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# Title of the degree thesis

Magister ( master) degree thesis

Field of the study: ………………...*\*)*



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Warsaw, July 2020

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**Field of the thesis (codes according to the Erasmus program)**

Economics (14300)

# Thematic classification

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# The title of the thesis in Polish

*<The title of the thesis translated into Polish>*

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# INTRODUCTION

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**Abstract:**

Viticulture is among the most climate-sensitive agricultural sectors, with the economic viability of quality wine production (*Vitis vinifera*) strictly bound by narrow thermal and hydrological niches. Anthropogenic climate change is rapidly destabilizing these traditional geographical boundaries, driving a poleward migration of the "viticultural belt." While existing literature has extensively modeled the decline of traditional southern regions, there is a paucity of rigorous, high-resolution research quantifying the economic potential of emerging markets in Northern and Central Europe.

This thesis addresses this gap by developing a holistic **Spatial Machine Learning model** to forecast the redistribution of viticultural suitability under CMIP6 climate scenarios (SSP2-4.5 and SSP5-8.5) for the mid-to-late 21st century. Unlike traditional studies that rely on linear, temperature-based bioclimatic indices (such as the Huglin or Winkler Index) in isolation, this research employs a non-linear **Species Distribution Modeling (SDM)** approach.

The methodology integrates downscaled climate projections (WorldClim v2.1) with high-resolution edaphic (soil texture, pH, drainage) and topographic (slope, aspect) variables. By training a **Random Forest** classifier on current European vineyard distributions, the model captures the complex, multi-dimensional interactions of *terroir* that simple indices overlook.

The study aims to demonstrate that incorporating non-climatic constraints—specifically soil quality and topography—significantly reduces the false-positive rate of suitability predictions in emerging regions such as Poland, the United Kingdom, and the Baltic states. The resulting suitability maps provide a granular, scientifically robust basis for understanding the future economic geography of European wine production, moving beyond simple climatic feasibility to realistic agricultural viability.

**Keywords:** *Spatial Machine Learning, Viticulture, Climate Change, CMIP6, Species Distribution Modeling, Emerging Markets, Precision Agriculture.*

**CHAPTER I**

**Introduction**

## 1.1 Background of the Study: The Climate-Viticulture Nexus

Viticulture represents one of the most climate-sensitive sectors of global agriculture. Unlike broad-acre crops such as wheat or maize, which thrive across extensive latitudinal ranges, the commercial production of quality wine grapes (*Vitis vinifera*) is confined to remarkably narrow climatic envelopes. These envelopes are defined by specific thermal thresholds, daily temperature ranges, and hydrological balances—factors that collectively constitute what viticulturists term *terroir* [(Leeuwen & Seguin, 2006, pp. 1–3)](https://www.zotero.org/google-docs/?mkHPz8). Historically, these bioclimatic constraints have restricted the world's prestigious wine regions to two distinct latitudinal bands, approximately 30° to 50° in both hemispheres [(Robinson & Johnson, 2019, pp. 12–25)](https://www.zotero.org/google-docs/?QmWl2g). However, anthropogenic climate change is now fundamentally destabilising these traditional geographical boundaries.

The relationship between climate and viticulture has been a subject of systematic study since at least the mid-twentieth century. Amerine and Winkler's [(1944, pp. 493–675)](https://www.zotero.org/google-docs/?rdNtfr) pioneering work on heat summation indices established the foundational framework for classifying wine regions according to their thermal profiles. Their Growing Degree Day (GDD) system demonstrated that grape varieties possess specific thermal requirements for optimal ripening, with cooler regions favouring early-ripening cultivars such as Pinot Noir and Chardonnay, while warmer zones support late-ripening varieties like Cabernet Sauvignon and Grenache. This thermal determinism has shaped the global geography of wine production for centuries, creating what Jones [(2006, pp. 1–5)](https://www.zotero.org/google-docs/?u9pOt5) describes as a 'climatically constrained agricultural mosaic' characterised by regional specialisation.

According to the Intergovernmental Panel on Climate Change [(IPCC, 2023)](https://www.zotero.org/google-docs/?tFDlN8), the European continent is warming at a rate exceeding the global average, with mean temperatures projected to increase by 1.5°C to 4.5°C by the end of the century depending on emissions scenarios. This climatological shift poses a dual challenge for European viticulture. On one hand, it threatens the viability of established vineyards in Southern Europe through increased heat stress, water scarcity, and phenological disruptions [(Fraga et al., 2016, pp. 98–104)](https://www.zotero.org/google-docs/?8hRCyK). On the other hand, it simultaneously unlocks new agricultural potential in Northern Europe, as isotherms shift poleward and regions previously considered too cool for viticulture—such as southern England, Poland, Denmark, and the Baltic states—enter the bioclimatic zone suitable for Vitis vinifera cultivation ([(Schultz & Jones, n.d., pp. 137–145)](https://www.zotero.org/google-docs/?Z3VuGg)).

The implications of this climatic reorganisation were quantified in the landmark study by [(Hannah et al., 2013, pp. 6907–6912)](https://www.zotero.org/google-docs/?F9esT2), which projected a potential 25% to 73% loss of suitability in major traditional wine regions by 2050 under moderate to high emissions scenarios. While much of the subsequent academic discourse has focused on adaptation strategies for declining traditional regions—including varietal substitution, irrigation expansion, and elevation migration—there is a growing imperative to investigate the emergence of new viticultural frontiers. The northward migration of the viticultural belt represents not merely a climatological curiosity but a significant economic restructuring of the European agricultural landscape, transforming marginal agricultural land into potentially high-value viticultural assets.

## 1.2 Historical Context: Viticulture at the Margins

The notion that viticulture is expanding into 'new' territories in Northern Europe requires historical qualification. Archaeological and documentary evidence reveals that wine production in these regions has precedent, although discontinuous, stretching back nearly two thousand years. Understanding this historical geography is essential for contextualising current trends within longer-term climatic oscillations and for distinguishing between genuine climatic novelty and the recovery of historically viable zones.

### 1.2.1 The Roman Climatic Optimum and Viticultural Expansion

During the Roman Warm Period (approximately 250 BCE to 400 CE), mean temperatures in Europe approached or exceeded present-day levels, facilitating the northward expansion of viticulture alongside Roman military and economic conquest [(McCormick, 2012, pp. 169–220)](https://www.zotero.org/google-docs/?B3I6vt). Literary and archaeological sources attest to vineyard establishment in Roman Britain, with Tacitus noting in his *Agricola* (98 CE) that the climate, while inclement, did not preclude vine cultivation. Excavations at Wollaston in Northamptonshire have uncovered evidence of systematic viticulture dating to the late Roman period, including trenching patterns consistent with vineyard establishment and carbonised grape pips of *Vitis vinifera* [(Brown et al., 2001, pp. 748–752)](https://www.zotero.org/google-docs/?2a9Gwl). Similarly, vineyards flourished in the Rhineland, the Moselle Valley, and as far north as Cologne, establishing viticultural traditions that persist to these days.

### 1.2.2 Medieval Viticulture and the Little Ice Age Contraction

The Medieval Warm Period (approximately 900–1300 CE) witnessed a second expansion of Northern European viticulture. The **Domesday Book of 1086 records 46 vineyards in England**, concentrated in the southern counties but extending as far north as Yorkshire [(Unwin, 1996)](https://www.zotero.org/google-docs/?G1h5FA). In Central Europe, viticulture expanded into Bohemia, Moravia, and southern Poland, often concentrated on south-facing slopes that maximised solar radiation and minimised frost risk—a topographical strategy that remains relevant today. The Prague Basin, for instance, developed a significant viticultural tradition during this period, with monastic estates cultivating vines on the terraced hillsides surrounding the city [(Svobodová et al., 2014, pp. 2–14)](https://www.zotero.org/google-docs/?L9fDDf).

The onset of the Little Ice Age (approximately 1300–1850 CE) reversed these gains dramatically. Mean temperatures declined by an estimated 1°C to 2°C, compressing the viable viticultural zone southward and rendering marginal regions economically unviable [(Lamb, 1995)](https://www.zotero.org/google-docs/?NH8xyC). **English viticulture collapsed almost entirely by the fifteenth century**, not to recover until the late twentieth century. In Central Europe, vineyards retreated to the most thermally favourable microlocations, and many marginal sites were abandoned permanently. This climatic contraction established the 'traditional' wine map that persisted largely unchanged until the late twentieth century—a geography that contemporary observers often mistake for an immutable natural order rather than a historically contingent artefact of climatic conditions.

