Sheffield Hallam University

Viticulture Suitability Analysis in Great Britain: A GIS-based Multi-criteria Approach Using Weighted Overlay Analysis

KHALID HAMEED

33081764

SUPERVISOR:

DR REMY VENESS

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Viticulture Suitability Analysis in Great Britain: A GIS-based Multi-criteria Approach Using Weighted Overlay Analysis

Abstract

This study presents a comprehensive evaluation of viticulture suitability across Great Britain through an integrated Geographic Information Systems (GIS) approach, combining climatic and terrain factors using the Weighted Overlay tool in ArcGIS Pro. The methodology employs a carefully calibrated balanced weighting system (15% each for Growing Season Temperature, precipitation, aspect, slope, elevation, and land use; 10% for frost risk) to assess potential vineyard sites, representing a significant advancement from traditional climate-focused assessments. Climate data from UKCP18 at 12km resolution was integrated with high-resolution terrain data from SRTM (30m) and comprehensive land use information from OS MasterMap to identify optimal areas for vineyard establishment. Growing Season Temperature (6.0-14.1°C), precipitation patterns (271-2504mm), and April frost risk were analyzed alongside terrain parameters including elevation (optimal 25-80m), slope (optimal 5-10%), and aspect (prioritizing southern exposures). The analysis validates model predictions against 1,095 existing vineyard locations, revealing strong correlation between predicted suitability and current vineyard distribution, particularly for larger operations. Results demonstrate a clear southeast-northwest gradient in suitability, with highest potential in southeastern England and notable opportunities in East Anglia, where favorable combinations of climate and terrain factors create optimal growing conditions. Box plot and scatter plot analyses confirm that larger vineyards (>50 ha) consistently achieve higher suitability scores (3.5-4.0), suggesting more strategic site selection in commercial-scale operations. This research not only provides valuable insights for vineyard investment and expansion but also establishes a robust methodological framework for assessing viticulture potential in cool-climate regions. The findings are particularly relevant as climate change continues to influence growing conditions across Great Britain, offering evidence-based guidance for the sustainable development of the UK wine industry.

1 Introduction

The United Kingdom's wine industry has undergone a remarkable transformation in recent decades, evolving from a niche agricultural activity to a significant sector of growing economic importance. This expansion is evidenced by substantial growth in vineyard area, reaching 4,209 hectares in 2023, supporting 1,030 vineyards and 221 wineries. The industry's development is further demonstrated by its production capacity, with 8.8 million bottles sold in 2023, representing a 187% growth since 2018 (WineGB, 2024). This exponential growth reflects increasing confidence in UK viticulture and growing recognition of its products in international markets.

This dramatic expansion reflects multiple interrelated factors. Climate change has played a crucial role, with warming temperatures extending growing seasons and improving grape ripening conditions across many parts of the UK (Nesbitt et al., 2016). The industry's focus on sparkling wine production, accounting for 76% of total production, has proven particularly successful, with UK wines not only gaining international recognition but also winning prestigious awards in global competitions, challenging traditional wine-producing regions (WineGB, 2024). This success has attracted significant investment and expertise to the sector, further driving its development and professionalization.

The recent success of UK viticulture can be attributed to a combination of factors, including improved winemaking techniques, changing consumer preferences, and, significantly, more favorable climatic conditions (Georgeson and Maslin, 2017). Climate change has played a crucial role in this transformation, with warming temperatures extending the growing season and improving grape ripening conditions in many parts of the UK (Nesbitt et al., 2016).

The varietal composition of UK vineyards reveals both traditional approaches and innovative adaptations to local conditions. Chardonnay (32%), Pinot Noir (27%), and Pinot Meunier (9%) dominate plantings, reflecting the industry's focus on sparkling wine production. While the majority of UK vineyards have historically been concentrated in the southern counties of England, particularly Kent, Sussex, and Hampshire, the changing climate is prompting exploration of viticulture potential in other regions (Nesbitt et al., 2016; Georgeson and Maslin, 2017). These traditional areas benefit from chalky soils similar to those found in Champagne, France, and have offered suitable climate conditions for grape cultivation.

However, the presence of over 90 different grape varieties across UK vineyards demonstrates the industry's experimental nature and adaptability to changing conditions. This diversity suggests both the potential for further innovation in variety selection and the need for careful consideration of site-specific conditions in vineyard establishment.

As climate change continues to alter growing conditions across the country, understanding its implications for viticulture becomes increasingly critical. Changes in temperature patterns, precipitation regimes, and extreme weather events could significantly impact the suitability of current wine-growing regions while potentially opening new areas for cultivation (Jones et al., 2005). Rising temperatures may extend the geographical range suitable for viticulture northward, while changing precipitation patterns could affect disease pressure and grape quality. This evolving landscape presents both opportunities and challenges for the UK wine industry, necessitating comprehensive analysis for future planning.

The integration of Geographic Information Systems (GIS) with multi-criteria analysis provides powerful tools for assessing viticulture suitability. This study employs ArcGIS Pro's Weighted Overlay tool with a carefully calibrated balanced approach to factor weighting: 15% each for Growing Season Temperature (GST), precipitation, aspect, slope, elevation, and land use, with 10% assigned to frost risk. This innovative methodology builds upon previous work by Nesbitt et al. (2018) while incorporating additional parameters and updated climate projections from UKCP18. The use of balanced weighting represents a significant advancement in viticulture suitability assessment, moving beyond traditional climate-focused approaches to consider the full range of factors affecting vineyard success.

Understanding vineyard suitability through GIS analysis has become increasingly critical as the industry expands. Traditional methods of site selection, often based on local knowledge and limited climate data, are being supplemented by comprehensive spatial analysis that can identify optimal growing conditions across broad geographical areas. This approach is particularly valuable in the UK context, where the complex interaction between climate and terrain factors creates intricate patterns of viticulture suitability. The need for such analysis is further emphasized by the significant investment required for vineyard establishment and the long-term nature of viticulture operations.

The use of GIS allows for the integration and analysis of multiple spatial datasets, providing a comprehensive view of the factors affecting vineyard suitability. The AHP, a multi-criteria decision-making method, enables the weighting of different factors based on their relative importance to viticulture, allowing for a nuanced assessment of suitability (Vaidya and Kumar, 2006).

This research is timely and significant as it addresses a critical need in the rapidly growing UK wine industry for long-term planning tools in the face of climate change. The findings of this study will provide valuable insights for vineyard owners, potential investors, and policymakers, helping to guide decisions on vineyard establishment, expansion, and adaptation strategies in a changing climate.

1.1 Objectives

This research aims to achieve several interconnected objectives:

1. Develop a comprehensive assessment of viticulture suitability across Great Britain through detailed analysis of climate and terrain characteristics, utilizing advanced GIS techniques and multi-criteria analysis.

2. Validate the model's predictions against current vineyard distribution patterns, analyzing data from 1,095 existing locations to understand the relationship between predicted suitability and actual vineyard establishment.

3. Identify potential areas for industry expansion, particularly focusing on regions showing high suitability but current underutilization, providing valuable guidance for future investment and development.

4. Create a robust methodological framework for ongoing assessment of viticulture potential that can adapt to changing climatic conditions and industry requirements.

The significance of this research extends beyond its immediate practical applications in vineyard establishment. The study contributes to the theoretical understanding of cool-climate viticulture potential while providing practical insights for policy development and investment planning. As the UK wine industry continues its trajectory of rapid growth, the findings will be particularly valuable for:

- Potential investors evaluating new vineyard sites
- Existing vineyard operators considering expansion
- Regional development agencies planning industry support
- Policymakers developing agricultural and rural development strategies
- Researchers studying climate change impacts on agriculture

This comprehensive approach to viticulture suitability assessment represents a significant advancement in the field, providing a foundation for sustainable industry development in the face of changing environmental conditions.

2 Literature Review

2.1 Climate Change and Global Viticulture

Climate change has emerged as a significant factor influencing viticulture worldwide. Jones et al. (2005) conducted a seminal study examining the relationship between climate change and wine quality across major wine-producing regions globally. Their findings indicated that while moderate warming has generally benefited cooler wine regions, continued warming could challenge the production of premium wine varieties in traditionally established areas.

Fraga et al. (2012) provided a comprehensive overview of climate change impacts on European viticulture. They highlighted shifts in phenological timings, changes in grape composition, and alterations in pest and disease pressure as key consequences of climate change. The study emphasized the need for adaptation strategies, including changes in vineyard management practices and the potential shift of wine-growing regions to higher latitudes or altitudes.

More recently, van Leeuwen et al. (2019) explored the complex interactions between grapevines and their environment under changing climatic conditions. They noted that while increased temperatures can lead to earlier ripening and higher sugar content in grapes, it may also result in reduced acidity and altered aromatic profiles, potentially affecting wine quality and style.

2.2 UK Wine Industry: Current Status and Climate Change Implications

The UK wine industry has experienced significant growth in recent years, partly attributed to changing climatic conditions. Nesbitt et al. (2016) conducted a comprehensive study on the impact of recent climate change on UK viticulture. They combined weather and climate records with producers' perspectives, finding that climate change has generally improved growing conditions for viticulture in the UK, particularly for sparkling wine production.

Building on this work, Nesbitt et al. (2018) developed a suitability model for viticulture in England and Wales. Their research identified substantial areas of land with high suitability for viticulture, suggesting significant potential for industry expansion. However, they also noted the importance of considering future climate projections in long-term vineyard planning.

Georgeson and Maslin (2017) further explored the potential distribution of climate suitability for viticulture in the UK by 2100. Their study projected an expansion of suitable areas for viticulture northwards and westwards, potentially opening up new regions for wine production. However, they also cautioned about increased variability in suitable conditions and the potential for extreme weather events affecting vine cultivation.

The rapid growth of the UK wine industry is evident in recent statistics. According to WineGB (2024), the UK now boasts 1,030 vineyards and 221 wineries, with the area under vine reaching 4,209 hectares in 2023. This represents a 123% increase in vineyard numbers over the past decade. The industry's production has also seen substantial growth, with 8.8 million bottles sold in 2023, a 187% increase since 2018.

2.3 Vineyard Suitability Assessment Methods

Traditional methods of assessing vineyard suitability have relied heavily on climate indices such as the Winkler Index and the Huglin Index (Tonietto and Carbonneau, 2004). These indices primarily focus on temperature accumulation during the growing season. However, as our understanding of the complex interactions between grapevines and their environment has grown, so has the need for more comprehensive assessment methods.

Geographic Information Systems (GIS) have emerged as a powerful tool for integrating multiple spatial datasets relevant to vineyard suitability. Irimia et al. (2014) demonstrated the use of GIS in viticultural zoning, combining climatic, topographic, and soil data to assess suitability for different grape varieties in Romania. Their approach allowed for a more nuanced understanding of terroir and its impact on wine quality.

