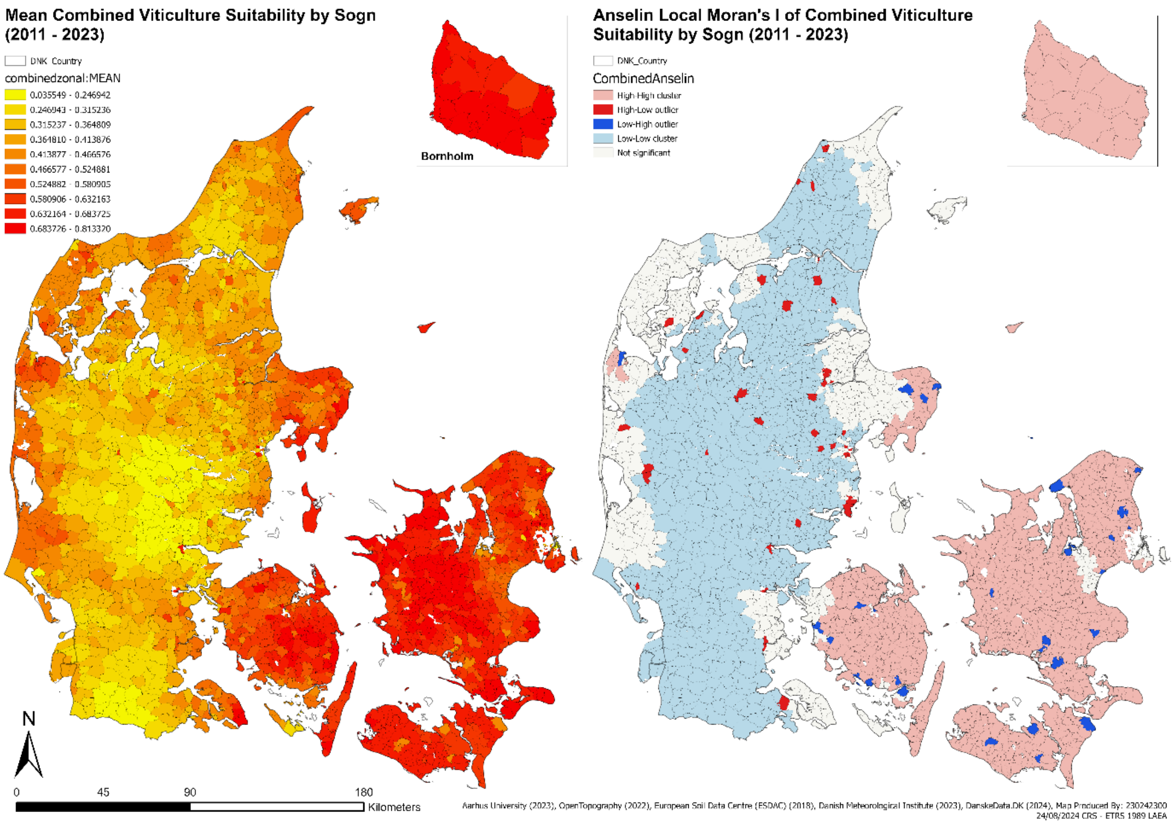

Figure 14 - Mean combined viticultural suitability by Sogn with LISA cluster and outlier spatial autocorrelations.