### 1.2.3 The Contemporary Renaissance

The resurgence of viticulture in Northern Europe since the 1980s represents the reversal of this Little Ice Age contraction. In England, the area under vine expanded from fewer than 100 hectares in 1975 to over 3,800 hectares by 2022, with sparkling wine from the chalky soils of Sussex, Kent, and Hampshire achieving international critical acclaim [(Wine GB, n.d.)](https://www.zotero.org/google-docs/?6qfRvw). Poland has experienced similar growth, with vineyard area increasing from negligible levels in 1990 to approximately 600 hectares across more than 300 registered producers by 2013 (Lisek, 2021). Denmark, Sweden, and the Baltic states have witnessed analogous developments, though from smaller bases. This expansion is not merely a response to warming temperatures but reflects the confluence of climatic opportunity, technological innovation in cold-climate viticulture, and shifting consumer preferences toward 'cool-climate' wine styles characterised by high acidity and aromatic intensity.

Viticulture is arguably the most-sensitive sector of global agriculture. Unlike broad-acre crops such as wheat or maize, which are grown across vast latitudinal ranges, the commercial production of quality wine grapes (*vitis vinifera*) is restricted to narow climatic biome. These biomes are defined by specific thermal thresholds, diurnal temperature ranges, and hydrological balances, often referred to collectively as terroir. Historically, these constraints have confined the world’s prestigious wine regions to two distict bands between 30° and 50° latitude both hemispheres. However, anthropogenic climate chnage is rapidly destabilizing these traditional geographical boundaries.

According to the Intergovernmental Panel on Climate Change (IPCC), the European continent is warming at a rate exceeding the global average. This climatological shift poses a dual challenge: it threatens the viability of established vineyards in Southern Europe through heat stress and drought, while simultaneously unlocking new agricultural potential in Northern Europe. As isotherms shift poleward, regions previously considered too cool for viticulture—such as Poland, the United Kingdom, and the Baltic states—are entering the bioclimatic zone suitable for Vitis vinifera. This phenomenon represents not merely a climatological anomaly but a significant economic restructuring of the European agricultural landscape.

The implications of this shift were highlighter in the landmark study by Hannah et al. (2013), which projcted a potential 25 % to 73 % loss of suitability in major traditional wine regions by 2025. While much of the academic discourse has focused on the adaptation or decline of these traditional regions, there is a growing imperative to investigate the “migration” of the viticultural belt. The emergence of new wine markets in Norther Europe offers a uniquau case study in how climate change creates new economic froniters, transforming marginal agricultural land into high-value viticultural assets.

## 1.3 Problem Statement: Limitations of Linear Indices in a Non-Linear World

Despite the clear trend of warming and the demonstrable expansion of viticulture into previously marginal regions, the current body of literature regarding future viticultural suitability remains limited in two key respects that this thesis seeks to address.

### 1.3.1 The Reductionism of Traditional Bioclimatic Indices

First, existing large-scale suitability studies predominantly rely on simplified, linear bioclimatic indices used in isolation. The **Winkler Index** (Growing Degree Days), Huglin Index (Heliothermal Index), and Cool Night Index have provided valuable heuristics for general climate classification since their development (Winkler et al., 1974; Huglin, 1978; Tonietto & Carbonneau, 2004). However, these temperature-based metrics fail to capture the complex, non-linear interactions that determine actual viticultural success at the landscape scale. Viticultural suitability is not determined by temperature alone; it emerges from a multidimensional relationship between climate, topography (slope gradient and aspect), and soil properties (texture, pH, drainage capacity, and water-holding capacity).

A linear index might classify a vast flat plain in northern Poland as 'suitable' based solely on accumulated heat units, while ignoring critical factors such as frost pocket formation, inadequate cold air drainage, waterlogging risk, or excessive soil fertility that would render commercial viticulture economically unviable (Gladstones, 2011). Conversely, a site classified as marginally suitable by temperature indices alone might possess topographical and edaphic characteristics—south-facing slope, free-draining gravelly soils, frost-protected position—that compensate for thermal limitations and enable successful production. The failure to integrate these factors produces suitability maps of limited practical utility for land-use planning and investment decisions.

### 1.3.2 The Geographical Bias Toward Traditional Regions

Second, there exists a significant geographical bias in the literature. The majority of high-resolution modelling studies focus on the preservation and adaptation of traditional regions—Bordeaux, Burgundy, Tuscany, Napa Valley, and their analogues—where substantial economic interests drive research investment (Moriondo et al., 2013; Santos et al., 2020). There is a lack of rigorous, spatially explicit research focused specifically on 'emerging markets' in Central and Northern Europe. As investors, policymakers, and agricultural planners in these countries begin to consider viticulture as a viable diversification strategy for rural economies, they confront a lack of granular, scientifically robust data to guide land-use decisions. Which specific locations within Poland, the Czech Republic, or the Baltic states offer the greatest potential? What are the limiting factors beyond temperature? How might suitability evolve under different climate scenarios? These questions remain inadequately addressed by existing research.

### 1.4 Research Objectives and Questions

This thesis seeks to address the identified gaps by developing a holistic, machine-learning-driven model of viticultural land suitability that integrates climatic, topographical, and edaphic variables. The study adopts a Species Distribution Modelling (SDM) approach—a methodology traditionally employed in ecology to predict species ranges—applied here to the economic 'species' of commercial vineyards. The central aim is to generate spatially explicit suitability projections for European viticulture under current and future climate scenarios, with particular attention to emerging markets in Central and Northern Europe.

The research is guided by the following objectives and corresponding research questions:

**Objective 1:** To develop a multivariate suitability model that integrates climate, topography, and soil data for European viticulture.

*RQ1:* What is the relative importance of climatic versus non-climatic variables (topography, soil) in determining viticultural suitability across Europe?

**Objective 2:** To map current (baseline) viticultural suitability and validate the model against known vineyard distributions.

*RQ2:* How accurately does the integrated model predict the current distribution of European vineyards compared to single-index approaches?

**Objective 3:** To project changes in viticultural suitability under contrasting climate scenarios (SSP2-4.5 and SSP5-8.5) for the mid-century (2041–2060) and late-century (2061–2080) periods.

*RQ3:* What is the projected magnitude and spatial pattern of suitability change across Europe under different emissions pathways?

**Objective 4:** To identify and characterise emerging viticultural regions in Central and Northern Europe with high future potential.

*RQ4:* Which specific regions in Poland, the United Kingdom, and the Baltic states exhibit the greatest expansion potential, and what factors constrain or enable this potential?

## 1.5 Methodology Overview

The methodology integrates high-resolution geospatial data from three primary domains. Climate data are derived from downscaled CMIP6 projections (WorldClim and CHELSA datasets), encompassing both historical baselines (1991–2020) and future projections under the SSP2-4.5 (intermediate mitigation) and SSP5-8.5 (fossil-fuelled development) scenarios. Topographical data, probably from ESDAC.

## 1.6 Significance of the Study

### 1.6.1 Economic Significance

The economic implications of viticultural expansion into Northern Europe are substantial. Premium wine production represents one of the highest-value agricultural land uses in Europe, with vineyard land in established regions commanding prices orders of magnitude greater than arable farmland (OIV, 2022). The emergence of new wine regions creates opportunities for agricultural diversification in rural economies facing structural challenges from commodity crop competition and Common Agricultural Policy reforms. Furthermore, wine tourism—encompassing cellar door sales, accommodation, and gastronomy—generates significant multiplier effects in regional economies. Understanding which specific locations possess genuine viticultural potential is therefore not merely an academic exercise but a matter of considerable economic consequence for land valuation, investment allocation, and regional development strategy.

### 1.6.2 Methodological Significance

From a methodological perspective, this study contributes to the broader literature on climate-driven agricultural suitability modelling by demonstrating the application of machine-learning techniques and multi-criteria analysis to a high-value perennial crop. The integration of edaphic and topographical variables with climate data addresses a recognised limitation of existing viticultural suitability studies and provides a template applicable to other climate-sensitive agricultural systems. The explicit treatment of spatial autocorrelation through blocked cross-validation advances methodological rigour in agricultural SDM applications.

## 1.7 Structure of the Thesis

This thesis is organised into several chapters. Following this introduction, **Chapter 2** presents a comprehensive literature review encompassing the fundamentals of viticulture and *terroir*, the historical geography of wine production, established bioclimatic indices and their limitations, and the theoretical foundations of Species Distribution Modelling as applied to agricultural systems. This chapter establishes the domain knowledge prerequisite to the subsequent data science methodology.

Chapter 3,

**CHAPTER II**

**Literature Review and Theoretical Background**

The preceding chapter established the empirical context motivating this research: anthropogenic climate change is restructuring the geography of European viticulture, yet existing analytical frameworks inadequately capture the multidimensional nature of viticultural suitability. Before developing the data science methodology to address this gap, it is essential to establish the domain knowledge that informs model specification—specifically, what environmental variables matter for viticulture and why. This chapter therefore serves a dual purpose: first, to synthesise the viticultural science that defines the target phenomenon; and second, to review the computational approaches available for modelling species and crop distributions under environmental change. The integration of these two literatures—one agronomic, one methodological—provides the theoretical foundation for the machine learning approach developed in Chapter 3.