Similarly, Fraga et al. (2014) used GIS to assess the impact of climate change on viticultural suitability in Europe. By integrating climate model projections with a range of bioclimatic indices, they were able to project shifts in suitable areas for viticulture across the continent

2.4 Application of Analytic Hierarchy Process (AHP) in Agriculture

The integration of Geographic Information Systems (GIS) with the Analytic Hierarchy Process (AHP) has proven to be a powerful approach in assessing land suitability for various agricultural purposes, including viticulture. Jovanovic et al. (2022) demonstrated the effectiveness of this integrated approach in evaluating the potential for ecotourism in the viticultural regions of Central Serbia. Their study incorporated a wide range of criteria, including physical-geographical elements (such as topography, altitude, slope, and land use) and socio-economic data (like proximity to tourist attractions and distance from major roads). This comprehensive approach allowed for a nuanced assessment of the landscape's potential for both viticulture and ecotourism activities.

The Analytic Hierarchy Process (AHP), as described by Franek and Kresta (2014), is a widely used method in multi-criteria decision-making, including applications in agriculture and land use planning. The authors highlight AHP's ability to handle both quantitative and qualitative criteria, making it particularly useful for complex decision problems where multiple factors need to be considered.

Vaidya and Kumar (2006) provided a comprehensive overview of AHP applications, highlighting its flexibility and ability to handle both quantitative and qualitative criteria.

In the context of viticulture, Yau et al. (2014) applied AHP in combination with GIS to assess vineyard site suitability in Taiwan. Their study demonstrated how AHP could be used to weight various factors influencing vineyard suitability, including climate, soil, and topography, providing a more robust assessment than climate indices alone.

Mokarram and Aminzadeh (2010) used a similar approach to evaluate land suitability for viticulture in Iran. Their study showcased how AHP could be used to prioritize different land characteristics based on their relative importance to grape cultivation, resulting in a more tailored suitability assessment.

2.5 Multi-criteria and Weighted Overlay Analysis in Land Suitability Assessment

Geographic Information Systems (GIS) integrated with multi-criteria analysis has emerged as a powerful tool for land suitability assessment in agriculture. The integration of multiple spatial datasets through weighted overlay analysis provides a comprehensive framework for evaluating complex land use decisions, particularly valuable in viticulture where successful site selection depends on numerous interacting environmental factors.

The weighted overlay technique enables systematic combination of different spatial criteria, with weights assigned based on their relative importance to overall suitability (Romano et al., 2015). This methodological approach has evolved significantly over the past decade, moving from simple Boolean operations to more sophisticated multi-criteria evaluations. Malczewski (2006) highlighted the advantages of this evolution, noting that weighted overlay analysis better reflects the complex nature of real-world environmental decision-making.

In viticulture applications, weighted overlay analysis has demonstrated particular effectiveness. Irimia et al. (2011) employed this approach in Romanian viticulture, successfully integrating climate, terrain, and soil factors to identify optimal growing areas. Their work demonstrated how different weights could be assigned to various environmental parameters based on their relative importance to grape cultivation. Similarly, Yau et al. (2014) applied this methodology to assess vineyard site suitability in the Pacific Northwest, showing how weighted overlay analysis could effectively incorporate both physical and climatic factors.

The method's flexibility in handling multiple variables while maintaining transparency in the decision-making process represents a significant advantage. Jovanovic et al. (2022) demonstrated this in their analysis of Serbian viticultural regions, where weighted overlay analysis enabled integration of both physical-geographical elements and socio-economic factors. The ability to adjust weights based on expert knowledge and regional conditions makes this approach particularly valuable for emerging wine regions. Recent applications have further refined the methodology. Santos et al. (2020) incorporated climate change scenarios into their assessment of European viticulture, demonstrating how weighted overlay analysis can adapt to evaluate future suitability under changing environmental conditions

2.6 Climate Change Projections for the UK

Understanding future climate scenarios is crucial for assessing long-term vineyard suitability. The UK Climate Projections (UKCP18) provide the most up-to-date assessment of how the UK climate may change over the 21st century (Lowe et al., 2018). These projections suggest a trend towards warmer, wetter winters and hotter, drier summers across the UK, with regional variations.

Specifically for viticulture, Mozell and Thach (2014) discussed how such changes might affect wine regions globally, including emerging regions like the UK. They highlighted potential benefits such as extended growing seasons and reduced frost risk, but also noted challenges such as increased disease pressure and the need for irrigation in traditionally rain-fed areas.

2.7 Adaptation Strategies in Viticulture

As climate change continues to impact wine-growing regions, adaptation strategies are becoming increasingly important. Nicholas and Durham (2012) explored how wine producers in California are adapting to climate change, highlighting strategies such as changes in canopy management, irrigation practices, and even the consideration of alternative grape varieties.

In the context of the UK, Nesbitt et al. (2016) noted that producers are already adapting to climate variability by adjusting harvest dates and exploring new varieties. However, they emphasized the need for longer-term strategies, including careful site selection for new vineyards.

2.8 Gaps in Current Research

While significant research has been conducted on climate change impacts on viticulture globally, there are still gaps in our understanding of how these changes will manifest in emerging wine regions like the UK. Mosedale et al. (2015) highlighted the need for more detailed, local-scale projections of climate change impacts on viticulture, particularly in regions where the industry is relatively young.

Furthermore, while GIS and AHP have been applied separately in various viticultural studies, there is a lack of research integrating these approaches for comprehensive suitability assessment in the UK context. This gap presents an opportunity for the current study to contribute significantly to the field.

3 Methodology

3.1 Study Area

The study encompasses Great Britain, an island covering approximately 209,331 square kilometers, spanning from the Isles of Scilly (49°N) to Shetland (61°N). The region is characterized by diverse topography, from the chalk downs of southern England and gentle hills of East Anglia to the mountainous regions of Wales and Scotland. Elevations range from below sea level in parts of the Fens to over 1,300 meters in the Scottish Highlands, creating varied microclimates and growing conditions.

The current concentration of viticulture in southern England, particularly in Kent, Sussex, and Hampshire, reflects historically favorable growing conditions in these regions. These areas benefit from chalky soils similar to those found in Champagne, France, combined with suitable climatic conditions for cool-climate viticulture (Nesbitt et al., 2018).

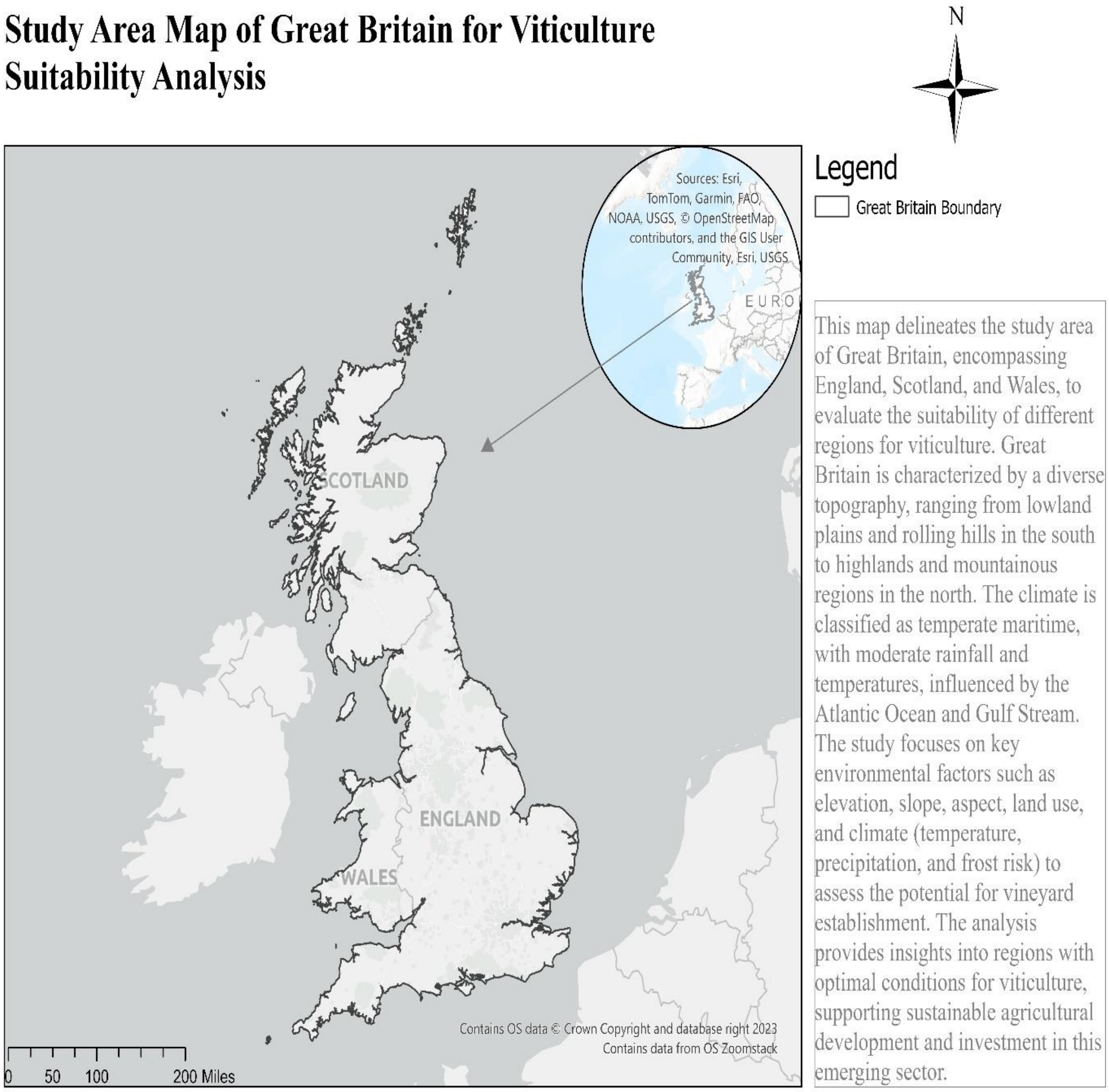

Figure 1 Study Area Map

3.2 Data Collection and Processing

3.2.1 Climate Data

Climate Data Collection and Processing

The climate variables for viticulture suitability assessment were derived from UK Climate Projections (UKCP18) 12km regional model outputs, following methodologies established in previous viticulture-climate studies (Nesbitt et al., 2018; Jones et al., 2005). This high-resolution data provides comprehensive coverage of Great Britain's diverse climate conditions.