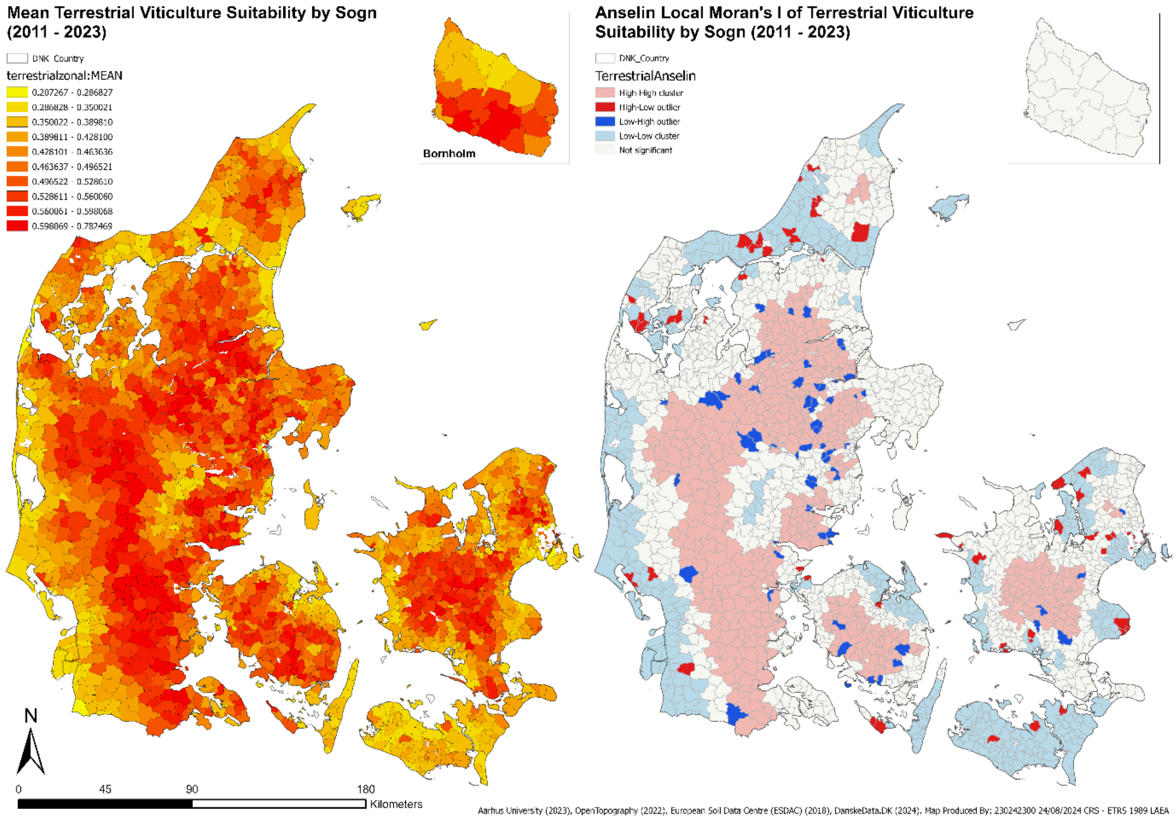

Figure 15 - Mean terrestrial suitability by Sogn with LISA cluster and outlier spatial autocorrelations.

Research Question 3

Table 8 ranks existing Danish vineyards according to climatic variables integrated within the DWVS. 70.7% of existing vineyards are positioned in locations with GST greater than 13°C, where 13°C represents the climate/maturity threshold for cool climate viticulture (Jones, Duff and Myers, 2006). Only 3.9% of vineyards are in regions experiencing GSTs greater than 14°C, which represents the climate/maturity thresholds for Chardonnay and Pinot Noir, the predominant cultivar planted in England and Wales (Nesbitt et al., 2022). April and May air frost is observed in all Danish vineyards, some as little as 1.3 days per year, however observations of 10.34 days per year were recorded. 97.4% of vineyards experienced fewer than 4.1 days of air frost per month during the study period with 68.9 % averaging fewer than three days of air frost per month.

41.56% of existing Danish vineyards experience 4691.63 - 5285.72mm of accumulated precipitation across the growing season while 92.2% of vineyards experience less than 6469.18 mm of precipitation, equivalent to 2.33 mm of rain per day across the growing season. The driest vineyards average just 1.69 mm of rain per growing season day across the study period, 52.3% of existing vineyards experience less than 2mm of rain per day. The 10 wettest existing vineyards experience mean combined daily precipitation of 24 mm per day across the growing season. June precipitation typically accounts for 10.4 - 14.8% of total GSP, despite accounting for 14.1% of growing season length. Daily June precipitation appears lowing than mean GSP, with 64.9% of existing vineyards experiencing less than 2 mm of daily rainfall. The mean June rainfall value was 1.88 mm per day, 56.4 mm per month.

All existing vineyards were in areas of GSP standard deviation of 7.73 mm, the range of standard deviations 6.97 mm, with an overall mean of 10.7 mm during the growing season. The top 10 most 'stable' by GSP experienced a mean of 8.88 mm, while the bottom 10 least 'stable' vineyards experience greater GSP variance of 13.33 mm. All vineyards observe GST standard deviation of 0.53°C or higher, with mean GST standard deviation calculated at 0.59. There is little evidence to suggest spatial clustering of GST variance, with high variance vineyards (>0.61) interspersed with low variance vineyards (<0.57) across Sjælland and Hovedstaden.

