Geospatial trends of bioclimatic indexes in the topographically complex region of Barolo DOCG

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Abstract

Bioclimatic indexes and temperature-based characteristics are regularly used in viticulture to evaluate growing region quality potential, identify climatic risks, and to develop vineyard management strategies. In this study, linear models were developed for temperature and bioclimatic index dependent variables (Huglin Index (HI), Average Growing Season Temperature (GST), Diurnal Range (DR) as well as Maximum Monthly Temperature (TMax), Minimum Monthly Temperature (TMin) and Average Monthly Temperature (TAvg)) using topographical characteristics (Elevation, Aspect, Slope, Latitude) as independent variables. The data from 45 weather stations within a 40 km radius of the Barolo DOCG growing region from 1996 to 2019 was used to develop these models. Bioclimatic indexes and temperature characteristics with higher temperature values (TMax and TAvg) had a significant negative relationship with elevation. However, minimum monthly temperature of all months and the maximum monthly temperature in colder months (December to February) rarely displayed a significant relationship with elevation and in some cases showed a slightly significant positive relationship with north and west aspects.

Introduction

Barolo DOCG is produced from the cv. Nebbiolo in a small but economically important wine region in Piemonte in northwestern Italy. It lies approximately 55 km southwest of Torino and covers 70 km^2 of land. The southern end of the region increases in elevation as it encroaches on the Apennine Mountain foothills. The Tanaro river flows outside the western edge of Barolo DOCG, making a sharp turn eastward above the northern boundary of the region. Three valleys have been carved into the region from Southwest to North, South to North and Southeast to North (Figure 1).

The area has an unusual tortuous topography formed from the receding of the Adriatic Sea which eroded three valleys leaving a landscape of steep and winding hills. Elevation ranges between approximately 170 m and 580 m. The overall morphology of the region is an amphitheatre opening and decreasing in elevation to the northeast. Slopes can have a gradient as great as 35 degrees.

It is commonly accepted that temperature normally decreases with increasing elevation (known as the lapse rate, Fairbridge & Oliver, 2005). Most observations that confirm this are at the macro-scale. However, due to thermal inversions, this effect can be dampened or reversed at the meso-scale in some regions (Maraun & Widmann, 2018).

Geospatial analysis using geostatistical techniques to identify relationships between topographical features and meso-scale climate variation can help to identify local climate characteristics influenced by topography that may not be identified at the macro-scale (Maraun & Widmann, 2018).