## 2.1 Fundamentals of Viticulture

### 2.1.1 Biological Characteristics of the Grapevine

The grapevine (*Vitis vinifera L.*) is a perennial woody climbing plant of the family *Vitaceae*, originating in the Caucasus region and domesticated approximately 6,000–8,000 years ago (This et al., 2006). Unlike annual crops, which complete their life cycle within a single growing season, grapevines represent long-term investments with productive lifespans of 30–50 years or more under favourable conditions. This perennial nature has profound implications for suitability modelling: site selection decisions are essentially irreversible over decadal timescales, and the cumulative effects of climate over the vine's lifetime—rather than single-season conditions—determine economic viability (Gladstones, 2011).

The annual growth cycle of *Vitis vinifera* comprises several phenological stages, each with distinct climatic requirements. Budburst occurs in spring when mean daily temperatures exceed approximately 10°C, triggering the emergence of shoots from dormant buds. Flowering follows 6–8 weeks later, requiring warm, dry conditions for successful pollination; excessive rainfall or cold during this period causes *coulure* (flower abortion) and reduced yields. The period from fruit set to *véraison* (the onset of ripening, marked by colour change and sugar accumulation) is characterised by rapid berry growth and acid development. The final ripening phase—from véraison to harvest—is critical for quality, requiring warm days for sugar accumulation and cool nights for acid retention and aromatic compound development (Coombe & Iland, 2004). This phenological sequence explains why viticulture is constrained to specific thermal regimes: insufficient heat prevents full ripening, while excessive heat accelerates sugar accumulation at the expense of flavour complexity.

### 2.1.2 Vitis vinifera Versus Hybrid Varieties

A distinction must be drawn between *Vitis vinifera*—the European species from which all premium wine varieties derive—and interspecific hybrids developed by crossing *V. vinifera* with cold-hardy American species such as *Vitis riparia* or *Vitis labrusca*. Hybrid varieties such as Marquette, Solaris, and Regent exhibit substantially greater cold tolerance, surviving winter temperatures as low as −30°C compared to the −15°C to −20°C threshold for most *V. vinifera* cultivars (Reisch et al., 2012). This cold hardiness extends the potential geographical range of viticulture into regions where *V. vinifera* would suffer lethal winter injury.

However, hybrid varieties occupy an ambiguous position in the quality hierarchy. European Union regulations historically prohibited their use in Protected Designation of Origin (PDO) wines, reflecting a cultural valorisation of *V. vinifera* purity. While recent regulatory reforms have relaxed these restrictions for sustainability purposes, market perceptions continue to favour traditional varieties (Anderson & Pinilla, 2018). For the purposes of this thesis, which focuses on commercially significant viticulture, the suitability model is parameterised for *V. vinifera* cultivation. This represents a conservative approach: regions suitable for *V. vinifera* are necessarily suitable for hardier hybrids, but the reverse does not hold.

### 2.1.3 The Concept of Terroir: A Multidimensional Framework

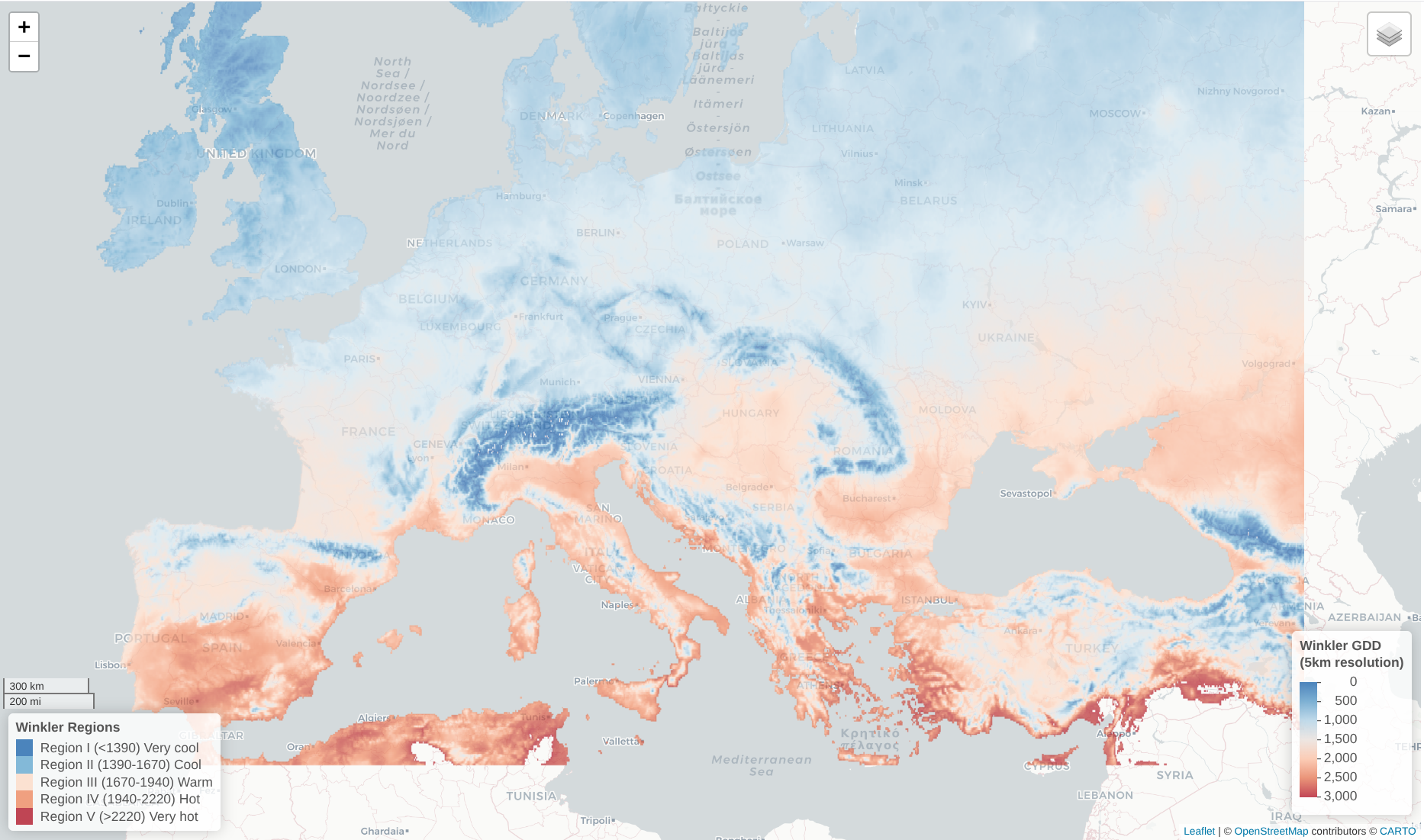
The French concept of *terroir* encapsulates the holistic interaction between grapevine, environment, and human practice that produces wines of distinctive character. While often invoked in marketing discourse, *terroir* has rigorous scientific foundations that are directly relevant to suitability modelling. Van Leeuwen and Seguin (2006) define *terroir* as 'an interactive ecosystem, in a given place, including climate, soil, and the vine,' emphasising that wine quality emerges from the integration of multiple environmental factors rather than any single variable in isolation.

The *terroir* framework identifies three primary environmental domains—climate, soil, and topography—that interact to determine viticultural outcomes. Climate operates at multiple spatial scales: macroclimate (regional), mesoclimate (vineyard), and microclimate (canopy). Soil influences vine performance through water availability, nutrient supply, and thermal properties. Topography modifies both climate (through elevation, slope, and aspect effects on temperature and radiation) and soil (through drainage and erosion patterns). Crucially, these factors do not operate additively but interact in complex, often non-linear ways. A warm climate on poorly drained clay soils may produce inferior results to a cooler climate on well-drained gravels; southern aspect may be advantageous in cool regions but detrimental in warm ones (Gladstones, 2011). This inherent multicollinearity and interaction structure provides the conceptual justification for machine learning approaches that can capture non-linear relationships without requiring *a priori* specification of functional forms.

## 2.2 Climatic Determinants of Viticultural Suitability

### 2.2.1 Thermal Requirements and Heat Accumulation

Temperature is the primary climatic constraint on viticulture, operating through multiple mechanisms. The concept of heat accumulation—the cumulative thermal energy available during the growing season—provides the foundation for most viticultural climate classifications. Amerine and Winkler's (1944) Growing Degree Day (GDD) system, developed for California but subsequently applied globally, calculates the sum of daily mean temperatures exceeding a 10°C base threshold during the April–October growing season (Northern Hemisphere). This base threshold reflects the approximate temperature below which vine physiological activity ceases. Winkler and colleagues classified California's wine regions into five thermal zones, from Region I (<1,390 GDD, suitable for early-ripening varieties) to Region V (>2,220 GDD, suitable only for table grapes and fortified wine production).



The Huglin Index (HI) offers a refinement by incorporating day length as a coefficient, recognising that longer summer days at higher latitudes compensate for lower daily temperatures through extended photosynthetic activity (Huglin, 1978). The HI correlates well with potential grape sugar content at harvest, making it particularly useful for predicting wine style potential. Values below 1,500 indicate conditions too cool for reliable V. vinifera ripening; values between 1,500 and 2,100 suit cool-climate varieties; values between 2,100 and 2,700 accommodate intermediate varieties; and values exceeding 2,700 favour late-ripening, heat-tolerant cultivars (Tonietto & Carbonneau, 2004).