Solar irradiance of existing vineyards ranged from 442.6 – 505.6 MJ/m^2, with 62.3% of vineyards experiencing mean solar irradiance greater than 474 MJ/m^2. Vineyards with both high and low solar irradiance were found to be spatially autocorrelated i.e. located near each other (Moran's I = 0.67, Z-score – 16.1, $P < 0.05$). Low lying and South facing coastal margins, in addition to smaller islands and peninsulas across Sjælland and Hovedstaden account for the ten sunniest existing vineyards in Denmark. Among the 10 least sunny vineyards, solar irradiance totalled just 4,477.48 Mj/m^2, with mean solar irradiance of 447.75 MJ/m^2.

Mean GDD count across existing Danish vineyard was 854.06, with a maximum observed GDD count of 993, and a minimum of 718.64. The top 10 vineyard site averaged 984 GDDs per year, with the bottom 10 vineyards averaging 732. 67.5% (52) of vineyards were in areas experiencing more than 800 GDDs per year, 33.77% (26) of vineyards averaged more than 900 GDDs per year, while none were observed to have more than 1000. Considering 2018 alone, 80.5% (62) of vineyards observed GDD of more than 1000 across the growing season, 50.65% (39) of vineyards experienced more than 1100 combined GDD, and 14.29% (11) experienced GDD sums greater than 1200. During 2018, the lowest GDD observed was 936.2 and 1259.7 being the highest. GDD sums of the 10 highest GDD vineyards was 1228.27.

Table 8 – Existing Danish vineyards ranked by Bioclimatic indices.

Rank Order	Vineyards (%)	Solar	Vineyards (%)	GDD	Vineyards (%)	GST	Vineyards (%)	GST SD	Vineyards (%)	GSP	Vineyards (%)	GSP SD	Vineyards (%)	Days of Frost (April-May)	Vineyards (%)	June Rainfall (mm)
1	23.38	489.86 - 505.62	25.97%	924.49 - 993.11	22.08%	13.722 - 14.035	25.97%	0.539 to 0.567	41.56	4691.63 - 5285.72	24.68	7.72 - 9.47	42.86%	16.894 - 46.789	3.90	494.69 - 598.27
2	38.96	474.11 - 489.86	36.36%	855.87 - 924.49	27.27%	13.445 - 13.722	28.57%	0.568 to 0.596	23.38	5285.72 - 5877.45	38.96	9.47 - 11.22	25.97%	46.789 - 76.684	37.66	598.27 - 701.45
3	16.88	458.35 - 474.11	9.09%	787.26 - 855.87	24.68%	12.838 - 13.445	20.78%	0.597 to 0.615	27.27	5877.45 - 6469.18	27.27	11.22 - 12.96	28.57%	76.684 - 106.579	27.27	701.45 - 804.62
4	20.78	442.54 - 458.35	28.57%	718.64 - 787.26	25.97%	12.538 - 12.838	24.68%	0.616 to 0.657	7.79	6469.18 - 7060.90	9.09	12.96 - 14.70	2.60%	106.579 - 136.475	31.17	804.62 - 907.80

6. Discussion

This investigation has employed fuzzy logic GIS and spatial statistics to evaluate quantitative relationships between terrestrial and climatic input variables for Danish viticulture. The first research question¬ aimed to first evaluate whether climatic and terrestrial conditions in Denmark currently support cool climate viticulture according to the DVSM model, incorporating both terrestrial and climate inputs. Evaluation of spatial clustering and distribution at both global and local scale to determine to what extent terrestrial, climate and combined fuzzy suitability values tend to be geographically collocated. Research question 3 applied DVSM fuzzy suitability results, in addition to model input variables, to evaluate whether existing Danish vineyards are currently optimally located, according to growing season precipitation, temperature and variance thereof, Solar Irradiance, June rainfall, Frost prevalence and GDD sums.

A first analysis evaluating research question 1 employed both Fuzzy and Boolean membership functions. Boolean membership defined exclusion criteria in which terrestrial characteristics were deemed ‘incompatible’ with viticultural development. Where suitability membership isn’t binary, fuzzy membership type, mid-point and spread values determined the width and character of the transition zone of association from 0 (not a member) to 1 (a member) (Malczewski, 2004; Nesbitt, Dorling and Lovett, 2018). Terrestrial, Climate and combined models indicate where fuzzy suitability is regarded as highest, and lowest. Where fuzzy overlay was employed to combine terrestrial and climate layers, and produce a combined model of viticultural suitability, a fuzzy gamma value was applied to control the intersection (AND) and union (OR) operators of the input layers, which determines the shape and steepness of the fuzzy overlay function (Esri Ltd., 2024).