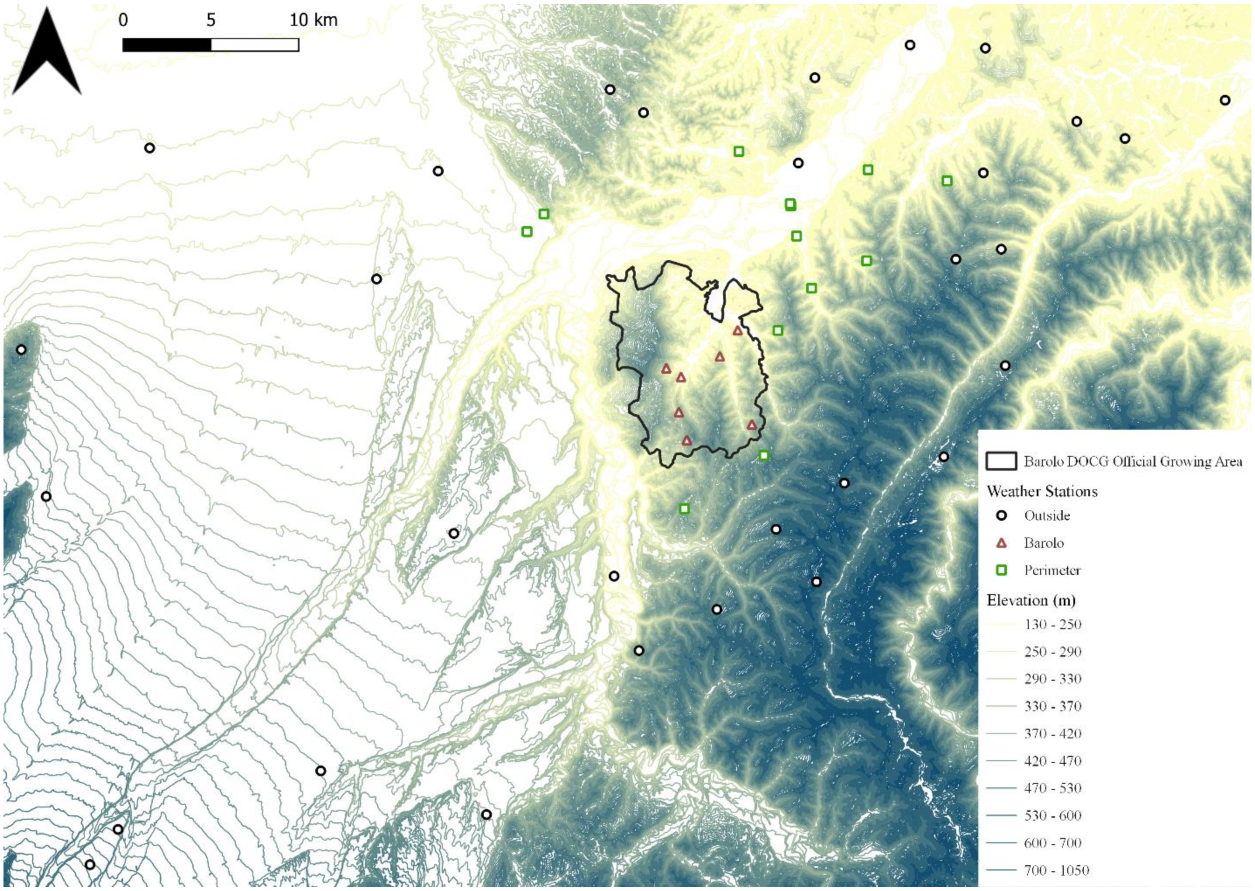

Figure 1. Area map showing Barolo DOCG growing area, weather stations used for linear model development, and elevation (m). Weather stations are subdivided by proximity to the Barolo region (Outside: >~15 km away from Barolo center; Perimeter: 10 km to 15 km from center; Barolo: inside growing region

Materials and methods

Data from 45 weather stations found within a 40 km radius of the center of the Barolo DOCG growing region was collected from the years between 1996 and 2019 (Figure 1). Prior to 1996 too few weather stations were operating in the region to produce reliable models. Independent variables associated with the local topography were extracted from a 10 m resolution Digital Elevation Model (DEM) (Tarquini et al., 2012). These variables included elevation, aspect, slope gradient and latitude. The independent variables were plotted against the Huglin Index (HI) (Huglin, 1978), average Growing Season Temperature (GST) (Jones, 2005), monthly Minimum Temperature (TMin), monthly Maximum Temperature (TMax), monthly Average Temperature (TAvg), and average monthly Diurnal Range from July to October (DR) calculated as Average Monthly TMax – Average Monthly TMin. Linear models and multiple-linear models were evaluated between independent and dependent variables to determine which relationships were consistently significant over all years of the study.

Kriging was performed using a grid at 100 m scale developed from the DEM with the independent variables Elevation (m), Slope (°), Aspect (°) and Latitude (m) extracted. Model selection was done through Leave One Out Cross Validation (LOOCV). Kriging with External Drift was used in cases where significant relationships were found in linear, additive, or interactive models between dependent and independent variables (Hengl et al., 2003). Ordinary Kriging was used in cases where no significant relationships with topography were identified in the linear models. Kriging results are not presented in this paper.

All statistical analysis was performed using R Statistical software (version 4.1.2) and RStudio (Build 351) (R Core Team, 2020; RStudio Team, 2019). Final maps were developed using QGIS 3.24 (QGIS Development Team, 2019).

Results and discussion

Results discussed are specific to the last year of the study (2019). They reflect a consistent trend found in all years, however, the strength of these trends depreciated in earlier years when fewer weather stations were operating.