### 2.2.2 Temperature Extremes and Limiting Factors

Beyond heat accumulation, temperature extremes impose absolute constraints on viticultural viability. Winter minimum temperatures determine vine survival: most V. vinifera cultivars suffer lethal injury when dormant wood temperatures fall below −15°C to −20°C, with the precise threshold varying by variety and acclimation status (Fennell, 2004). Spring frost represents perhaps the most economically significant climatic hazard, as temperatures below −2°C during budburst can destroy the entire season's crop. The timing of last spring frost relative to budburst date—itself temperature-dependent—creates complex risk profiles that vary spatially with topography and temporally with climate change.

At the warm extreme, temperatures exceeding 35°C inhibit photosynthesis, accelerate berry dehydration, and promote the degradation of anthocyanins and aromatic compounds that determine wine quality (Greer & Weston, 2010). Prolonged heatwaves, increasingly frequent under climate change, can cause irreversible vine damage. The diurnal temperature range—the difference between daily maximum and minimum temperatures—is equally important: cool nights during ripening preserve acidity and promote aromatic complexity, while uniformly warm conditions produce wines perceived as 'flabby' and lacking freshness Tonietto & Carbonneau, 2004). This explains why continental climates with large diurnal ranges often produce more aromatic wines than maritime climates with equivalent heat accumulation.

**2.2.3 Precipitation and Water Balance**

Water availability influences viticulture through both excess and deficit. Moderate water stress during ripening is generally considered beneficial, concentrating sugars and flavour compounds in smaller berries; this is the basis for the viticultural preference for well-drained soils and the practice of deficit irrigation in warm climates (Van Leeuwen et al., 2009). Excessive rainfall, conversely, promotes vegetative vigour at the expense of fruit quality, increases disease pressure (particularly fungal pathogens such as Botrytis cinerea and downy mildew), and causes berry splitting and dilution prior to harvest.

The Dryness Index (DI), developed as part of the Géoviticulture Multicriteria Classification System, quantifies the water balance during the growing season by comparing potential evapotranspiration with precipitation and soil water reserves (Tonietto & Carbonneau, 2004). Values below −100 mm indicate significant water deficit requiring irrigation for commercial production; values between −100 mm and +50 mm represent optimal conditions with moderate stress; values exceeding +150 mm suggest excessive humidity with elevated disease risk. Importantly, the hydrological regime interacts with soil properties: sandy soils with low water-holding capacity may experience drought stress under precipitation regimes adequate for clay soils, while clay soils may become waterlogged under conditions well-tolerated by free-draining gravels.

## 2.3 Edaphic Factors in Viticultural Suitability

While climate defines the broad envelope of viticultural possibility, soil properties operate as fine-scale constraints that determine site-specific suitability within climatically viable zones. The viticultural literature consistently emphasises that 'great wines are made on poor soils'—an aphorism reflecting the observation that moderate nutrient and water stress promotes fruit quality over vegetative vigour (White, 2015). However, the precise mechanisms by which soil properties influence wine quality remain subjects of ongoing research and some controversy.

### 2.3.1 Soil Texture and Drainage

Soil texture—the relative proportions of sand, silt, and clay particles—fundamentally influences water dynamics and root environment. Coarse-textured soils (sands, gravels) drain freely, warming rapidly in spring and imposing water stress during dry periods; fine-textured soils (clays, silts) retain moisture longer but risk waterlogging and delayed warming. The celebrated vineyards of the Médoc owe their reputation partly to deep gravel deposits that provide excellent drainage while retaining sufficient moisture at depth; conversely, the clay-dominated soils of Pomerol produce distinctly different wine styles through their greater water retention (Van Leeuwen, 2010).

For suitability modelling, texture class provides a readily available proxy for multiple hydrological and thermal properties. The European Soil Data Centre (ESDAC) provides pan-European texture classifications at 500-metre resolution, distinguishing coarse (sandy), medium, medium-fine, fine (clayey), and very fine texture classes. While imperfect, this classification captures the primary axis of variation relevant to viticultural drainage requirements.

### 2.3.2 Soil pH and Calcium Carbonate Content

Soil pH influences nutrient availability and root development. Vitis vinifera tolerates a wide pH range (5.5–8.5), but optimal growth typically occurs between 6.0 and 7.5 (White, 2015). Highly alkaline soils (pH > 8.5), often associated with high calcium carbonate content, can induce iron chlorosis in sensitive rootstocks, manifesting as interveinal yellowing and reduced vigour. Conversely, strongly acidic soils (pH < 5.5) may exhibit aluminium toxicity and phosphorus deficiency. The famed chalk soils of Champagne and southern England (pH 7.5–8.2) fall within the acceptable range while providing the excellent drainage and thermal properties that contribute to sparkling wine quality.

**2.3.3 Soil Depth and Water-Holding Capacity**

Effective soil depth—the depth to bedrock or an impermeable layer—determines the available volume for root exploration and water storage. Shallow soils over bedrock impose earlier and more severe water stress, which may be desirable for quality in humid climates but limiting in dry ones. Available Water Capacity (AWC), measured as the volume of water retained between field capacity and permanent wilting point, integrates texture, depth, and organic matter content into a single metric of hydrological relevance. High AWC soils buffer against drought but may promote excessive vigour; low AWC soils enhance stress but risk vine mortality during extended dry periods. The interaction between AWC and precipitation regime exemplifies the non-additive relationships that simple index-based approaches fail to capture.

## 2.4 Topographic Modifiers of Suitability

Topography modifies climate at the mesoscale, creating microclimatic variation that can exceed the magnitude of projected climate change over short horizontal distances. Two topographic parameters are of primary relevance: slope gradient and aspect (orientation).

**2.4.1 Slope Gradient and Cold Air Drainage**

Slope gradient influences viticultural suitability through multiple mechanisms. Sloping terrain facilitates cold air drainage, as dense, cold air flows downslope under gravity during nocturnal radiative cooling. Valley floors and enclosed basins accumulate this cold air, forming 'frost pockets' where spring frost frequency and severity far exceed hillslope positions at equivalent elevation. Jackson (2008) documents temperature differentials of 5–10°C between valley floors and mid-slope positions on clear, calm nights—a difference equivalent to several degrees of latitude. This cold air pooling effect renders many otherwise suitable valley floor sites unviable for frost-sensitive V. vinifera cultivation.

Slope gradient also affects soil drainage and erosion susceptibility. Steep slopes (>25°) shed precipitation rapidly, reducing waterlogging risk but increasing erosion hazard and complicating mechanised cultivation. Moderate slopes (5–15°) typically offer optimal conditions, balancing drainage benefits against practical management constraints. Flat terrain (<2%) may suffer from poor air and water drainage, though this can be mitigated by appropriate soil conditions (Gladstones, 2011). For the emerging viticultural regions of Northern Europe, where frost risk represents a primary limiting factor, slope position may prove as important as macroclimate in determining site viability.

### 2.4.2 Aspect and Solar Radiation Receipt

Slope aspect—the compass orientation of the slope face—determines the angle of solar incidence and thus the intensity of received radiation. In the Northern Hemisphere, south-facing slopes receive maximum radiation, with effective irradiance decreasing through southeast/southwest, east/west, and reaching minimum on north-facing aspects. The thermal effect is substantial: south-facing slopes may experience growing season temperatures 1–3°C warmer than adjacent north-facing slopes, a difference sufficient to shift suitability class or enable ripening of later-maturing varieties (Jones, 2006).

The optimal aspect is climate-dependent. In cool, marginal regions such as the Mosel Valley, England, or Poland, south-facing slopes are strongly preferred to maximise heat accumulation and ripening potential. In warm regions approaching thermal excess, east-facing slopes (with morning sun and afternoon shade) may be preferable to mitigate heat stress. This climate-aspect interaction exemplifies the non-stationarity of predictor-response relationships across environmental gradients—a phenomenon that global models must accommodate.

## 2.5 Bioclimatic Indices: Traditional Approaches and Their Limitations

The preceding sections have established that viticultural suitability emerges from the complex interaction of climatic, edaphic, and topographic factors. However, the traditional approach to viticultural climate classification has relied on simplified univariate or multivariate indices that reduce this complexity to single numerical values. While these indices have proven useful for broad regional classification, their limitations become apparent when applied to fine-scale suitability mapping and climate change projection.

## 2.5 Bioclimatic Indices for Viticultural Zoning

The quantification of climate suitability for viticulture has historically relied on bioclimatic indices—composite metrics that integrate temperature and, in some cases, precipitation data over the growing season to produce single values characterising a location's viticultural potential. These indices emerged from empirical observations correlating climate parameters with grape quality and yield, and remain widely used in viticultural zoning despite their acknowledged limitations. This section presents the principal indices employed in the literature, their mathematical formulations, and a critical assessment of their applicability to emerging wine regions.