Growing Season Temperature (GST), a critical factor in determining grape ripening potential and varietal suitability (Jones, 2006), was calculated using monthly mean temperatures from April to October. Following the methodology of Nesbitt et al. (2016), each monthly temperature dataset was converted from NetCDF format to raster using ArcGIS Pro's Make NetCDF Raster Layer tool. The resulting GST values ranged from 6.0°C to 14.1°C across Great Britain. Based on established cool-climate viticulture parameters (Fraga et al., 2013), these values were reclassified into suitability classes, with particular attention to the critical 13°C threshold identified for cool-climate viticulture.

Growing Season Precipitation analysis was conducted following methods established by Nesbitt et al. (2018) and Jones et al. (2005). Monthly precipitation data for April through October was processed, revealing values ranging from 271mm to 2504mm across the study area. The reclassification scheme prioritized areas with lower precipitation totals, reflecting the negative impact of excessive rainfall on disease pressure and grape quality (Fraga et al., 2012).

Frost risk assessment focused on April minimum temperatures, a period identified by Mosedale et al. (2015) as critical for early vine development in cool-climate regions. This timing corresponds to the increased vulnerability of emerging buds to frost damage, a significant risk factor in marginal viticulture regions (Nesbitt et al., 2016). Temperature thresholds for frost risk classification were established based on documented impacts on grapevine development and survival rates.

3.2.2 Terrain Data Analysis

The topographic characteristics of potential vineyard sites play a crucial role in viticulture success, particularly in cool-climate regions where terrain can significantly influence microclimate conditions. Our analysis utilized digital elevation data from the Shuttle Radar Topography Mission (SRTM) at 30-meter resolution, providing detailed topographic information across Great Britain.

Elevation analysis emerged as a critical component, given its complex influence on temperature regimes, frost risk, and overall vineyard operations. Building on research by Nesbitt et al. (2018), optimal elevation ranges were identified between 25-80m, representing a balance between avoiding frost-prone lowlands and excessively cool higher elevations. This aligns with recent findings demonstrating the importance of elevation in cool-climate viticulture (van Leeuwen et al., 2019).

Slope characteristics were analyzed for their dual impact on vineyard operations and vine growth conditions. Following established viticultural parameters (Jones & Webb, 2010), slopes between 5-10% were identified as optimal, providing adequate drainage while remaining suitable for mechanical operations. This range reflects both traditional knowledge and modern mechanization requirements, as documented by Jones, Snead, and Nelson (2004) in their comprehensive analysis of terrain factors in viticulture.

Aspect analysis focused on maximizing solar radiation interception, particularly crucial in cool-climate regions where heat accumulation can be limiting. South-facing slopes received highest suitability scores, supported by Hunter and Bonnardot's (2011) research on the relationship between aspect and key physiological processes in grapevines. The aspect classification emphasized the importance of solar radiation for grape ripening and disease management in maritime climates.

3.2.3 Land Cover Analysis

The assessment of land use suitability formed a critical component of this study, recognizing its fundamental role in determining viable vineyard locations. Land cover information was obtained from (Digimap), providing comprehensive coverage of Great Britain's current land use patterns. This high-resolution dataset underwent detailed analysis and reclassification to reflect viticulture potential.

Building on methodologies established by Nesbitt et al. (2018) and incorporating current industry practices, a five-class reclassification scheme was developed. Arable and horticultural land received the highest suitability scores (class 5), reflecting their optimal characteristics including existing agricultural infrastructure, proven cultivation capability, and established soil management practices (Jones & Webb, 2010). These areas typically present fewer conversion challenges and often benefit from existing irrigation systems and access infrastructure.

Improved grassland was classified as highly suitable (class 4), recognizing its potential for relatively straightforward conversion to viticulture. These areas generally feature good drainage characteristics and soil conditions suitable for vine cultivation, with minimal land preparation requirements (van Leeuwen et al., 2019).

Neutral and calcareous grasslands were assigned moderate suitability scores (class 3), acknowledging their potential for viticulture while recognizing the increased preparation requirements. These areas often feature suitable soil types but may require more significant infrastructure development for vineyard establishment.

Rough grassland received lower suitability scores (class 2), reflecting the greater challenges and costs associated with conversion to viticulture. Areas classified as unsuitable (class 1) included urban developments, woodland, water bodies, and other land uses incompatible with vineyard establishment.

Variable	Data Source & Resolution	Processing Steps	Suitability Classification
Climate Factors			
GST (April to October)	UKCP18 12km resolution	-NETCDF To Raster -Monthly Mean Calculation	**1:** <12°C (unsuitable) **2:** 12-13°C (marginally suitable) **3:** 13-13.5°C (suitable) **4:** 13.5-14°C (highly suitable) **5:** >14°C (optimal)

Growing Season Precipitation	UKCP18 12km resolution	-NETCDF To Raster -Monthly precipitation Calculation	**5:** <400mm **4:** 400-500mm **3:** 500-600mm **2:** 600-700mm **1:** >700mm
Frost Days	UKCP18 12km resolution	-NETCDF To Raster -April Minimum Air Temperature	**1:** <-2°C **2:** -2 to -1°C **3:** -1 to 0°C **4:** 0 to 1°C **5:** >1°C
Terrain Factor			
Dem	SRTM (30M)	-Dem -Reclassify	**1:** <1m & >150m (unsuitable) **2:** 1-10m & 140-150m **3:** 10-25m & 120-140m **4:** 80-120m & 25-40m **5:** 40-80m (optimal range)
Slope	Derived from SRTM DEM	-Slope Tool -Reclassify	**1:** <1% & >15% (unsuitable - frost risk/erosion risk) **2:** 1-3% & 13-15% **3:** 3-5% & 11-13% **4:** 10-11% & 5-7% **5:** 7-10% (optimal for operations)
Aspect	Derived from SRTM DEM	-Aspect Tool -Reclassify	**1:** North (337.5-22.5°) **2:** NE/NW (22.5-67.5° & 292.5-337.5°) **3:** E/W (67.5-112.5° & 247.5-292.5°) **4:** SE/SW (112.5-157.5° & 202.5-247.5°) **5:** South (157.5-202.5°)

Figure 2 Data Sources and Process Table

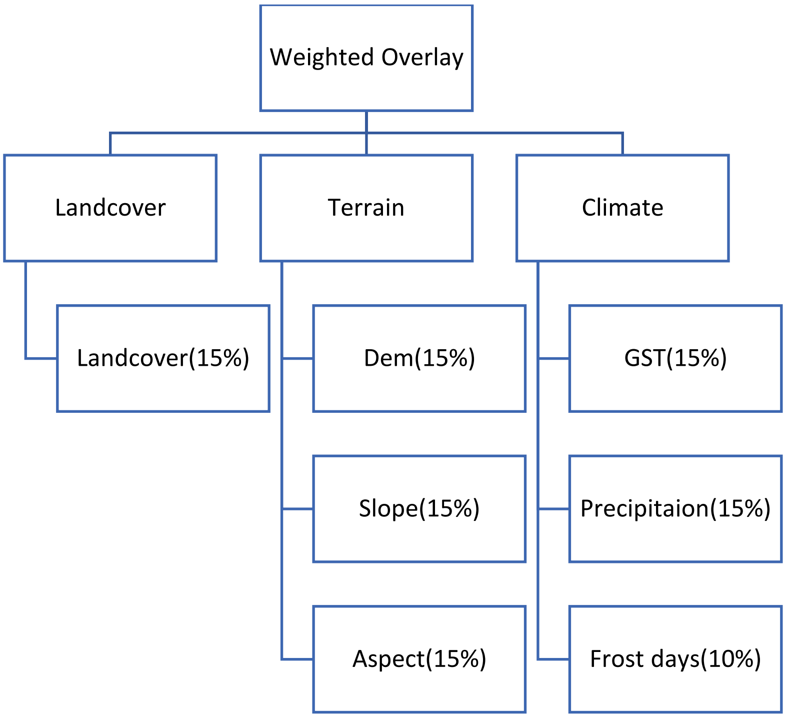

Figure 3 Weighted Overlay

3.3 Integration of Factors Using Weighted Overlay

The integration of multiple suitability factors was accomplished using the Weighted Overlay tool in ArcGIS Pro, employing a carefully calibrated weighting system. This approach represents a significant advancement from previous studies by applying balanced weights across most factors, reflecting their equal importance in vineyard success.

The weighting scheme was developed based on extensive literature review and industry understanding:

- Growing Season Temperature (GST): 15% weighting reflects its critical role in grape ripening and variety suitability
- Growing Season Precipitation: 15% acknowledges rainfall's impact on disease pressure and berry development
- Aspect: 15% recognizes the importance of solar radiation for grape maturation
- Slope: 15% considers both mechanical cultivation requirements and drainage characteristics
- Elevation: 15% accounts for frost risk mitigation and general climatic conditions
- Land Use: 15% reflects the practical feasibility of vineyard establishment
- Frost Risk: 10% represents spring frost threat to early vine development

Each input factor underwent rigorous preparation for the overlay process:

1. Standardization to ensure compatible scales and units
2. Reclassification to a consistent 1-5 suitability scale
3. Quality assessment to verify accurate representation
4. Edge effect analysis to ensure smooth transitions

The Weighted Overlay tool processing involved:

- Data alignment to ensure precise spatial correspondence
- Application of specified weights to each factor
- Mathematical combination of weighted values
- Output generation on a 1-5 suitability scale
- Quality control checks at each processing stage

3.4 Model Validation and Analysis

Current vineyard locations and planted areas were obtained from the UK Vineyards Association database (UKVA, 2023), providing comprehensive data on 1,095 operational vineyards across Great Britain.The validation process integrated multiple approaches to assess model reliability and practical applicability. Existing vineyard locations served as ground-truth data, enabling quantitative assessment of model predictions against current successful viticulture sites.

3.4.1 Statistical Validation

The validation methodology for this study employed a comprehensive approach to assess the model's effectiveness in predicting vineyard suitability. Using ArcGIS Pro's Extract Values to Points tool, suitability scores were extracted for all 1,095 existing vineyard locations across Great Britain. This process provided crucial validation data linking predicted suitability with actual vineyard establishment patterns, enabling detailed analysis of the model's predictive accuracy.

Statistical analysis of the extracted values focused on understanding the relationship between vineyard size and predicted suitability. The analysis categorized vineyards into three distinct size classes: small (<10 ha), medium (10-50 ha), and large (>50 ha). This classification enabled examination of whether larger, commercially successful operations aligned more closely with areas of higher predicted suitability, potentially indicating more rigorous site selection processes in commercial-scale ventures.