This analysis suggests that 10 Kommuner contained 218,129.9 ha of terrestrially suitable land, of which Viborg, Ringkøbing-Skjern. and Vejle performed strongly. Calculation of terrestrial suitability as a proportion of total land area revealed that Haderslev (24.56%), Vesthimmerlands (25.09%) and Vejen (24.26%) contained high proportions of terrestrially suitable land area. Strikingly, Vejen Kommune was identified as having mean fuzzy suitability of 0.58 across 19,754.95 ha. Interpretation of terrestrial suitability should consider both area and mean suitability value when identifying viticultural potential.

Alternating thin till beds, Selandian sand, Eocene Svind Marl and Freshwater Peat exhibited suitability values greater than 0.55 within the DVSM. A further 20 sediment classes exhibited suitability greater than 0.5, of which 40% were predominantly, clay, sand or gravel based. Clay and sand till underlay 447,804.4 ha of terrestrially suitable land. Despite this, Chalk and Limestone substrata, commonly found throughout the Champagne region of France, are relatively rare in

Denmark, comprising 3,221.8 ha of terrestrially suitable land at 0.41 mean suitability. Just 0.38 % of terrestrially suitable Danish land was underlain by chalk or limestone substrata. This finding is significantly less than found by (Nesbitt, Dorling and Lovett, 2018), who report 27,384 ha of terrestrially suitable land, on shallow lime-rich soils over chalk or limestone within Hampshire, UK alone. Total terrestrially suitable Limestone and Bedrock substrata area in Denmark totals 9.6% of the area of chalk and limestone substrata found in the Champagne viticulture region of France (33,500 ha).

The fact that 70.7 % of Danish Kommuner saw GST >13°C across the study indicates that the climate/ maturity threshold for cool-climate viticulture as defined by Jones (2006) has been crossed in 70% of Kommuner. Although 29.3% of Kommuner fail to achieve GST >13°C, this investigation does not consider that substantial potential benefit of vineyard amelioration methods from row orientation, shelterbelt construction and canopy management (Cataldo, Fucile and Mattii, 2021).

April – May air frost was found to be prevalent through the Danish interior, with specific localities averaging 5.69 days of monthly air frost throughout the study period. Frost risk was found to be spatially clustered (Moran's I = 0.73, $P < 0.05$), with specific localities averaging 5.69 days of monthly air frost throughout the study period. Frost risk was found to diminish at coastal margins particularly across Hovedstaden and Sjælland. Such findings exhibit striking similarity to Nesbitt, Dorling and Lovett (2018) who report 1-3 days of mean air frost per month across East Anglia, south-central and south-east England over a study period of 1981-2010. The temporal discrepancy of data observations between this investigation (2011-2023) and Nesbitt, Dorling and Lovett (1981-2010) suggests that Denmark experiences more spring frost than present day England and Wales assuming continued decline of spring frost days under recent climate change. Therefore, direct comparison between studies is limited to the theoretical.

Regarding GSP and GST standard deviation, low lying coastal regions experienced more 'stable' weather (GST ~ 0.5°C, GSP ~ 7-10 mm) compared to Central and Southern Syddanmark (GST ~ 0.7°C, GSP ~ 15-17 mm). It is hypothesised that proximity to coastal areas is positively associated with lower GST and GSP variability. The higher specific heat capacity of water in comparison to land masses is far greater, requiring a significant amount more heat energy to raise its temperature, per gram. Therefore, interannual sea surface temperature is considerably less variable than Danish land masses meaning that proximal land areas may benefit from more 'stable' precipitation and air temperature. This implication suggests that all other things being equal, coastal margins will be more favourably suited to supporting existing and future Danish vineyards. The range of GST standard deviation observed was 0.24°C. Compared to existing studies, Danish GST variance is 0.085°C more stable than was observed in England and Wales (0.325°C) by Nesbitt, Dorling and Lovett (2018). Within the same study interannual GSP standard deviation range was 395mm compared with 9.58 mm shown in figure 11.