### *2.5.1 The Winkler Index (Growing Degree Days)*

The Winkler Index, also known as Growing Degree Days (GDD), represents the foundational heat accumulation metric in viticultural climatology. Developed by Amerine and Winkler (1944) at the University of California, Davis, the index quantifies the thermal energy available for vine growth during the growing season by summing daily temperatures above a base threshold of 10°C—the approximate temperature below which *Vitis vinifera* ceases active growth.

The Winkler Index is calculated as:

GDD = Σ *(Tmean* − 10) for Tmean > 10°C, April 1 – October 31

where Tmean is the daily mean temperature (°C) and the summation extends over the growing season (April 1 to October 31 in the Northern Hemisphere). Days with mean temperatures at or below 10°C contribute zero to the total.

Based on extensive field trials in California, Amerine and Winkler (1944) established a five-region classification system correlating GDD accumulation with optimal grape variety selection and wine style:

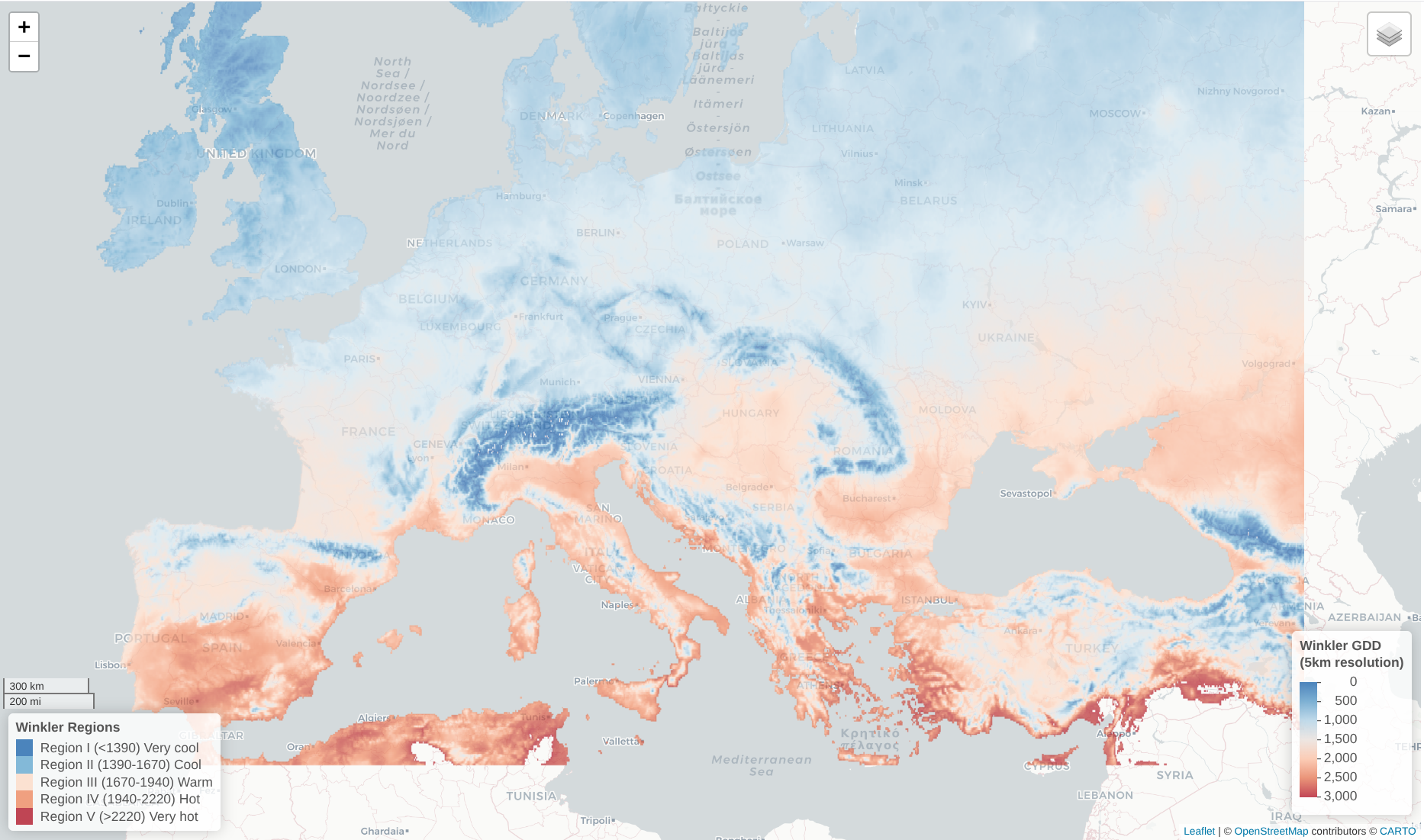
**Table 2.1**

*Winkler Index Classification System*

| **Region** | **GDD Range** | **Climate Class** | **Suited Varieties** |
| --- | --- | --- | --- |
| I | < 1,390 | Very Cool | Pinot Noir, Chardonnay, Riesling |
| II | 1,390–1,670 | Cool | Cabernet Sauvignon, Merlot, Sauvignon Blanc |
| III | 1,670–1,940 | Warm | Zinfandel, Barbera, Semillon |
| IV | 1,940–2,220 | Hot | Fortified wines, table grapes |
| V | > 2,220 | Very Hot | Table grapes, raisins |

*Note.* GDD values in degree-days Celsius. Adapted from Winkler et al. (1974).

Figure xx presents the spatial distribution of the Winkler Index across Europe, calculated from WorldClim baseline climate data at 5 km resolution. The map reveals clear latitudinal gradients, with Mediterranean regions (southern Spain, southern Italy, Greece) predominantly falling within Regions IV–V, while Northern Europe (UK, Poland, Baltic states) lies largely within Region I or below the viticultural threshold.



Winkler Index (Growing Degree Days) across Europe at 5 km resolution. Colour scale indicates GDD accumulation from 0 (dark blue) to 3,000+ (dark red). Legend shows Winkler Region classifications (I–V). Source: Author's calculations from WorldClim v2.1 data.

### *2.5.2 The Huglin Index (Heliothermal Index)*

The Huglin Index, or Heliothermal Index (HI), was developed by Pierre Huglin (1978) to address a limitation of the Winkler Index—namely, its failure to account for day length variation with latitude. At higher latitudes, longer summer days provide extended photosynthetic periods that partially compensate for lower temperatures, a phenomenon not captured by simple heat summation. The Huglin Index incorporates both maximum temperature (reflecting peak daytime conditions) and a latitude-dependent day length coefficient.

The Huglin Index is calculated as:

HI = Σ *[(Tmean* − 10) + (T*max* − 10)] / 2 × *k*

where Tmean is daily mean temperature (°C), Tmax is daily maximum temperature (°C), and *k* is a latitude-dependent day length coefficient. The summation extends from April 1 to September 30 in the Northern Hemisphere. Negative values within the brackets are set to zero before summation.

The day length coefficient *k* varies with latitude as follows:

**Table x**

*Huglin Index Day Length Coefficient (k) by Latitude*

| **Latitude Range** | **Coefficient (k)** |
| --- | --- |
| 40°00′ – 40°59′ N/S | 1.02 |
| 41°00′ – 42°59′ N/S | 1.03 |
| 43°00′ – 44°59′ N/S | 1.04 |
| 45°00′ – 46°59′ N/S | 1.05 |
| 47°00′ – 50°00′ N/S | 1.06 |

*Note.* Adapted from Huglin (1978). For latitudes below 40°, k = 1.00.