3.4.2 Size-Based Analysis

The validation process employed both visual and statistical methods to assess model performance. Box plot analysis revealed the distribution of suitability scores across vineyard size categories, providing insights into the relationship between operational scale and site suitability. The results showed particular consistency in larger operations, with vineyards over 50 hectares predominantly located in areas with suitability scores between 3.5 and 4.0, suggesting strategic site selection in commercial ventures.

Scatter plot analysis further examined the relationship between vineyard size and suitability scores, revealing important patterns in site selection. This analysis demonstrated a slight positive correlation between vineyard size and suitability scores, with larger operations consistently achieving higher suitability ratings. The plot also revealed clustering patterns that helped identify potential thresholds for commercial viability.

3.4.3 Regional Analysis

Regional validation examined spatial patterns in model predictions against known viticultural regions. Particular attention was paid to established wine-growing areas in southeast England, while also analyzing model predictions for emerging regions such as East Anglia. This approach helped verify the model's ability to identify both traditional and potential new viticultural areas, providing valuable insights for industry expansion.

4 Results

4.1 Reclassified Maps

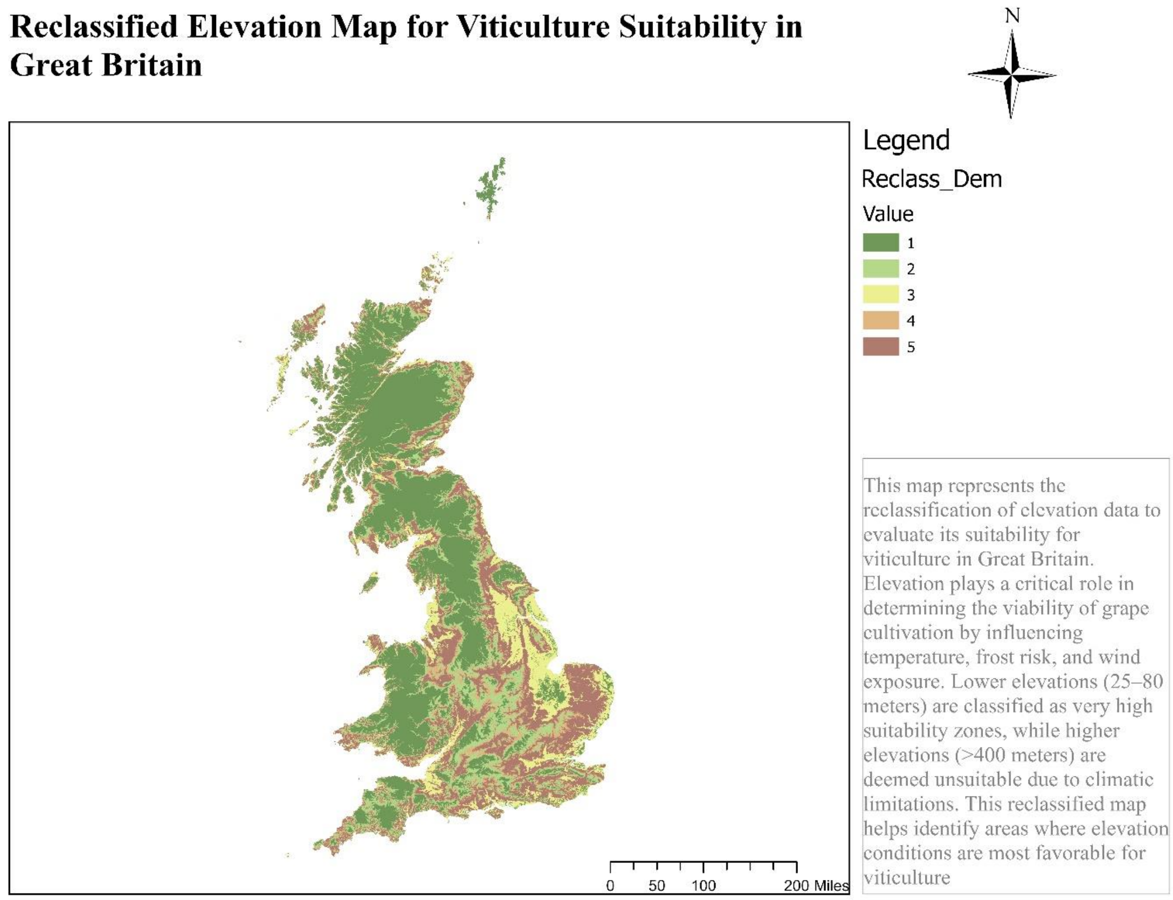

Figure 4 Reclassified Dem Map

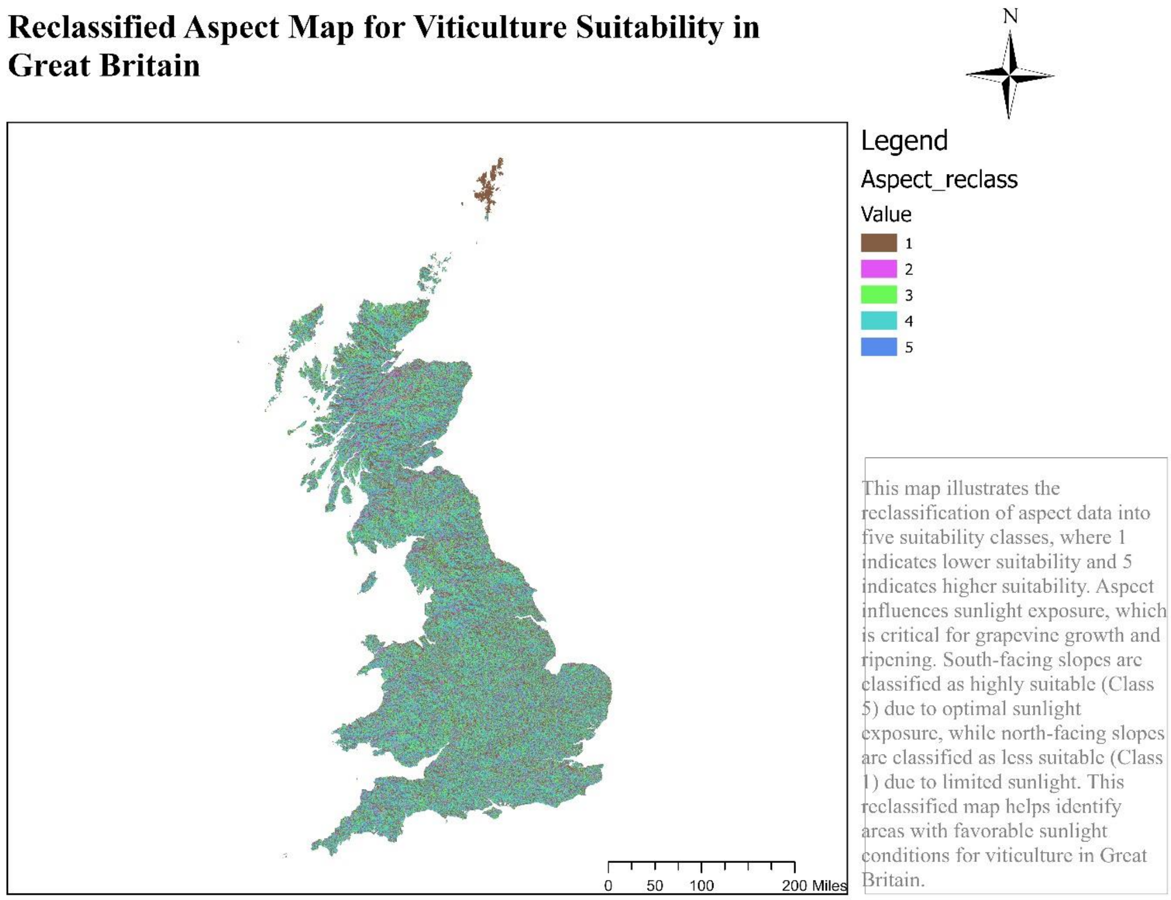

Figure 5 Reclassified Aspect Map

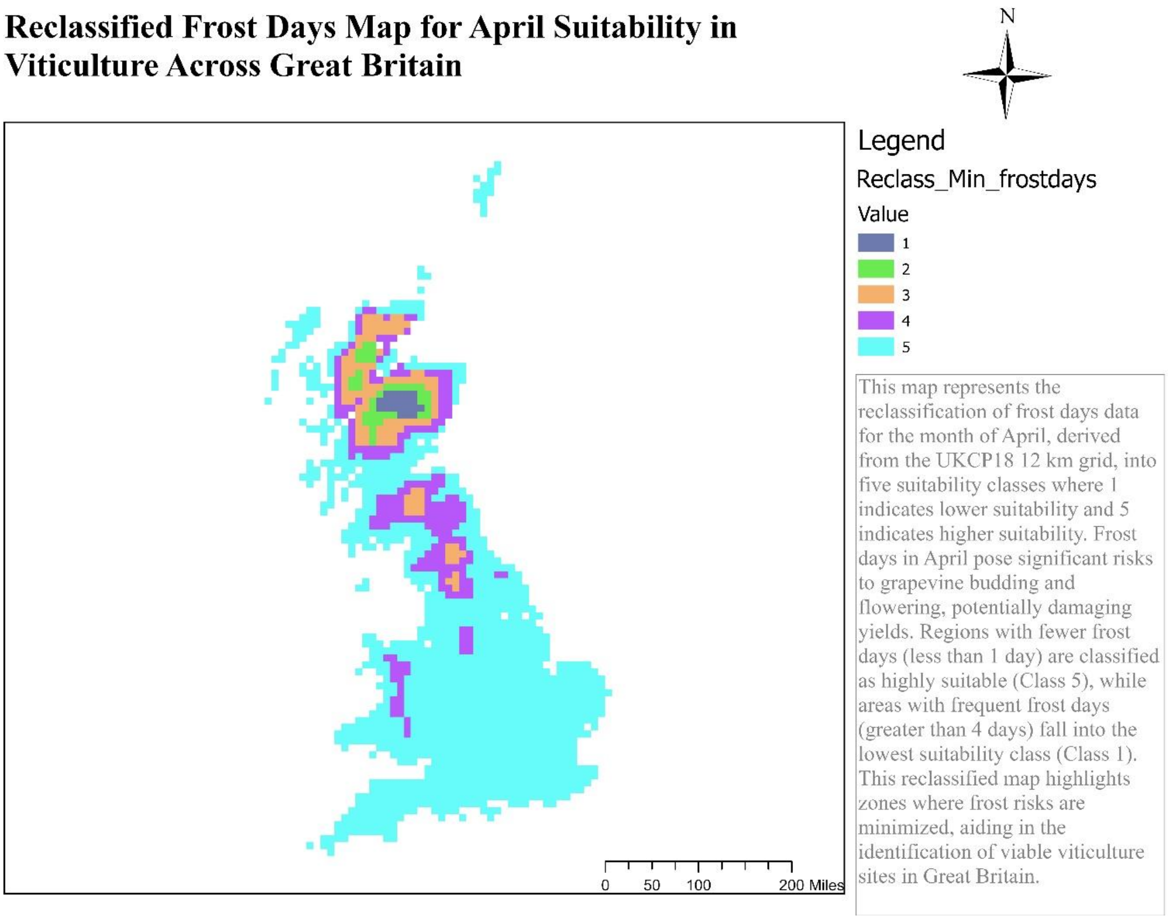

Figure 6 Reclassified Frost days map

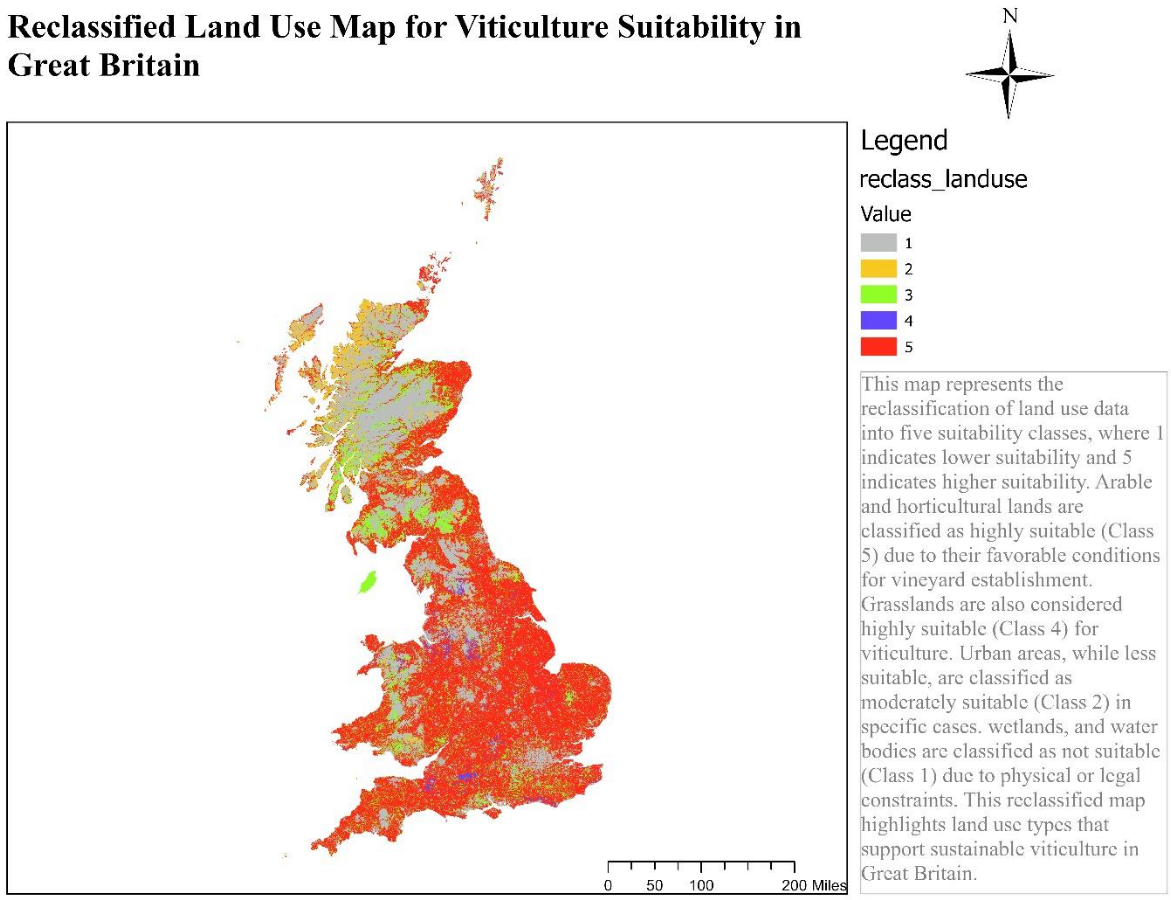

Figure 7 Reclassified Landuse Map

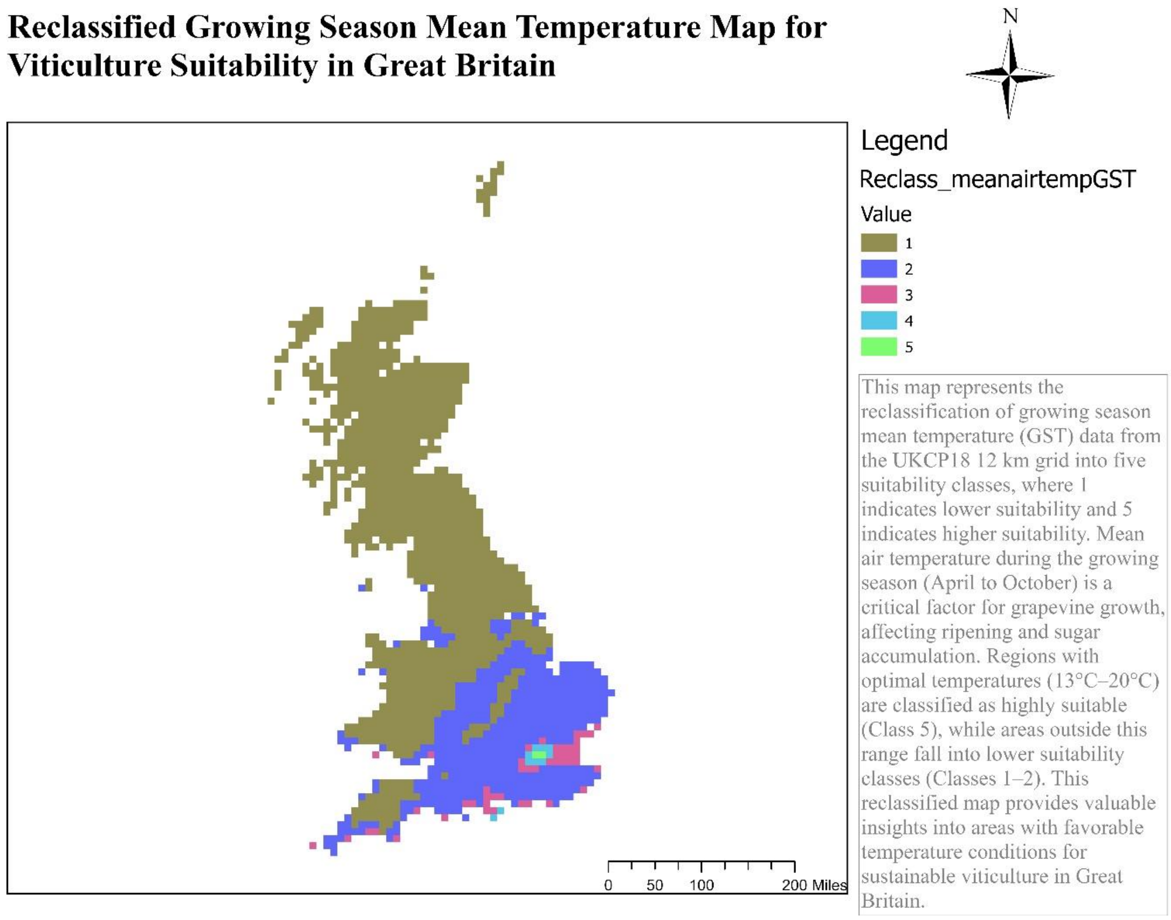

Figure 8 Reclassified Mean Air Temp Map

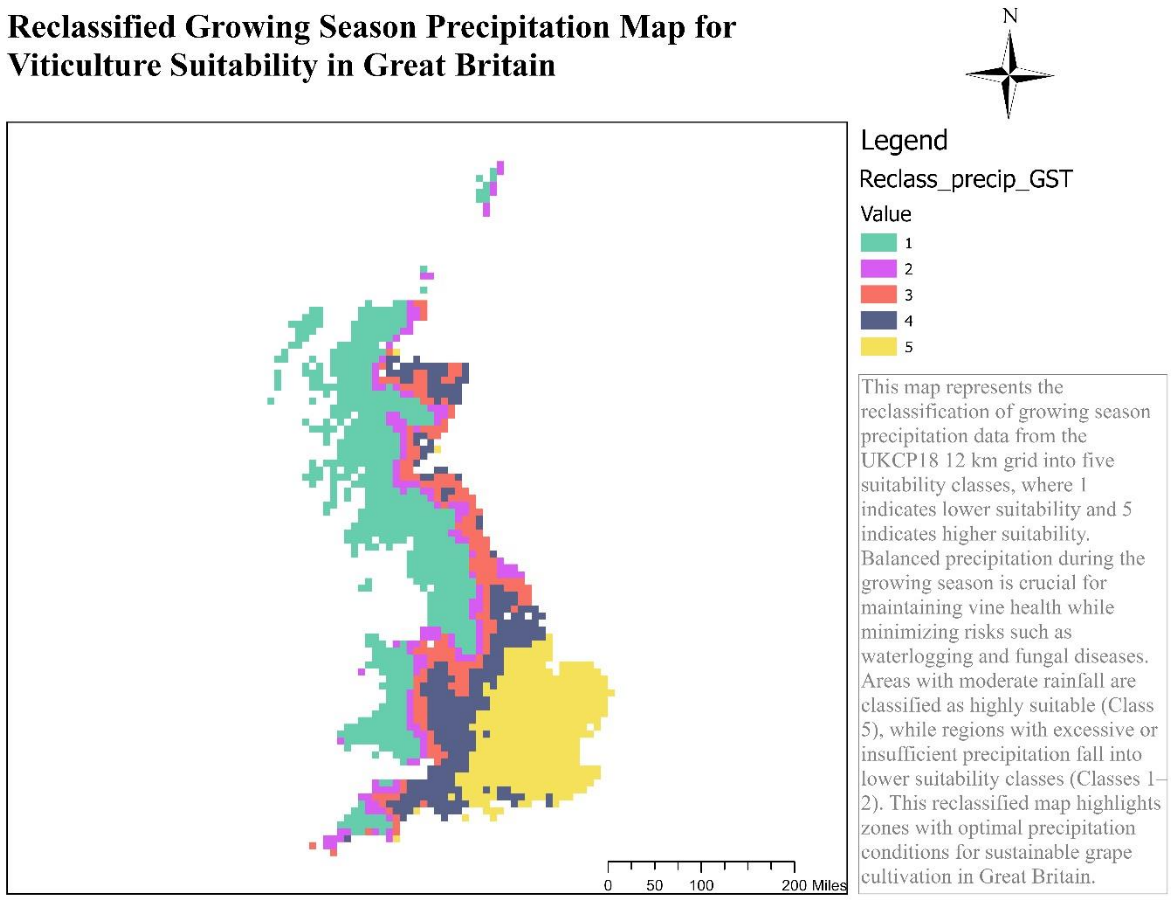

Figure 9 Reclassified Precipitation Map

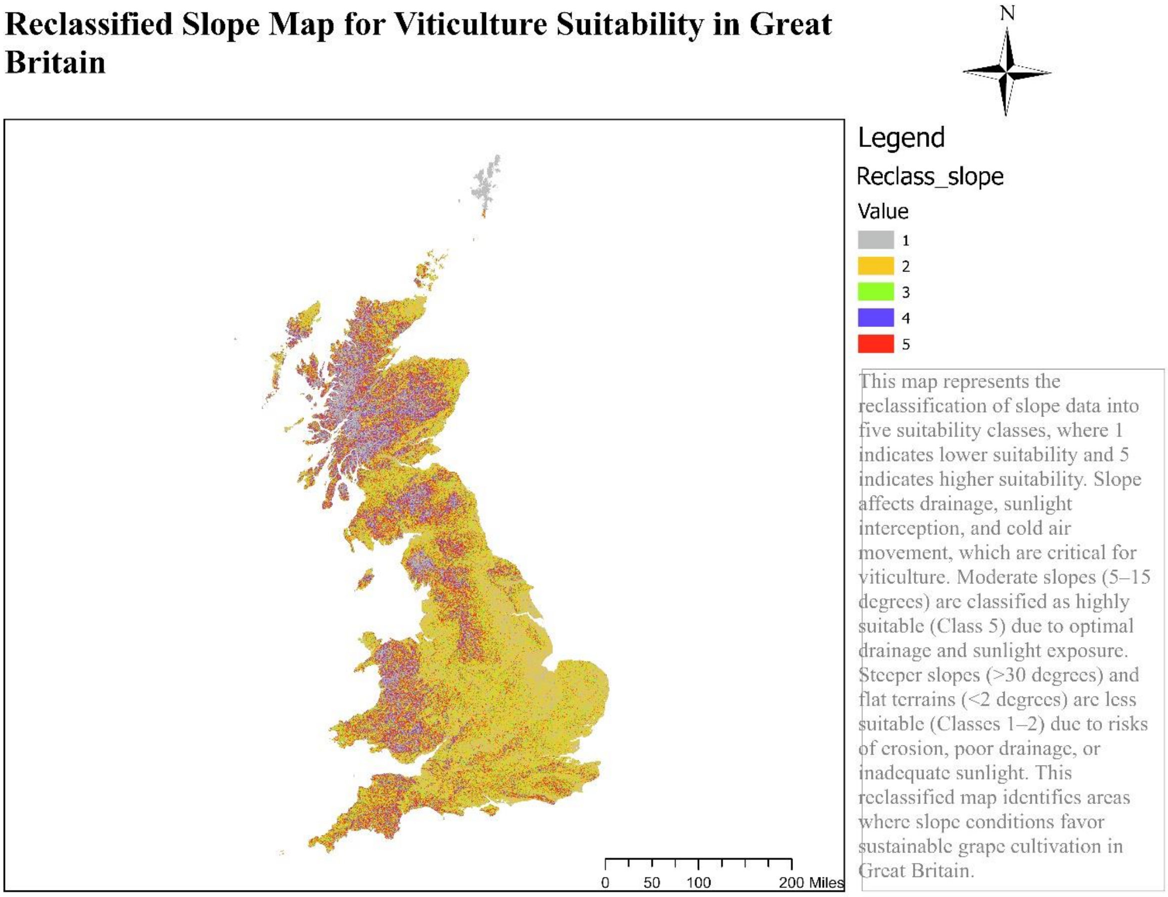

Figure 10 Reclassified Slope Map

4.2 Terrain Suitability Analysis

The terrain suitability assessment revealed distinct patterns of physical landscape capability for viticulture across England and Wales. Southern England demonstrated consistently favorable terrain characteristics, particularly in the chalk downlands of Sussex and Kent, where elevation ranges of 25-80m combined with optimal south-facing slopes create ideal conditions for vineyard establishment.

Analysis of elevation patterns showed that approximately 35% of the study area falls within the optimal range (25-80m), with the highest concentration of suitable elevations in southeast England. These areas benefit from reduced frost risk compared to lower elevations while avoiding the operational challenges and temperature limitations of higher altitudes.