Research question 2 sought to analyse the spatial distribution and clustering relationship of fuzzy suitability values developed via the DVSM in research question 1. Mean fuzzy suitability was aggregated to 2144 Sogn polygons across Denmark. Three iterations of each spatial autocorrelation method sought to tease out nuanced spatial patterns among climatic, terrestrial and combined viticultural suitability. In each case, spatial relationships between features were conceptualised using k-nearest neighbours, considering the 15 closest neighbouring features, such that spatial autocorrelation at Sogne with no contiguous neighbours could be evaluated. Spatial autocorrelation was initially assessed globally, using Global Moran's I. spatial clustering was confirmed in each case. Climate suitability values were strongly positively clustered (Moran's I = 0.84, $P < 0.05$) with combined suitability demonstrating moderate spatial autocorrelation (Moran's I = 0.82, $P < 0.05$). Spatial clustering of terrestrial suitability is less distinct although still moderately positively clustered (Moran's I = 0.45, $P < 0.05$), which suggests that both high and low fuzzy suitability values are more uniformly distributed across Denmark, than in the case of climatic, or combined fuzzy suitability. In each case the null hypothesis was rejected at the ($p < 0.05$), concluding that fuzzy suitability in all cases was moderately to strongly clustered in Denmark. Rejection of the null hypothesis implies that the terrestrial and climate phenomenon governing fuzzy suitability are non-randomly distributed, and by extension confirms Tobler's first law of geography that "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). Discrepancies between strength of spatial autocorrelation of climate and terrestrial fuzzy suitability suggests that climatic suitability is more spatially clustered than terrestrial suitability. This contention not only reflects spatial patterns suggested by figures 13-14 in section 5, but is consistent with existing studies by Nesbitt, Dorling and Lovett (2018) and Cepnioglu (2021) which found climatic suitability consistently lower in the Northern margins of study areas compared to Southern areas. This effect is probably caused by lower GSTs, increased risk of spring air frost, and significantly diminished solar irradiance at higher latitudes due to more oblique angle of incidence of solar radiation. This effect is compounded even further in England and Wales, Sweden and Denmark, due to their comparatively high latitudes. This effect is common within national scale site suitability analyses, which span larger latitudinal areas and penalise lower solar irradiance values whether by fuzzy membership decline or lower suitability classification within conventional weighted sum methods.

Having established moderate to strong positive spatial clustering of viticultural suitability at the global (population) level, LISA was used to evaluate clusters and outlier features at the Sogn level on a case-by-case basis. As before three iterations of viticultural suitability were generated. Figures 13-15 suggest a distinct East-West divide in climatic suitability, whereby clusters of low suitability, surrounded by similarly low suitability are found throughout Midtjylland, Syddanmark and Nordjylland. In contrast Hovedstaden and Sjælland contains many high climatic suitability Sogne. Outliers, in which viticultural suitability within a Sogn contrast within surrounding Sogne are present, and skewed toward coastal margins, which may suggest that underlying environmental conditions determining suitability may be increasingly variable in these areas. In contrast clusters and outliers in terms of terrestrial suitability reflect environmental conditions which are far less variable across Denmark. Within research question 1, unfavourable climatic conditions were shown to polarise Danish viticulture into the broadly less suitable Midtjylland, Syddanmkar and Nordjylland and more suitable Hovedstaden and Sjælland., however the same is not the case for terrestrial clusters and outliers. Moderate positive spatial autocorrelation determined during Global Moran's I analysis is reflect with LISA analysis through a far less polarised distribution of high and low clusters of suitability. As a result, outliers of both high and low terrestrial suitability are increasingly distributed across Denmark, reflecting more outlier Sogne of both high and low suitability. It is significant to note in figure 14 that outliers are increasingly common within the Danish interior. The implication for Danish viticulture being that in terms of suitability, spatial trends of viticulturally suitable land cannot be grouped into more appropriate coastal margins and less suitable interior regions, it is increasingly possible that viticulturally suitable land may be found in both coastal and interior margins. LISA analysis of combined fuzzy suitability confirms the overwhelming spatial clustering relationship identified within the climate LISA. Terrestrial and Climatic cluster and outlier relationships show somewhat contrasting results, however when interpreting such findings, the importance of climate in determining successful grape growing conditions is reflected in the combined suitability LISA. This conclusion is commonly reflected within the literature, particularly in weighted sum analyses which overwhelming favour optimal bioclimatic parameters, particularly GST and GSP over terrestrial suitability parameters as discussed in section 2.2 (Kurtural, Dami and Taylor, 2007). Global and Local spatial autocorrelation estimates are limited by imperfect conceptualisation of spatial relationships. K-nearest neighbours was selected such that Sogn features in isolated regions have neighbouring values. This was deemed appropriate because Denmark is a country of many islands, therefore many Sogn share 0 contiguous borders. The implication that every Sogn is influenced by its 15 nearest neighbours is not necessarily accurate in all cases. This consideration should temper any assumptions made based on the results of spatial autocorrelation analysis.