Tonietto and Carbonneau (2004) established a widely adopted classification system for the Huglin Index:

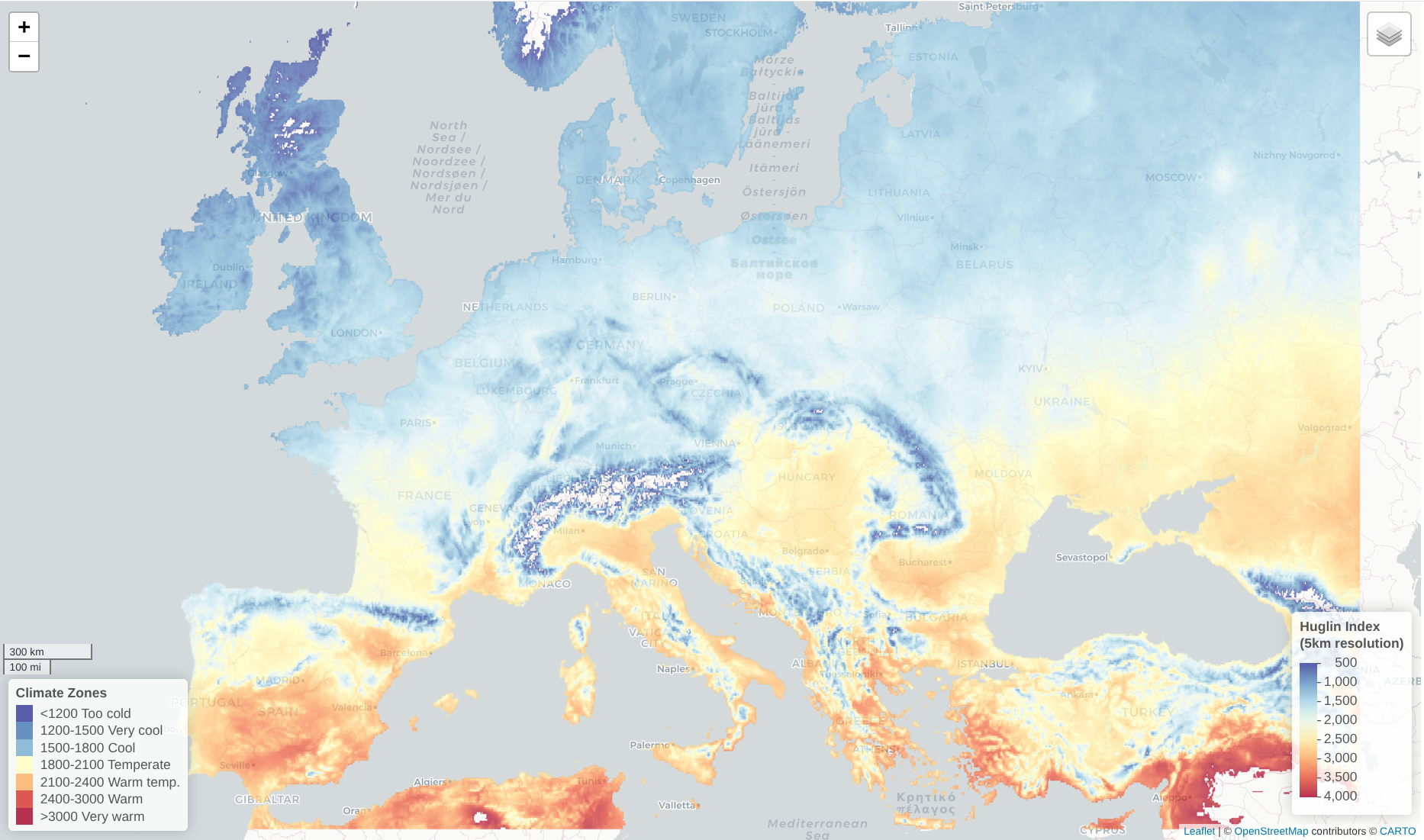
**Table x**

*Huglin Index Climate Classification*

| **HI Range** | **Climate Class** | **Viticultural Suitability** |
| --- | --- | --- |
| < 1,200 | Too Cold | Below viticultural threshold |
| 1,200–1,500 | Very Cool | Marginal; early varieties only |
| 1,500–1,800 | Cool | Suited for cool-climate varieties |
| 1,800–2,100 | Temperate | Broad variety range |
| 2,100–2,400 | Warm Temperate | Late-ripening varieties |
| 2,400–3,000 | Warm | Heat-tolerant varieties |
| > 3,000 | Very Warm | Quality limitations; table grapes |

*Note.* Adapted from Tonietto & Carbonneau (2004).

Figure xx displays the Huglin Index distribution across Europe. The latitude correction produces slightly different spatial patterns compared to the Winkler Index, particularly in higher-latitude regions where the day length coefficient elevates HI values relative to simple GDD. Nevertheless, Northern Europe remains predominantly in the 'Too Cold' to 'Very Cool' categories under this classification.

**

Huglin Index (Heliothermal Index) across Europe at 5 km resolution. Colour scale indicates HI values from 500 (dark blue) to 4,000+ (dark red). Legend shows climate zone classifications. Source: Author's calculations from WorldClim v2.1 data.

### *2.5.3 The Cool Night Index*

The Cool Night Index (CI) was introduced by Tonietto and Carbonneau (2004) as part of their multicriteria climate classification system (MCC). Unlike heat accumulation indices, the CI focuses on nocturnal temperatures during the final ripening period, which influence the development of aromatic compounds, anthocyanins (colour pigments), and the preservation of organic acids that contribute to wine structure and freshness.

The Cool Night Index is defined simply as:

CI = Mean Tmin for September

where Tmin is the minimum daily temperature (°C) averaged over September (Northern Hemisphere). The classification thresholds are:

**Very Cool Nights:** CI ≤ 12°C — Favours aromatic varieties; high acid retention

**Cool Nights:** 12°C < CI ≤ 14°C — Good colour development; balanced acidity

**Temperate Nights:** 14°C < CI ≤ 18°C — Reduced aromatic complexity; lower acidity

**Warm Nights:** CI > 18°C — Limited aromatic potential; rapid acid degradation

The Cool Night Index provides information orthogonal to heat accumulation metrics—a region may accumulate sufficient GDD for ripening while still experiencing cool nights that preserve wine quality attributes. Conversely, warm nights in traditionally temperate regions (increasingly common under climate change) may diminish wine quality even when heat accumulation remains within historical ranges.

### *2.5.4 The Dryness Index*

The Dryness Index (DI), also developed by Tonietto and Carbonneau (2004), provides a measure of water availability during the growing season. Unlike purely thermal indices, the DI integrates precipitation, evapotranspiration, and soil water reserve to estimate the water balance experienced by vines.

The Dryness Index is calculated as:

DI = W0 + P − Tv − Es

where W0 is initial soil water reserve (conventionally 200 mm), P is growing season precipitation (mm), Tv is potential transpiration by the vineyard, and Es is direct soil evaporation. The calculation is performed monthly from April to September, with carryover between months. Positive DI values indicate water surplus; negative values indicate deficit.

Classification thresholds distinguish: **Humid** (DI > 150 mm), **Sub-humid** (50 < DI ≤ 150 mm), **Moderately Dry** (−100 < DI ≤ 50 mm), and **Very Dry** (DI ≤ −100 mm). Moderate water stress (sub-humid to moderately dry) is generally considered optimal for quality wine production, limiting vegetative growth and concentrating flavour compounds.

### *2.5.5 Limitations of Traditional Bioclimatic Indices*

While bioclimatic indices provide valuable first-order assessments of viticultural suitability, their application—particularly to emerging wine regions—is constrained by several fundamental limitations that motivate the machine learning approach adopted in this research.

**Climate-only focus.** Traditional indices consider only thermal (and in the case of DI, hydric) conditions, ignoring topographic and edaphic factors that substantially influence site suitability. Two locations with identical GDD may differ markedly in viticultural potential due to differences in slope, aspect, soil drainage, or frost exposure. The indices thus provide necessary but not sufficient conditions for viticulture.

**Linear assumptions.** The indices assume linear relationships between heat accumulation and vine performance—each additional degree-day is treated as equivalent regardless of when it occurs or what baseline temperature has already been reached. In reality, vine response to temperature is non-linear, with diminishing returns at high temperatures and potential heat stress above approximately 35°C that may actually impair ripening.

**Calibration bias toward traditional regions.** The classification thresholds for all major indices were calibrated in established wine regions—California for Winkler, France and Portugal for the MCC system. These thresholds may not transfer directly to emerging regions with different variety portfolios, viticultural practices, or quality standards. For instance, the threshold of HI < 1,200 as 'too cold' assumes *V. vinifera* cultivation, yet frost-hardy hybrid varieties successfully ripen at lower heat accumulations.

**Temporal aggregation obscures extreme events.** Growing season averages mask the influence of discrete events—late spring frosts, summer heatwaves, harvest-period rainfall—that can devastate production regardless of favourable seasonal means. A single frost event in May can destroy an entire year's crop even in a location with otherwise optimal GDD accumulation.

**Static thresholds under climate change.** The fixed thresholds embedded in these classification systems assume stationary climate, yet climate change is shifting isotherms poleward and upslope. Regions currently marginal may become optimal; currently optimal regions may become unsuitable. Applying static thresholds to dynamic climate projections risks systematic misclassification of future suitability.

These limitations do not render bioclimatic indices useless—they remain valuable for broad characterisation and historical comparison. However, they argue strongly for complementary approaches that can integrate multiple environmental dimensions, capture non-linear relationships, and adapt to changing conditions. The species distribution modelling framework introduced in Section 2.6 addresses these requirements through machine learning methods trained on observed vineyard distributions rather than predetermined thresholds.

### *2.5.6 Section Summary*

This section has presented the principal bioclimatic indices used in viticultural zoning: the Winkler Index (GDD), Huglin Index (HI), Cool Night Index (CI), and Dryness Index (DI). The spatial analysis of Winkler and Huglin indices across Europe (Figures 2.1 and 2.2) demonstrates that Northern European emerging regions fall predominantly below or at the margins of traditional viticultural thresholds. However, the documented limitations of these indices—their climate-only focus, linear assumptions, calibration bias, temporal aggregation, and static thresholds—suggest that machine learning approaches may provide more accurate and flexible assessments of suitability, particularly under climate change scenarios.