The aspect analysis identified substantial areas with favorable southern exposures, particularly in the North and South Downs. These south-facing slopes receive optimal solar radiation, crucial for grape ripening in the UK's cool climate viticultural context. East Anglia, while generally flatter, showed moderate to high terrain suitability due to its gentle slopes and optimal elevations, particularly in Suffolk and Essex.

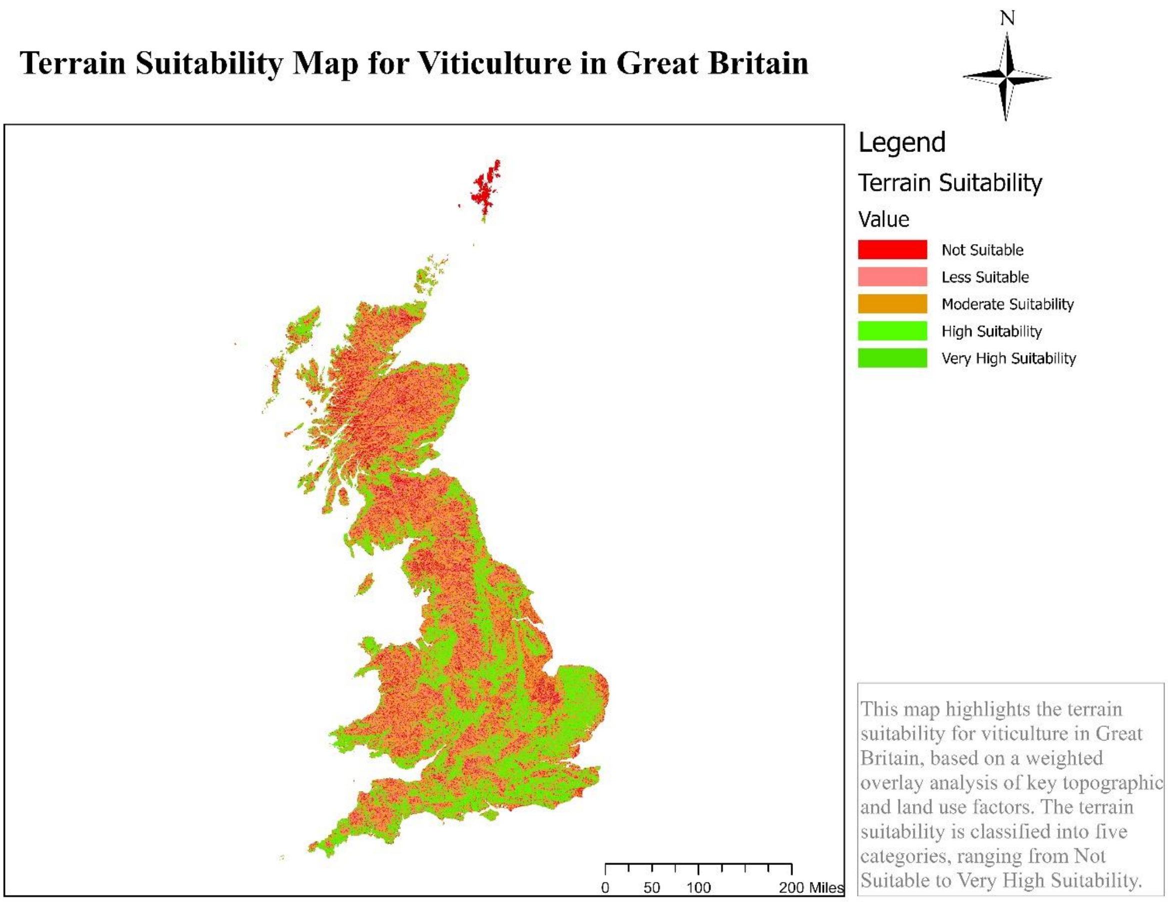

Figure 11 Terrain Suitabilty Map

4.3 Climate Suitability Analysis

Climate suitability mapping revealed a clear southeast-northwest gradient in growing conditions. The analysis of Growing Season Temperature (GST) showed that southeastern regions, particularly Essex and the Isle of Wight, experience the warmest growing season temperatures (13.9°C), aligning with previous findings by Nesbitt et al. (2018).

Precipitation analysis identified areas of optimal growing season rainfall (400-500mm) predominantly in eastern regions. Essex demonstrated particularly favorable conditions with the lowest growing season rainfall (346mm), followed by Suffolk (362mm), suggesting potential for expanded viticulture in these areas.