Evaluation of existing Danish vineyards was achieved through application of DVSM model input variables to 77 existing Danish vineyard polygons from OpenStreetMap Overpass API. Zonal statistics were used to extract minimum, maximum and mean values of critical climate variables on which Danish vineyards are currently located. Between 2011-2023, 67.5% of existing vineyards averaged more than 800 GDDs per year, while 33.8% average more than 900. 2018 was isolated due to its significantly warmer GSTs, and by extension a higher number of GDDs than the 2011-2023 average. In 2018, more than half of existing vineyards experienced GDD sums greater than 1100, with 14.29% experiencing more than 1200 GDDs per growing season. Taken in isolation, mean GDD sums across the study period continues to threaten successful grape development and maturation, despite hybrid cultivars which can mature successfully at GDD sums of 850-100. However, considered in the context of anthropogenic climate warming and increasing frequency of bumper harvests such as 2018, the viability of 'traditional' grape varieties, including Pinot Noir and Chardonnay is increased. This is substantiated by the fact that 70.7% of existing vineyards were positioned in areas where GST >13°C. Furthermore during 2018 100 % of existing vineyards were in regions experiencing GST > 13°C, 92% experience GST >14°C and nearly a third experienced GST >15°C. These findings imply that during particularly warm growing seasons of GST > 14°C, and GDD sums >1100 GDD, Danish viticulture may be able to support Pinot Noir, Chardonnay and Sauvignon Blanc grape varieties, in certain specific localities. Previous evaluation of site allocation of English and Welsh vineyards by Nesbitt, Dorling and Lovett (2018) found that 85% of existing vineyards exceeded GSTs >13°C, however only 10% experienced GST > 14°C, lower than the observationally determined threshold for Pinot Noir and Chardonnay, despite these being the predominantly planted cultivars within England and Wales.

Interannual variability of growing season rainfall has previously been shown to negatively affect English and Welsh grapevine yields (Nesbitt, Dorling and Lovett, 2018). Existing Danish vineyards were found to have more 'stable' climates, both in terms of temperature and precipitation variability than English and Welsh vineyards. This investigation finds identical minimum temperature standard deviation of existing vineyards (0.53°C) in comparison with Nesbitt, Dorling and Lovett (2018), however maximum observed variability was significantly less at 0.66°C compared to at least 0.68°C. Future site suitability should be informed by GSP and GST variance found herein. Although there was little evidence to suggest spatial clustering of GSP and GST variance across existing vineyards, this investigation observed lower GSP and GST variability at coastal margins. As discussed previously, the low temperature variability of the sea moderates both precipitation volume and GST in areas adjacent to the sea. Currently, only 26% of vineyards are in the lowest quartile of GST variability, while 24.7% are within the most variable quartile.

Evaluation of the model results and discussion provided must consider several limitations inherent to the research design and methodology. Low spatial resolution of DMI climate datasets retrieved during DVSM construction are the most significant limiting factor within the methodology presented. These datasets, comprised of meteorological observations of 59 Danish weather stations, are subject to modified IDW interpolation methods before being aggregated to 10 x 10km grids. The spatial resolution of 10 km is far below the 1–5 km resolution grids used in fuzzy suitability analysis of English and Welsh vineyards. This limitation will detrimentally impact model accuracy by failing appropriately model climatic processes, spatial variability operating at sub 10 x 10km spatial resolution, which threaten productivity and modify sub-regional climate - viticulture relationships (White et al., 2006).

Similarly, this investigation has limited ability to draw out long term bioclimatic phenomenon, in addition to sub-daily to sub-hourly temporal trends. This investigation utilised the full extent of existing gridded bioclimatic datasets available, from January 2011 to January 2024. Although hourly climatic observations are available in some instances, a sub-daily investigation of BCIs was not practical within the scope of this research. As with practically all viticultural site suitability analyses, a trade of between scale and resolution is frequently inevitable. The DVSM presented is intended as a reference tool, as a precursor to more detailed, site-specific analysis. Future research may choose to employ ground truthing or primary data collection to capture the nature of complex bioclimatic phenomenon at very fine spatiotemporal scale.