## 2.6 Species Distribution Modelling: From Ecology to Agriculture

Species Distribution Models (SDMs), also termed ecological niche models or habitat suitability models, comprise a family of statistical and machine learning techniques that relate species occurrence records to environmental variables to estimate the probability of presence across geographical space (Elith & Leathwick, 2009). Originally developed in conservation biology to predict endangered species distributions and inform reserve design, SDMs have been increasingly applied to agricultural contexts, including crop suitability mapping under climate change scenarios.

### 2.6.1 Theoretical Foundations: Niche Concepts

SDMs are grounded in ecological niche theory, particularly Hutchinson's (1957) distinction between the fundamental niche (the full range of environmental conditions under which a species can persist) and the realised niche (the subset of conditions actually occupied, constrained by competition, dispersal limitation, and historical contingency). For agricultural species such as *V. vinifera*, this distinction has particular relevance: the fundamental niche is defined by biological tolerances (temperature, water, soil requirements), while the realised niche is additionally constrained by economic factors (land prices, labour availability, market access) and historical path dependencies (established wine regions attract further investment).

SDMs typically model the realised niche, using observed occurrence locations to infer environmental associations. When projected onto future climate scenarios, they therefore estimate where suitable conditions will exist, not necessarily where production will actually occur—a distinction critical for interpretation. The approach taken in this thesis employs existing vineyard locations (from CORINE land cover) as presence data, thereby modelling where viticulture is currently practised rather than where it could theoretically persist. This grounds predictions in demonstrated economic viability rather than purely biological potential.

### 2.6.2 Algorithm Selection: Random Forest Classification

Among the diverse algorithms available for SDM—including generalised linear models (GLM), generalised additive models (GAM), maximum entropy (MaxEnt), boosted regression trees (BRT), and neural networks—Random Forest (RF) classification offers several advantages for the present application. Developed by Breiman (2001), Random Forest is an ensemble learning method that constructs multiple decision trees during training and outputs the mode of their individual predictions (for classification) or mean prediction (for regression). Each tree is trained on a bootstrap sample of the data, and at each split, a random subset of predictor variables is considered, introducing decorrelation among trees and reducing overfitting.

Several properties recommend Random Forest for viticultural suitability modelling. First, RF accommodates mixed predictor types (continuous climate variables, categorical soil texture) without requiring transformation. Second, RF captures non-linear relationships and interactions without explicit specification—the tree-splitting mechanism naturally partitions predictor space into regions of homogeneous response, accommodating threshold effects and complex interactions that linear models cannot represent. Third, RF provides variable importance metrics that quantify the relative contribution of each predictor to model performance, offering interpretable insight into which environmental factors most strongly determine suitability. Fourth, RF is relatively robust to multicollinearity among predictors, which is endemic in environmental datasets where temperature, precipitation, and elevation are intercorrelated (James et al., 2013).

### 2.6.3 Addressing Spatial Autocorrelation

A critical methodological challenge in SDM is spatial autocorrelation—the tendency for nearby locations to exhibit similar values due to spatial processes rather than independent responses to environmental conditions. Standard cross-validation procedures that randomly partition data into training and testing sets violate the assumption of independence when observations are spatially clustered, leading to inflated performance estimates and overconfident predictions (Roberts et al., 2017).

Vineyard locations are particularly prone to spatial clustering: viticulture concentrates in recognised wine regions through positive feedback mechanisms (knowledge spillovers, marketing benefits, infrastructure availability), producing non-independent occurrence records. A model trained on one portion of the Mosel Valley and tested on an adjacent portion will appear highly accurate simply because both areas share unmeasured spatial factors, not because the model has learned generalisable environmental relationships.

To address this, the methodology developed in Chapter 3 employs spatial block cross-validation, which partitions data into geographically disjoint blocks such that training and testing sets are spatially separated by distances exceeding the range of autocorrelation. This approach provides conservative, more realistic estimates of predictive performance for genuinely novel locations—precisely the 'emerging markets' of interest in this study (Valavi et al., 2019).

## 2.7 Synthesis and Gap Identification

This chapter has established the domain knowledge prerequisite to rigorous viticultural suitability modelling. The biological requirements of *Vitis vinifera*—thermal accumulation for ripening, freedom from lethal frost and extreme heat, moderate water stress, appropriate soil conditions for drainage and nutrient balance—define the environmental envelope within which production is possible. The concept of *terroir* provides a theoretical framework emphasising the interactive, multidimensional nature of site suitability, while traditional bioclimatic indices, though useful, inadequately capture this complexity.

Species Distribution Modelling, adapted from ecological applications, provides a computational framework for relating occurrence data to environmental predictors and projecting suitability under climate change scenarios. Among available algorithms, Random Forest offers advantages in flexibility, interpretability, and robustness that recommend it for this application. Spatial cross-validation addresses the autocorrelation inherent in clustered vineyard locations, providing realistic performance estimates for predictions in novel regions.

The methodological gap this thesis addresses lies in the integration of these elements: combining climate data with topographical and edaphic variables in a machine learning framework to produce suitability estimates that transcend the limitations of single-index approaches, with particular attention to emerging viticultural regions inadequately represented in existing research. The following chapter details the data sources, processing procedures, and analytical strategy employed to realise this integration.

## Models

home/ondrej-marvan/Documents/General/Studies/Diploma Thesis/data

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│ ├── wc2.1\_2.5m\_bioc\_EC-Earth3-Veg\_ssp585\_2041-2060.tif

│ ├── wc2.1\_2.5m\_prec\_EC-Earth3-Veg\_ssp585\_2041-2060.tif

│ ├── wc2.1\_2.5m\_tmax\_EC-Earth3-Veg\_ssp585\_2041-2060.tif

│ └── wc2.1\_2.5m\_tmin\_EC-Earth3-Veg\_ssp585\_2041-2060.tif

└── MPI-ESM1-2-HR

├── ssp245

│ ├── wc2.1\_2.5m\_bioc\_MPI-ESM1-2-HR\_ssp245\_2041-2060.tif

│ ├── wc2.1\_2.5m\_prec\_MPI-ESM1-2-HR\_ssp245\_2041-2060.tif

│ ├── wc2.1\_2.5m\_tmax\_MPI-ESM1-2-HR\_ssp245\_2041-2060.tif

│ └── wc2.1\_2.5m\_tmin\_MPI-ESM1-2-HR\_ssp245\_2041-2060.tif

└── ssp585

├── wc2.1\_2.5m\_bioc\_MPI-ESM1-2-HR\_ssp585\_2041-2060.tif

├── wc2.1\_2.5m\_prec\_MPI-ESM1-2-HR\_ssp585\_2041-2060.tif

├── wc2.1\_2.5m\_tmax\_MPI-ESM1-2-HR\_ssp585\_2041-2060.tif

└── wc2.1\_2.5m\_tmin\_MPI-ESM1-2-HR\_ssp585\_2041-2060.tif

**CHAPTER III**

**Literature Review and Theoretical Background**

History

Literature:

First viticultural

Roman Empire and its vineyrads in Britannica

Prague vineyards possibility unlocked by slopes with south orientation

Evolve of vineyerds around the world

Chapter 2 – Literature review

Chapter 3 (methodology and Data)

Chapter 4 (Results)

Chapter 5 Conclusion

Table 1. [Name of the table]Compilation of basic values of the parameters of asessment of companies in european countries in 2000-2004

| **Lp.** | **Nazwy parametrów oceny** | **values of the parameters of asessment [million PLN] in years** | | | |
| --- | --- | --- | --- | --- | --- |
| **2000** | **2001** | **2003** | **2004** |
| 1. | Parameter 1 | 1200 | 123 | 234 | 345 |
| 2. | Parameter 2 | 234 | 234 | 67 | 543 |
| 3. | Parameter 3 | 234 | 43567 | 789 | 876 |
| 4. | Parameter 4 | 12345 | 234 | 765 | 987 |
| 4. | Parameter 5 | 123 | 56 | 897 | 123 |
| 6. | Parameter 6 | 5478 | 2 | 234 | 345 |

*Source:* Own study, based on: J. Kowalski „Parameters of asessment of companies in european countries”, PWN, Warszawa 2005, page 234.

**Pictures**

In terms of drawings, a uniform notation is provided (to standardize and simplify the whole thesis), assuming that the drawing is a chart, diagram and graphic image. The numerical order of drawings is similar to the tables: from "1" to "n" in the whole thesis, starting with the short "Fig."with a space and a number with a dot (ordinal numeral. It is possibile to describe the drawings in two ways (examples in figures 1, 2 and 3):

• above the drawing, than the description of the drawing looks similar to the description of the table (without a dot at the end, as it is a suptitle)

• under the drawing, than a dot is placed at the end of the description, because it is a sentence. In this case, additional information, interpreting the drawing, can be added to the description.