Table 1. Linear model results for each temperature metric/bioclimatic index compared to topographical characteristics in 2019.

Climatic Measure	Elevation	Latitude	Aspect	Slope	Notes
HI	*** R^2 = 0.54 -	*** R^2 = 0.28 +	NS R^2 = 0.005 0	NS R^2 = 0.005 0	Latitude had a positive relationship with HI, GST, TMax and DR as elevation drops to the North-Northeast.
GST	*** R^2 = 0.49 -	** R^2 = 0.18 +	NS R^2 = 0.01 0	NS R^2 = 0.03 0	Similar results were observed for GST as for HI. However, in some years an additive model with elevation and aspect performed best.
TMax	*** R^2 = 0.43 -	*** R^2 = 0.26 +	NS R^2 = 0.00 0	NS R^2 = 0.01 0	Elevation and latitude influence TMax during warmer months. However, colder months often showed no relationship with elevation or, in some cases a slightly significant positive relationship with elevation.
TMin	NS R^2 = 0.01 0	NS R^2 = 0.00 0	NS R^2 = 0.03 0	NS R^2 = 0.02 0	Minimum Temperature rarely had a significant relationship with elevation. However, in some years (but not 2019) there was a slightly significant relationship with aspect.
DR	*** R^2 = 0.23 -	** R^2 = 0.18 +	NS R^2 = 0.01 0	NS R^2 = 0.03 0	In some years an additive model with elevation and aspect performed best. In all cases, DR had a negative relationship with elevation.

TMax, TMin and DR for September 2019; P-value: '***' = 0; '**' = 0.001; '*' = 0.05; '.' = 0.1; 'NS' = Not Significant; R^2 = Coefficient of Determination; +, -, 0 = positive, negative or zero relationship.

HI and GST each had a consistently significant negative relationship with elevation as did TMax and TAvg from April to October in all years (Table 1). Maximum and Average monthly temperatures in colder months (December to February) had less significant or completely non-significant relationships with elevation and in some cases the relationship became positive.

All average Minimum Monthly temperatures had no significant relationship with elevation (Table 1). In some months, a slightly positive significant relationship could be identified between TMin or TMax (in colder months (November to March) and western or northern facing aspect. This relationship was inconsistent likely due to scale issues wherein, the influence of aspect on temperature occurs at a smaller scale than was reflected in this work (Mania et al., 2021; Quénol & Bonnardot, 2014).

Due to the unexpected lack of relationship between TMin and elevation, diurnal range (TMax-TMin) was investigated. DR displayed a significant negative relationship with elevation (Table 1), suggesting that it was possible that higher elevations have a lower variation in temperature compared to lower elevations in this region of study.

This is contrary to other studies which typically observed a significantly positive relationship between diurnal range and elevation (Zhang et al., 2021).

DR presented a low R^2 with elevation and latitude in all years (Table 1). However, this relationship was moderately to strongly negatively significant in all years. Many other factors influencing regional climate were not considered such as wind, proximity to mountains (both the Apennines to the south and the Alps in the west and north), soil moisture, and the impact of insolation were not included in models due to a lack of data, and the complexity of these variables.