7. Conclusion

The number of registered commercial vineyards in Denmark increased by 1100% from 8 to 96 during 2000 – 2017 (Becker and Toldam-Andersen, 2021). This growth reflects the emergence of cool-climate viticulture in Denmark, supported by increasing GSTs during April – October (Bentzen and Smith, 2009). Despite this, quantitatively defined relationships between fundamental environmental variables and vineyard suitability are not yet objectively established. Traditionally, Danish vineyard site selection has been assessed on a case-by-case basis, lacking in systematic spatial analysis and comprehensive evaluation. Consequently, Danish vineyards remain exposed to subjective judgement and substantial variability in harvest quality and yields, of which terrestrial and climatic factors are substantial contributors (Olsen et al., 2011).

This investigation developed a Danish Vineyards Suitability Model (DVSM) to objectively assess terrestrial and climatic suitability. A fuzzy logic-based GIS integrated environmental parameters which were identified via a literature review, including soil typology, GDDs and GSTs. Distinct spatial patterns of terrestrial and climatic suitability suggest that processes governing terrestrial and climatic suitability appear to operate independently of one another. It was hypothesised that topography and proximity to the sea are responsible for the observed variance in GST standard deviation of ~ 0.2°C and GSP of ~ 7.5mm (Nesbitt, Dorling and Lovett, 2018).

Research question 1 found that 70.7% of Danish Kommuner had GSTs exceeding 13°C, consistent with the reference range for cool-climate viticulture (Jones, 2006). This is particularly notable in the context of Nesbitt, Dorling and Lovett (2018) who found 85% of English and Welsh vineyards were in regions with GSTs greater than 13°C, though these were primarily concentrated in the warmer Southeast. Traditionally successful Chalk and Limestone substrata was found to underlay just 0.38% (3221.8 ha) of terrestrially suitable land in Denmark. This finding contrasts sharply with England and Wales, where 27,384 ha of terrestrially suitable land is underlain by Chalk and Limestone bedrock in Hampshire alone (Nesbitt, Dorling and Lovett, 2018). Existing literature emphasises that uniform soil composition may be of greater importance than composition itself for consistent berry growth (Jackson, 2008). In this investigation, 40% of soil types with suitability greater than 0.5 were predominantly clay, sand or gravel-based, types which are considered of highest viticultural relevance (Jackson, 2008). DMI climate datasets of 10km resolution somewhat limit the spatial resolution of DVSM outputs, which should be subject to further refinement in future analyses.

Research question 2 was answered via a secondary analysis examining spatial clustering of viticultural suitability. Statistically significant ($p < 0.05$) moderate to strong positive spatial autocorrelations were found terrestrially (Moran's I = 0.45), climatically (Moran's I = 0.84), and in combination (Moran's I = 0.82). High suitability clusters occurred in North and West Nordjylland and Midtjylland, while lower suitability clusters were observed in Hovedstaden and Sjælland. It is hypothesised that decreased solar irradiance at higher latitudes is responsible for the observed discrepancy, and has previously been observed in English, Welsh and Swedish vineyards (Nesbitt, Dorling and Lovett, 2018; Cepnioglu, 2021).

To determine whether existing Danish vineyards are optimally located, DVSM suitability and model input variables were applied to 77 vineyard polygons. Bioclimatic indices suggest that the 13°C 'cool climate' GST threshold was met by 72.7% of existing vineyards between 2011-2023. The 2018 climate proxy year indicated that growing degree sums greater than 1100 occurred in more than half of the studied vineyards with 14.29% experiencing more than 1200 GDDs per season. Although it was suggested that these results are within reference range for cultivation of Pinot Noir and Chardonnay, it is unlikely that 2018 growing season temperatures will become climatically 'normal' in the near future. Moreover, variance of GSP and GST, although less than observed in England and Wales, is concerning, particularly because 54.5% of existing vineyards experience 1.7-4.1 days of spring air frost per growing season.

To conclude, this investigation has successfully developed a fuzzy logic-based DVSM for Denmark based on open-source terrestrial and climate datasets. Statistical methods were first applied to evaluate both Global and Local cluster and outlier relationships at the Sogn level, before model suitability and variable inputs were used to objectively assess whether 77 existing Danish vineyards are optimally located. It is hoped that the DVSM will prove a valuable quantitative reference tool, under continued increases in Growing Season Temperatures and Danish viticulture development scenarios.

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Appendices

Appendix 1 – Evidence of Ethics Approval

The University Of Sheffield.