Pic. 1.[Name of the picture] Wykres zmian parametru osi pionowej w latach 2000-2004



*Source:* Own study, based on: J. Nowak „Zmienność parametrów jakościowych wirtualnego banku komercyjnego w latach 2000-2004”, PWN, Warszawa 2005, p. 23.





Pic. 1. [Name of the Picture]Wykres zmian parametru osi pionowej w latach 2000-2004.

Oznaczenia: jm. - jednostka miary.

*Source:* Own study, based on: J. Nowak „Zmienność parametrów jakościowych wirtualnego banku komercyjnego w latach 2000-2004”, PWN, Warszawa 2005, p. 23.

Pic. 2. [Name of the picture]Schemat struktury przedsiębiorstwa X w układzie pionowym



*Source:* Own study based on: J. Jankowska-Kowalska „Kształtowanie się wielkości firm z uwzględnieniem zarządzania pionowego i poziomego”, PWN, Warszawa 2005, s. 123.



Pic. 2. [Name of the picture]Schemat struktury przedsiębiorstwa X w układzie pionowym.

*Source:* Own study based on: J. Jankowska-Kowalska „Kształtowanie się wielkości firm z uwzględnieniem zarządzania pionowego i poziomego”, PWN, Warszawa 2005, p. 123.

Pic. 3. [Name of the picture] Widok świetlanej perspektywy firmy X



*Source:* Opracowanie własne na podstawie: M. Yanki-Yank „Obrazy rozwojowe firm w koncepcji wirtualnej”, Wydawnictwo Y, Tokyo 2005, p. 213.





*Source:* Opracowanie własne na podstawie: M. Yanki-Yank „Obrazy rozwojowe firm w koncepcji wirtualnej”, Wydawnictwo Y, Tokyo 2005, p. 213.

Pic. 3. [Name of the picture] Widok świetlanej perspektywy firmy X.

It is recommended to use for drawings a similar system of using a single paragraph as for the table. Aa a consequence, all sources such as tables or drawings will be more compact and distinguished from the text

**Numerical lists**

Numerical lists are lists of options that we want to extract one below each other as next elements. The list is preceded by a colon. If the list is based on source, the source should be given as a footnote, before the colon. To standardize and improve the readability of the text of the thesis, it is advisable to:

• precede the letters with a dash and start from the left margin

• at the end of enumerated items you can not put any sign (recommended), comma or semicolon. However, there should be a dot at the end of the last enumerated item

• each enumerated element should be coherent as a sentence with the beginning of the text that starts the list (as if it was independent from the others).

To maintain the elegance of the list, it is recommended to use an automatic list creation system (using the Format / Bullets and numbering option).

Enumerated list numbering is generally used in case of:

• the importance of keeping the order of enumerated items

• reference in the text to the specified number of the enumerated item.

**Formulas**

Formulas appearing in the thesis can be numbered, which is justified in case of referencing to the number in the text of the thesis. Formulas should be centered between right and left margins. Longer formulas (exceeding 1 row) should start from the left margin. In case of using numbering of the formulas, it is recommended to use square brackets and number the subsequent elements with Arabic numbers. Font size and type: 12 points, Times New Roman. It is not recommended to write formulas in bold or use a larger font than for the rest of the text. However, it is recommended to use a space of 1 line above and below the formula. If the formula includes symbols that require commenting (description), the word "where" (from the left margin and lowercase) should be given under the formula, and a list of explanatory elements should be created starting with a 1 cm tab. The spaces in the list should be single, with separators as in the lists listed in the text. Three examples of creating formulas and their forms with descriptions.

**Example 1** of formula for indicator X[[1]](#footnote-0):

Parameter Y

Indicator X = -----------------------

Parameter Z

where:

Parameter Y - parameter located in the numerator, is the numerator of the fraction

Parameter Z - parameter located in the denominator, being the denominator of the fraction.

**Example 2** of formula for indicator X[[2]](#footnote-1):



where:

Parametr Y - parameter located in the numerator, is the numerator of the fraction

Parametr Z - parameter located in the denominator, being the denominator of the fraction.

**Example 3** pattern for indicator X[[3]](#footnote-2):

where:

Parameter Y - parameter located in the is the numerator of the fraction

Parametr Z - parameetr located in the denominator, being the denominator of the fraction.

**CHAPTER I**

# <title of the chapter 1>

The text of this chapter as a paragraph should begin with a tab equal to 1 cm, centered (alignment between right and left margins), maintaining a distance between the lines of 1.5 verse.

Next paragraph ....

Between the title CHAPTER I and its content - keep the distance of 1 verse, between this content and the further content of the chapter - distance of 1.5 verses (as above). Similarly, subsections should be numbered in Arabic numbers as subsections of a given chapter, e.g. 1.1. for CHAPTER I, keeping the distance between the text above and below the sub-chapter equal to 1.5 verse. Do not use automatic numbering of chapters, nor subsections.

## 1.1. <Subheading shoud be written in bold, and in case of longer text going to the the next line, wrap with the lifting of the subsection number and single verse space. Center the subheading>

Begin - as a paragraph - with a tab equal to 1 cm, following 1.5 verse space from the subtitle of this chapter, center the text.

### 1.1.1. <Subheading>

Keep the space between the text and the subtitle 1.5 verse. Start the title from the left margin, center the text in the content of this subheading.

**1.1.2. <Subheading>**

Next subheading with its text.

**1.1.3. <Subheading>**

Next subheading on the same level and its text.

**1.2. <Subheading>**

Subheading on higher level than the previous one.

**1.2.1. <Subheading>**

Keep the distance between the text and subheading 1,5 verse. Start the title from the left margin, center the text in the content of this subheading.

**1.2.2. <Subheading>**

Next subheading with its text.

**1.2.3. <Subheading>**

Next subheading on the same level and its text .

**CHAPTER II**

**<title of the chapter>**

**2.1. <Subheading>**

..................................................................

**2.1.1. <Subheading>**

...................................................................

**2.1.2. <Subheading>**

......................................................................

**2.1.3. <Subheading>**

.......................................................................

**2.2. <Subheading>**

.......................................................................

**2.2.1. <Subheading>**

.......................................................................

**2.2.2. <Subheading>**

.......................................................................

### BIBLIOGRAPHY

<Note: Rules of bibliographic description are given in accordance to the latest Polish standards PN-ISO 690: 2002 (printed documents) and PN-ISO 690-2: 1999 (electronic documents). The bibliographic description may be more expanded (e.g. with the name of the publishing house), which is not shown in the examples below..>

<Surname and first letter of the author, name of the work, publishing house, place and year. The bibliography can be devided into subchapters, e.g. Books, Magazines, Legal acts, Conference materials, Websites - when it is justified by their large number in particular group types>

<Next bibliography item - 1 line space. Separate subsections of bibliography should be treated similarly to subsections at dissertation - maintaining the space between the subsection title and the text of the listing -1.5-line verse.>

*Examples*:

Assorodobraj Nina. Początki klasy robotniczej. Problem rąk roboczych w przemyśle polskim epoki stanisławowskiej. Warszawa 1966.

Atkinson A.B. The Economic Consequences of Rolling Back the Welfare State. Cambridge 1999.

Janos Andrew C. The Politics of Backwardness in Hungary, 1825-1945. Princeton 1982.

\_\_\_\_ Politics and Paradigms. Changing Theories of Change in Social Science. Stanford 1986.

\_\_\_\_ East Central Europe in the Modern World: The Politics of the Borderlands from Pre- to Postcommunism. Stanford, 2000.

Reykowski Janusz. Czy doświadczenie transformacji ujawniło prawdziwe oblicze Polaków? In Dylematy nauki i konflikty wartości. Red. Ewa Chmielecka et al. Warszawa 2005, p. 341-345.

Ruciński Robert. O sposobach finansowania studiów przez mieszkańców miast pruskich w późnym średniowieczu. Roczniki Dziejów Społecznych i Gospodarczych. T. LXIII, 2003, p. 87-101.

World Bank. Meeting the Challenge of Africa’s Development: A World Bank Group Action Plan. World Bank, September 2005. On line. Date of Access: September 9th 2005.

http://siteresources.worldbank.org/INTAFRICA/Resources/aap\_9\_7\_05.pdf

**LIST OF APPENDICES**

*<On May 23, 2007, Vice-Dean J. Kudła changed the LIST OF INDEXES to the LIST OF APPENDICES according to the following layout>*

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| --- | --- | --- |
| ISO | - | International Standard Organisation (Międzynarodowa Organizacja Normalizacyjna) |

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**ANNEXES**

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...............................................

**Annex 2. Questionnaire type B**

.........................

**Annex 3. View of the SAS computer printout sheet**

..............................

**Annex 4. Summary table of data characterising company X**

...................................

1. By using the text edition. [↑](#footnote-ref-0)
2. By using the option: Draw / Draw a text field. [↑](#footnote-ref-1)
3. By using the option: Insert / Object / Microsoft Equation. [↑](#footnote-ref-2)