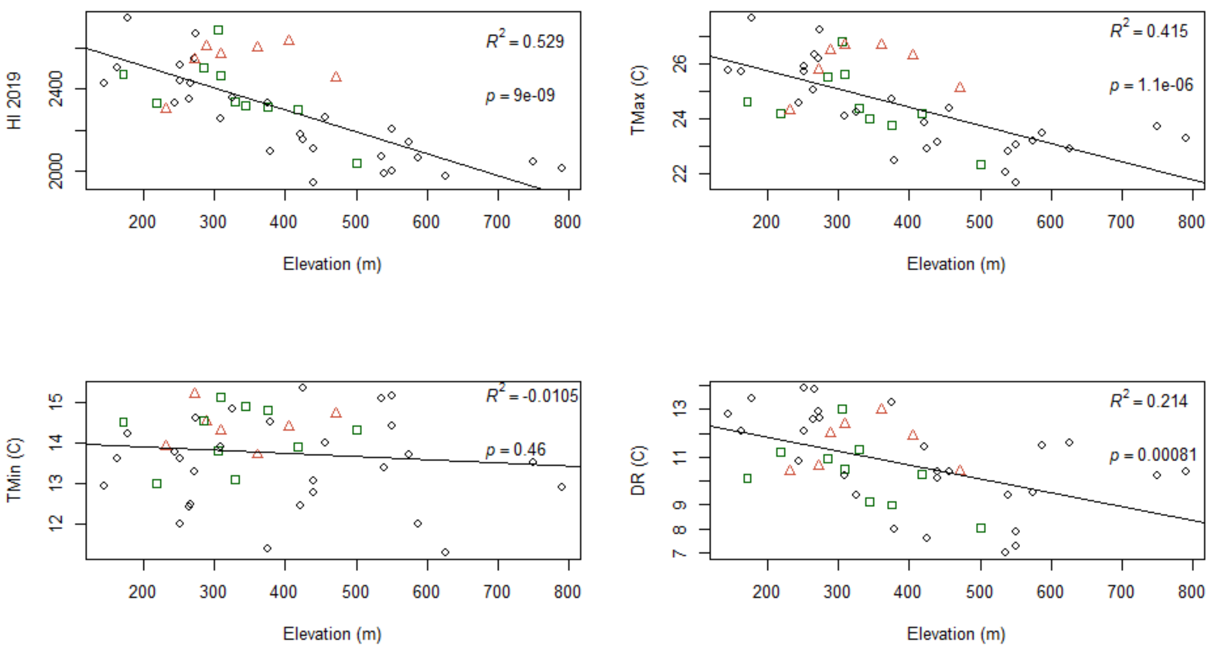

Figure 2. Linear Models for HI, and TMax, TMin and DR of September 2019.

Symbols correlate with weather station locations (Figure 1): (○) Outside; (□) Perimeter; (△) Barolo

The seven weather stations in Barolo DOCG growing region (Δ) suggest a non-linear relationship between HI, TMax and DR with Elevation (Figure 2). Further, it appears that TMax, HI and DR increase to a maximum between 300 m and 400 m elevation and then decline again. This could be due to a more complex relationship between these variables within the growing region which is possibly more topographically tortuous. This trend could be elaborated or dismissed with the addition of more data from within the growing area.

Some research shows that larger diurnal ranges may improve grape qualities by preserving anthocyanins and acid profiles (Cohen et al., 2012a; Mori et al., 2005; Yan et al., 2020). However, other research suggests that a large diurnal range may not be optimal if day temperatures are too high or night temperatures are too low and that the optimal diurnal range could actually be close to zero as in the case of one research piece which established that the optimal temperature was almost the same for both night and day at 22 C (Kobayashi et al., 1967). Further, several studies suggest that extreme maximum temperatures are more of an influencing factor on quality grape production than diurnal range (Cohen et al., 2012b; Mori et al., 2007; Yan et al., 2020). However, identifying geospatial trends in monthly and annual climatic behaviour remains fundamental for strategic viticultural management and future mitigative planning for expected climatic changes in the future.

Conclusion

Due to the complex morphology of the Barolo DOCG region, macro-scale climate characteristics do not clearly represent meso-scale climate behaviour. Meso-scale geostatistical modelling is a useful tool that can be utilized to identify region specific anomalous meso-scale climate trends which can help to gain a deeper understanding of climate behaviour at the regional or local level. Understanding meso-scale climate behaviour and interactions with local topography can enable more refined risk analysis and vineyard management strategy.

Limitations to meso-scale temperature-based geostatistical and statistical analysis predominantly lies in data availability both spatially and temporally, along with the complexity derived from confounding and unknown variables. Geospatial analysis requires a suitable number of data points which is not always available. This was evident in this study before 1996 when so few data points were available that the model became highly unstable leading to more unreliable interpretation of the regional temperature behaviour.

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