Downloaded: 29/08/2024
Approved: 17/06/2024

Patch Tully
Registration number: 230242300
Urban Studies and Planning
Programme: Applied GIS

Dear Patch

PROJECT TITLE: "Blurred Vines: A Terrestrial and Climate Suitability Model for Danish Viticulture with Fuzzy Logic"
APPLICATION: Reference Number 060416

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 17/06/2024 the above-named project was **approved** on ethics grounds, on the basis that you will adhere to the following documentation that you submitted for ethics review:

- University research ethics application form 060416 (form submission date: 14/06/2024); (expected project end date: 30/08/2024).

If during the course of the project you need to deviate significantly from the above-approved documentation please inform me since written approval will be required.

Your responsibilities in delivering this research project are set out at the end of this letter.

Yours sincerely

Chloe Renwick
Ethics Admin
Urban Studies and Planning

Please note the following responsibilities of the researcher in delivering the research project:

- The project must abide by the University's Research Ethics Policy: https://www.sheffield.ac.uk/research-services/ethics-integrity/policy
- The project must abide by the University's Good Research & Innovation Practices Policy: https://www.sheffield.ac.uk/polopoly_fs/1.671066!/file/GRIPPolicy.pdf
- The researcher must inform their supervisor (in the case of a student) or Ethics Admin (in the case of a member of staff) of any significant changes to the project or the approved documentation.
- The researcher must comply with the requirements of the law and relevant guidelines relating to security and confidentiality of personal data.
- The researcher is responsible for effectively managing the data collected both during and after the end of the project in line with best practice, and any relevant legislative, regulatory or contractual requirements.

Appendix 2 – USDA Soil Classification Script

```
### Python codeblock to execute in ArcGIS Pro field calculator
# 230242300
# 18/8/24
# Python script to classify Danish soil data, value based on United States
Department of Agriculture (1987)
# Soil mechanics Level 1 Module 3 USDA Soil Textural Classification Study
Guide.
# Adapted from (Pappas, 2022).

typeID(!Clay!, !Sand1!, !Silt1!)

def typeID(clay, sand, silt):
    if (sand > 85 and (silt + (1.5 * clay)) <= 15):
        return "sand"
    elif (sand > 70 and sand <= 85 and (silt + (1.5 * clay)) > 15) or (sand >
85 and (silt + (2 * clay)) <= 30):
        return "loamy sand"
    elif (clay >= 7 and clay <= 20 and sand > 52 and (silt + 2 * clay) > 30)
or (clay < 7 and silt < 50 and sand > 43 and sand <= 52):
        return "sandy loam"
    elif (clay >= 7 and clay <= 27 and silt >= 28 and silt < 50 and sand <=
52):
        return "loam"
    elif (silt >= 50 and (clay >= 12 and clay < 27)) or (silt >= 50 and silt <
80 and clay < 12):
        return "silt loam"
    elif (silt >= 80 and clay < 12):
        return "silt"
    elif (clay >= 20 and clay < 35 and silt < 28 and sand > 45):
        return "sandy clay loam"
    elif (clay >= 27 and clay < 40 and sand > 20 and sand <= 45):
        return "clay loam"
    elif (clay >= 27 and clay < 40 and sand <= 20):
        return "silty clay loam"
    elif (clay >= 35 and sand <= 45):
        return "sandy clay"
    elif (clay >= 40 and silt >= 40):
        return "silty clay"
    elif (clay >= 40 and sand <= 45 and silt < 40):
        return "clay"
    return None
```

Appendix 3 – Danish Vineyards Address Geocoder

```
### Danish Vineyards Geocoder
# 230242300
# 18/8/24
# Python script to geocode and extract Danish Vineyard Addresses Latitude and Longitude coordinates

import pandas as pd
from arcgis.gis import GIS

# Make Dataframe use the pd.read_csv function
vineyards_df = pd.read_csv(r'U:\Modules\TRP483\data\vineyards\Danish_Vineyards.csv')

gis = GIS("home")

def geocoder(row):
    address = f"{row['address']}, {row['town']}, {row['zip']}, Denmark"
    result = geocode(address, as_featureset=True)
    if result and result.features:
        location = result.features[0].geometry
        return location[x], location['y']
    else:
        return None, None

# adding new columns called longitude and latitude to dataframe
vineyards_df[['Longitude','Latitude']] = vineyards_df.apply(geocoder, axis=1, result_type="expand")

# remove rows where no coordinates are present
vineyards_df = vineyards_df.dropna(subset=['Longitude', 'Latitude'])

# save the new geocoded layer as .csv
vineyards_df.to_csv('Danish_Vineyards_decoded.csv', index=False)
```