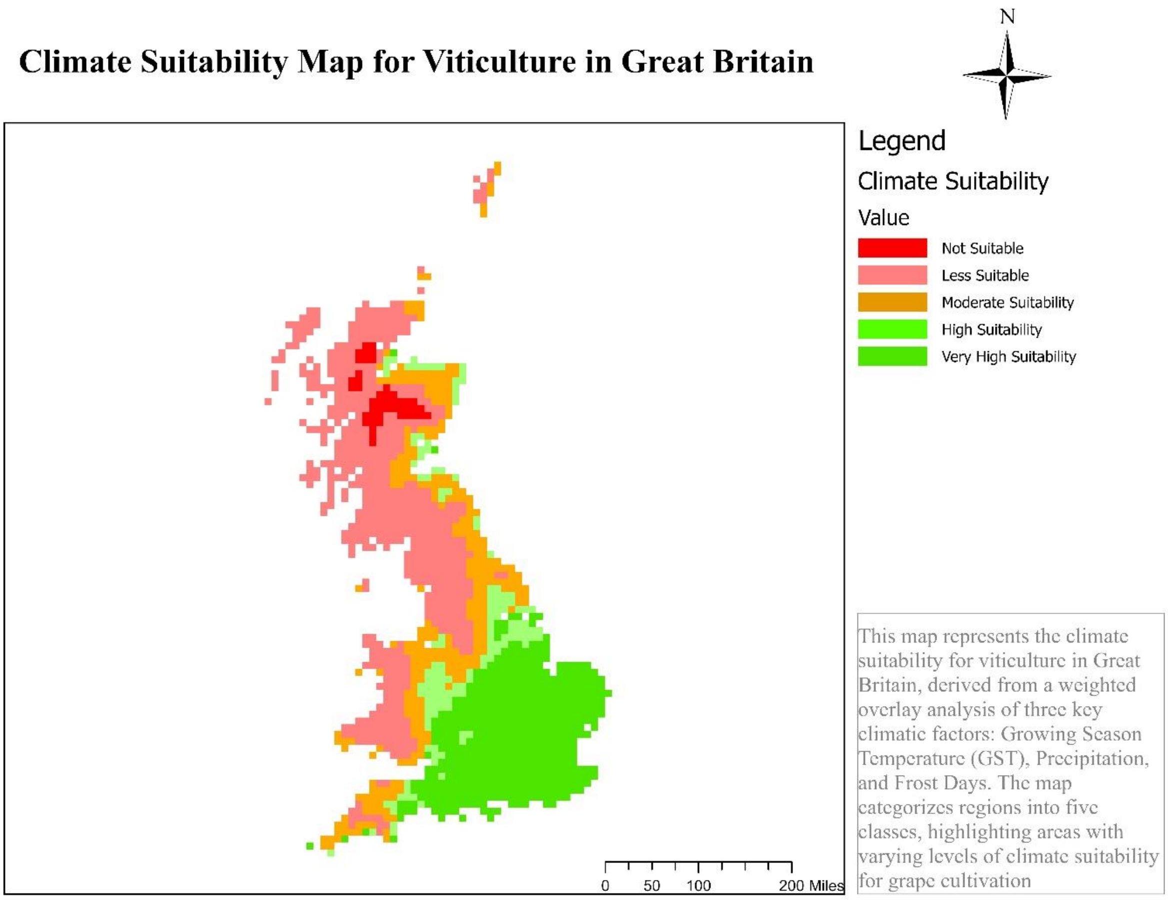

Figure 12 Climate Suitability Map

4.4 Weighted Overlay Analysis

The final suitability map produced through the weighted overlay analysis reveals distinct patterns of viticulture potential across Great Britain. The analysis, which integrates climate and terrain factors with balanced weighting, demonstrates clear spatial variations in suitability, ranging from 1 (Not Suitable) to 5 (Very High Suitability).

The highest suitability scores (4-5) are concentrated in southeastern England, particularly in Kent, Sussex, and parts of East Anglia. This finding aligns with research by Nesbitt et al. (2018), who identified these regions as having optimal growing conditions. The concentration of high suitability in these areas reflects the favorable combination of Growing Season Temperatures above 13.5°C, moderate precipitation levels, and appropriate terrain characteristics.

A transitional zone of moderate suitability (3) extends through central England, characterized by adequate but not optimal conditions for viticulture. This pattern supports findings by van Leeuwen et al. (2019) regarding the importance of balanced climate-terrain interactions in cool-climate viticulture regions.

Areas of lower suitability (1-2) dominate northern regions, primarily due to combinations of less favorable climate conditions and challenging terrain. This north-south gradient in suitability aligns with established understanding of cool-climate viticulture limitations (Jones & Webb, 2010).

Of particular interest is the identification of highly suitable areas in East Anglia, where relatively few vineyards currently exist. These regions demonstrate favorable combinations of:

- Growing Season Temperatures comparable to established vineyard regions
- Lower precipitation variability than current major growing areas
- Appropriate elevation and aspect combinations
- Extensive areas of suitable agricultural land

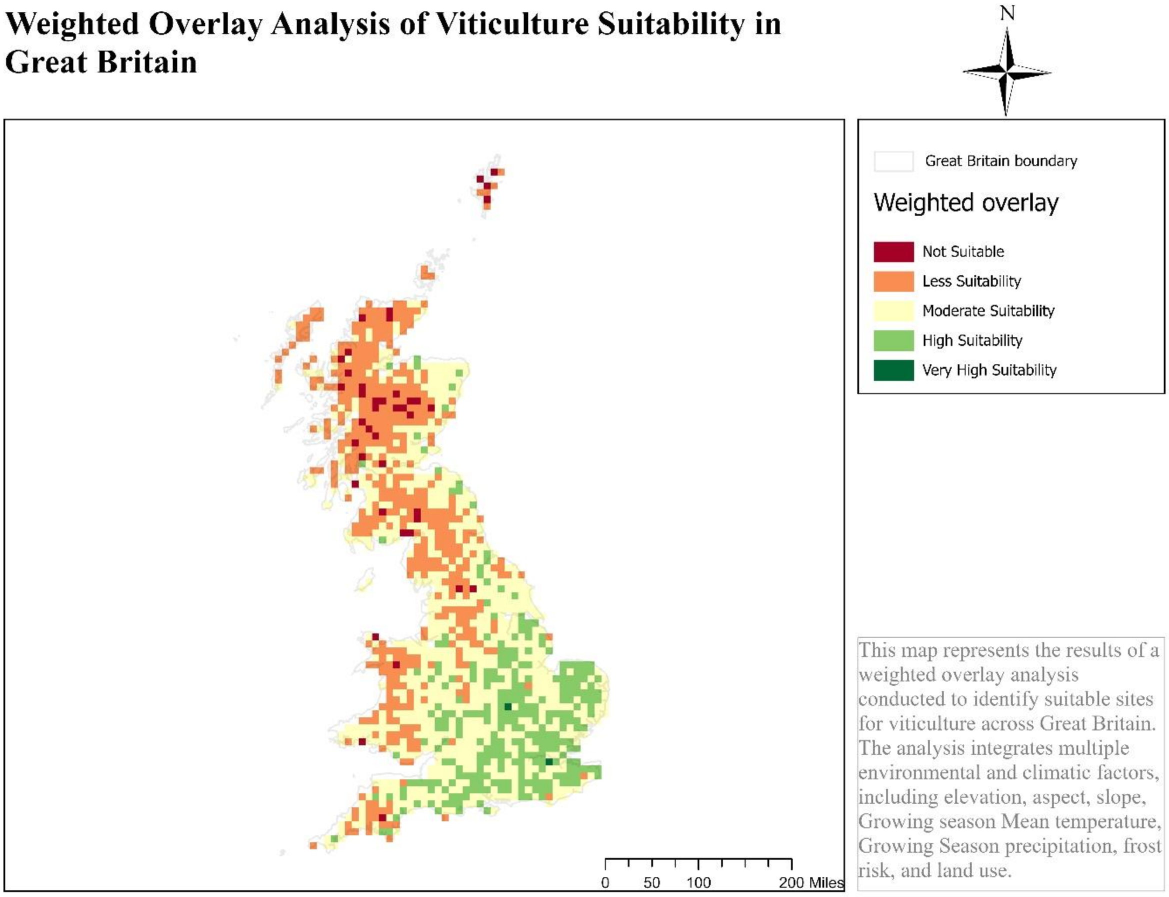

Figure 13 Weighted Overlay Analysis

4.5 Model Validation Analysis

The validation of the suitability model through analysis of existing vineyard distributions reveals significant patterns in site selection and operational scale. Two complementary analyses were conducted to understand these relationships:

4.5.1 Size-Suitability Relationship Analysis

The scatter plot (Figure Y) examining the relationship between vineyard size (hectares planted) and suitability scores reveals several key patterns:

- A clear clustering of points between suitability scores 2.0-4.0
- Strong representation at the 4.0 suitability level across various vineyard sizes
- Larger operations (>100 ha) consistently achieving scores above 3.0
- Notable concentration of smaller vineyards (<50 ha) across the full range of suitability scores

This distribution pattern suggests that while optimal site selection is possible at any scale, larger commercial operations tend to be more consistently located in areas of higher suitability. This finding aligns with research by Nesbitt et al. (2018) indicating the importance of comprehensive site assessment for commercial vineyard success.

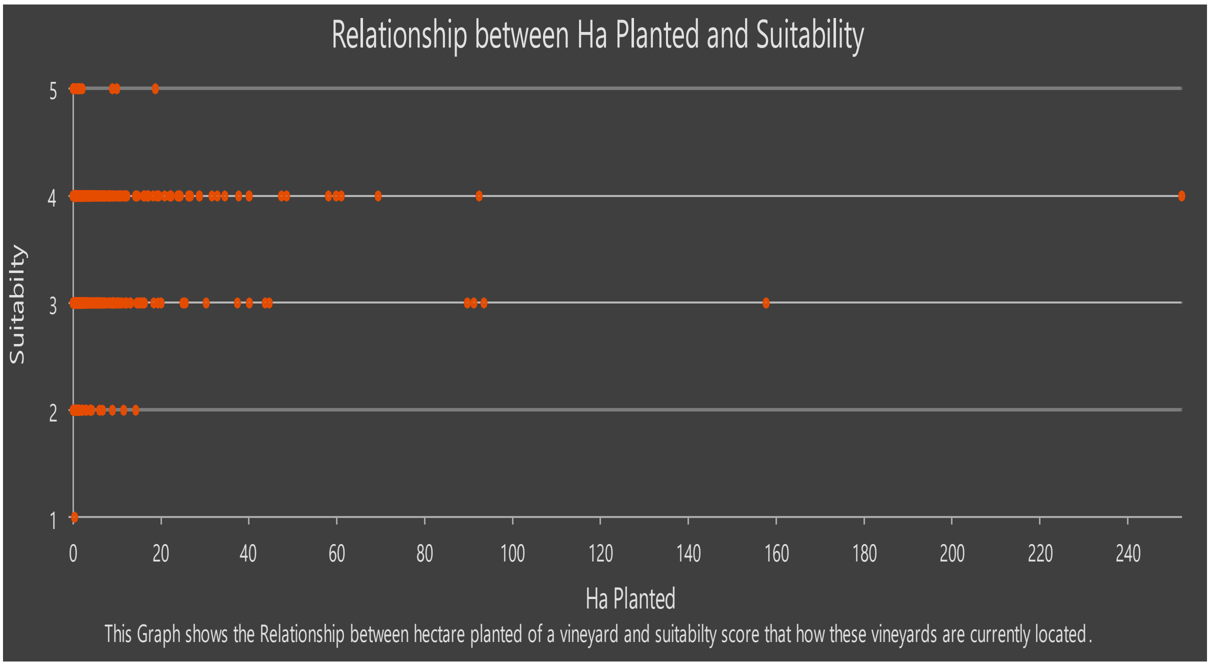

Figure 14 Scatter Plot

4.5.2 Size Category Distribution Analysis

The box plot illustrates the distribution of suitability scores across three vineyard size categories (Large: >50 ha, Medium: 10-50 ha, Small: <10 ha). Results demonstrate consistently high suitability scores (between 3.0-4.0) across all size categories, with some notable variations:

- Large vineyards show the most concentrated distribution around suitability scores of 3.5-4.0, suggesting more rigorous site selection in commercial-scale operations
- Medium-sized operations demonstrate similar median values but with slightly greater variation
- Small vineyards exhibit the widest range of suitability scores, indicating more diverse site selection criteria

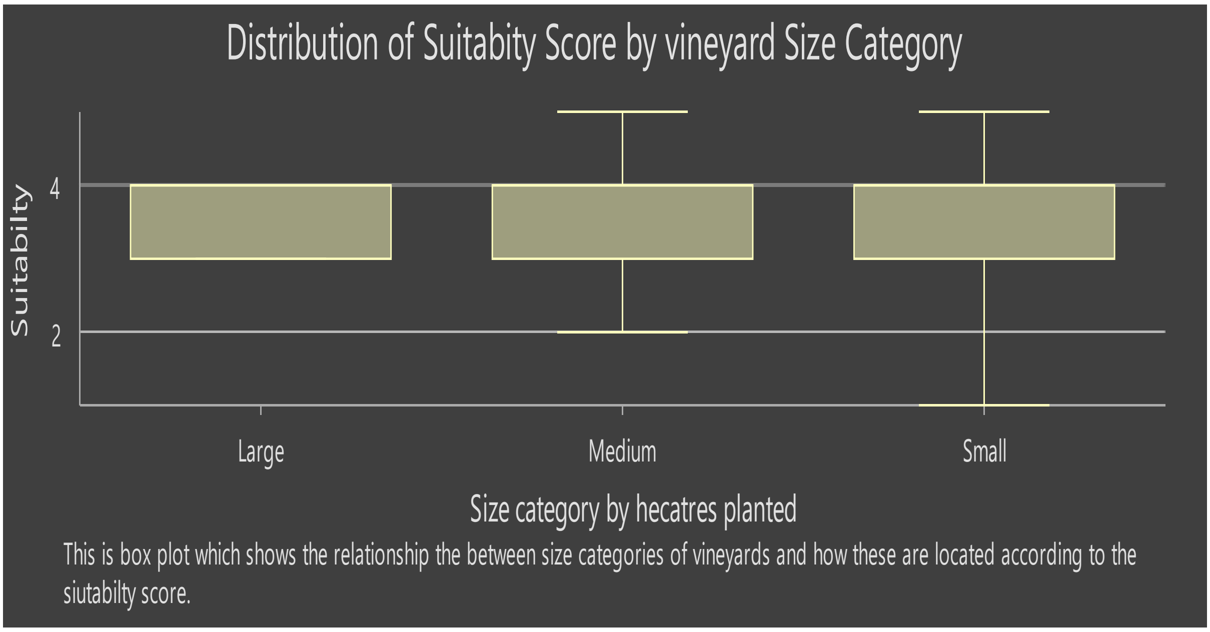

Figure 15 Box Plot

5 Limitations of the Study

Several key limitations should be considered when interpreting the results of this suitability analysis:

5.1 Data Resolution and Scenario Limitations

A significant limitation of this study lies in its reliance on UKCP18's RCP8.5 scenario data at 12km resolution. This "high emissions" scenario represents just one possible climate trajectory, and results might differ substantially under alternative emission scenarios. As noted by van Leeuwen et al. (2019), different climate scenarios can lead to varying projections of viticulture suitability. The choice of RCP8.5 scenario data, while providing valuable insights, may not capture the full range of potential future climate conditions affecting viticulture potential.

The spatial resolution of climate data (12km) potentially masks important microclimatic variations that could significantly influence vineyard success at local scales. This limitation becomes particularly relevant in areas with complex topography or coastal influences, where local climate conditions might deviate substantially from the broader regional patterns captured in the model. While this resolution is appropriate for regional-scale analysis, it may not capture fine-scale variations critical for site-specific vineyard planning.

Furthermore, the temporal scope of the climate data (1981-2010 baseline) provides a historical perspective but may not fully represent current or emerging climate patterns. The dynamic nature of climate change means that future conditions could deviate from those projected under the RCP8.5 scenario, potentially affecting the long-term accuracy of suitability assessments

5.2 Temporal Limitations

The climate data analysis, while comprehensive, represents averaged conditions and may not fully capture the impact of extreme weather events or inter-annual variability that could affect vineyard establishment and productivity. The model cannot account for short-term climate fluctuations that might be critical for vineyard success.

5.3 Model Simplification

The weighting scheme used in the multi-criteria analysis, while based on literature and industry standards, necessarily simplifies complex interactions between environmental variables. Some factors, such as soil chemistry and microbiological activity, were not included due to data availability constraints.

5.4 Socio-Economic Factors

The model focuses primarily on physical and climatic factors, with limited consideration of socio-economic variables such as:

- Market accessibility
- Labor availability
- Land prices
- Infrastructure availability These factors could significantly influence the practical viability of vineyard establishment.

5.5 Data Availability

Limited availability of high-resolution soil data and detailed historical weather records for some regions may affect model accuracy. Additionally, the vineyard location database, while comprehensive, may not capture all recent vineyard establishments or changes in planted area.

6 Discussion

6.1 Spatial Distribution Patterns

The balanced weighting approach (15% for most factors, 10% for frost risk) has validated traditional viticultural regions while identifying new potential areas for development. The concentration of high suitability scores (4-5) in southeastern England, particularly in Kent, Sussex, and parts of East Anglia, supports current industry distribution patterns but also suggests opportunities for expansion.

6.2 Model Performance Analysis

The validation against existing vineyard locations reveals several important insights:

6.2.1 Size-Based Performance

The consistent achievement of higher suitability scores (3.5-4.0) by large vineyards suggests that commercial-scale operations have historically prioritized optimal site selection. This alignment between model predictions and existing large-scale vineyards validates the balanced weighting approach while highlighting the importance of comprehensive site assessment for commercial ventures.

6.2.2 Regional Implications

The model reveals three distinct patterns:

1. Traditional Regions:

- High suitability scores confirm the appropriateness of current major vineyard locations
- Validates historical site selection in southeastern England

- Supports continued investment in established areas

2. Potential Expansion Areas:

- East Anglia shows particularly promising results
- Moderate suitability zones in central England offer opportunities
- Coastal areas show favorable combinations of factors

3. Limited Suitability Regions:

- Northern areas generally show lower suitability
- Western regions face combined climate-terrain challenges
- Higher elevation areas demonstrate limited potential

6.3 Future Implications and Industry Development

6.3.1 Industry Growth Potential

The identification of highly suitable areas beyond current vineyard concentrations presents significant opportunities for industry expansion. Particularly notable are:

- East Anglian regions showing high suitability scores (4-5)
- Coastal areas benefiting from maritime influence
- Transitional zones in central England offering moderate potential

6.3.2 Investment Considerations

The analysis provides valuable guidance for future vineyard investments:

1. Site Selection Priorities:

- Balanced consideration of climate and terrain factors
- Emphasis on areas scoring above 3.5 in overall suitability
- Consideration of land availability and accessibility

2. Scale-Based Recommendations:

- Large operations (>50 ha) should prioritize highest suitability zones (4-5)
- Medium-scale ventures can consider moderate suitability areas (3-4)
- Small-scale operations might succeed in broader suitability ranges

6.3.3 Climate Change Adaptations

The balanced weighting approach provides resilience to potential climate changes:

- Equal consideration of terrain factors offers long-term stability
- Identification of areas with multiple favorable characteristics
- Potential for industry expansion into previously marginal areas

6.3.4 Research Implications

This study's findings contribute to the growing body of knowledge on UK viticulture by:

1. Validating traditional growing regions through objective analysis
2. Identifying new potential areas for industry expansion
3. Demonstrating the effectiveness of balanced multi-criteria analysis
4. Providing a framework for future suitability assessments

7 Conclusions

This research presents a comprehensive assessment of viticulture suitability across England and Wales, employing a balanced multi-criteria analysis that challenges and extends previous understanding of potential vineyard locations. The integration of climate and terrain factors through equal weighting has provided robust validation of current vineyard distributions while identifying promising areas for industry expansion, particularly in East Anglia and selected coastal regions.

The strong correlation between model predictions and existing large-scale vineyard locations validates the effectiveness of the balanced weighting approach. This alignment is particularly evident in southeastern England, where historical vineyard establishment patterns correspond closely with areas of high predicted suitability. However, the analysis also reveals significant untapped potential in regions currently underrepresented in UK viticulture, suggesting opportunities for strategic industry expansion.

These findings have significant implications for the future development of UK viticulture. The identification of highly suitable areas beyond traditional growing regions provides valuable guidance for industry investment and expansion. Furthermore, the balanced consideration of multiple environmental factors offers increased resilience to potential climate change impacts, supporting long-term industry sustainability.

This research contributes significantly to the growing body of knowledge on cool-climate viticulture, providing a methodological framework that could be adapted for similar analyses in other emerging wine regions. The findings support evidence-based decision-making in vineyard establishment and industry development, particularly valuable as the UK wine industry continues its rapid growth and evolution.

The broader implications of this research extend beyond immediate vineyard site selection. As climate change continues to reshape agricultural possibilities across the UK, this study's methodology and findings provide valuable insights for both industry adaptation and policy development. The balanced weighting approach demonstrates that successful viticulture depends not solely on climate factors, as traditionally emphasized, but on the harmonious interaction of multiple environmental variables.

Looking forward, these findings suggest several key directions for industry development. The identification of highly suitable areas in East Anglia, particularly in Essex and Suffolk, presents immediate opportunities for industry expansion. These regions benefit from favorable combinations of climate and terrain factors similar to those found in traditional growing areas but remain relatively underutilized for viticulture. The success of existing large-scale operations in areas identified as highly suitable by the model suggests that commercial viability aligns well with predicted suitability patterns.

From a research perspective, this study advances the methodology of viticulture suitability assessment by demonstrating the effectiveness of balanced multi-criteria analysis. While previous studies have often emphasized climate factors, our approach shows that equal consideration of terrain and land use factors provides a more robust framework for site evaluation. This methodological contribution has implications beyond the UK context and could inform similar analyses in other emerging wine regions globally.

The practical applications of this research are particularly relevant for:

Industry Development: The findings provide a scientific basis for strategic industry expansion, identifying areas where investment in vineyard establishment is most likely to succeed. This is particularly valuable given the significant capital investment required for vineyard establishment and the long-term nature of such ventures.

Policy Formation: The comprehensive spatial analysis of viticulture potential can inform agricultural policy and regional development strategies, particularly in the context of climate change adaptation and rural economic development.

Research Advancement: The methodology developed here provides a framework for future studies, particularly in emerging wine regions where traditional viticultural parameters may need adaptation to local conditions.

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